A global assessment of the state of plant health

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 (1) provisioning (food, fiber, and material), (2) regulation (climate, atmosphere, water, and soils), and (3) cultural (re-creation, 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 greatest risk. The overview of results generated from this work enables identifying directions for future research to be championed by a new generation of scientists and revived public extension services. Breakthrough from science is 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.

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

Introduction

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 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 re-creation, 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 life. It seems that humans take for granted the food, the air, the water, the 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 co-exist with nature in the biosphere. Some aspects of this question may be addressed from the plant health standpoint, because the human appropriation of global resources (Vitousek et al. 1986; Rojstaczer et al. 2001) 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 2022a; b). 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 2022a;

2022b), arranged according to 16 Plant Systems, are then summarized. Key elements derived from the GPHA are addressed in a final section.

Objectives of the Global Plant Health Assessment

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 (1) are iconic in their contribution to human cultures and societies (cultural role); (2) that play critical roles in the mainstay of humanity, including, but not limited to, food security (provisioning role); and (3) 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, 1995; MEA, 2005) were selected for their specific roles towards 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 et al. 2012) 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 (10^2-10^4 years). Primeval forests have evolutionary time constants in the range of 10^4-10^6 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 are increasingly costly economically and environmentally. 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 which was standardized in format and size (Supplementary file A) through a specified set of questions. Each report is grounded on 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 x 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 outline in Sidebar 1 (see details in Supplementary File A).

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 (2005), the information gathered was verified internally as outlined in Sidebar 2. Each member of the Coordination Group acted as an Editor for a given report, and had the report reviewed by a Reviewer. Lead Experts 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) was thus assembled, constituting the basis of the GPHA Report (GPHA, 2022a; 2022b) 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 (Figure 1). Among these (Figure 2), 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. 2). 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. 2). 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, for 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. 3A; 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* × *acerifoli*a (Aiton) Willd, syn. *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. 3A) 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 coupled 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 South-East Asia, where two or three rice seasons per year are practiced, and amplify the virus populations. As the summer monsoon progresses from South-East 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, 2022a; 2022b).

Dramatic examples of past pathogen invasions include the destruction of North American chestnut forests by chestnut blight (*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 (1) the pathogen's geographic distribution, (2) the distribution of its host, and (3) 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 the third of Weltzien's conditions has not been sufficiently considered.

Evolutionary biology of plant pathogens

Weltzien's (1972) suitable "environmental factors" for the disease has 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 non-managed 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 for 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 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 non-host 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 co-evolved 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 (1) (following Gilbert 2002) pathogens are strong contributors to plant evolution; and (2) the larger the land mass (Wilson 1992), the longer-lasting the plant-pathogen co-evolution, 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. 3 B). The effects of climate change on plant diseases have been addressed in many studies and reviews (e.g., Chakraborty and Newton 2011; Sturrock et al. 2011; Garrett et al. 2011; Jeger, 2022). 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: (1) direct effects on the life-cycles of pathogens (e.g., rice and wheat in South Asia), (2) direct effects on pathogen vectors (through increased vector activity; vegetables in sub-Saharan Africa), (3) indirect effects via change in agricultural practices (maize in North America, wheat in South Asia), and (4) 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 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 Global Plant Health Assessment 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 interactions between pathogens and other micro-organisms in the phytobiome and macro-organisms 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 which prevails, or re-appears, in some plant systems (Fig. 3C, Tables 1 and 2, and Supplementary file C).

Perennial, complex, and multiple 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). Inter-specific 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 non-susceptible trees along the Canal du Midi, France, to generate botanical diversity and reduce epidemic spread (GPHA 2022a; 2022b). 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, South, and South-East Asia (GPHA 2022a; 2022b). 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 technology 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 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

US 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 cow-dung.

Taking inspiration from nature to better manage agroecosystems is an old and important idea (Zadoks and Schein 1979; Wulf 2015). 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 from nature will not ensure total health, but may ward off disasters in many cases. There is debate on how much agriculture should be re-natured, 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, pers. obs.), 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 x Ecoregion] reports (Supplementary File C; GPHA 2022a; 2022b; Fig. 3D). 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 South-east 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., Coyle 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 policy-makers.

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. 2008; Paseka et al. 2020). Yet one cannot help seeing the concept of ecosystem service as a very strange way indeed to see Nature. Nature is not meant, or designed, to "service" humans. Instead, humans contribute to the state of the Nature to which they belong. Sadly, human services to Nature often are negative. The concept of ecosystem services is anthropocentric and utilitarian. When applied to food supply or forestry, for example, the concept is particularly useful; it however 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 thoughts 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 thoughts to address these questions.

A first line of thoughts is that collective action (Nordman, 2021; among scientists and with support of scientific societies), on 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 re-construction of public advisory systems to farmers (i.e., extension services), are urgent in the Global South, sub-Saharan Africa in particular.

Global change might perhaps be slowed but is inexorable because of the inertia of Earth climate and its primary driver, human population. Resilience through botanical and genetic diversification seems essential to minimize the current and future impacts of global change. This has application 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 un-assessed 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. 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 multi-pathogen 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 which impair plant health, the diversity of their consequences on ecosystem services, and the diversity of factors which 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, 2011), which have to urgently be simultaneously addressed: climate (Skea et al. 2022), food (FAO, IFAD, UNICEF, WFP, and WHO, 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, 2011); 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.

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(2):80-86.

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

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. Schulze, ED., Mooney, H.A. (eds) Springer Science & Business Media.

Bonman, J. M., Khush, G. S., and Nelson, R. J., 1992. Breeding rice for resistance to pests. Annu. Rev. Phytopathol. 30(1):507-528.

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., et al. 2008. *Phytophthora cinnamomi* and Australia's biodiversity: impacts, predictions and progress towards control. Aust. J. Bot. 56(4):279-310.

Cardenas, R.E., Valencia, R., Kraft, N.J., 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(4):939-952.

Ceresini, P. C., Castroagudín, V. L., Rodrigues, F. Á., Rios, J. A., Eduardo Aucique-Pérez, C., Moreira, S. I., et al. 2018. Wheat blast: past, present, and future. Annu. Rev. Phytopathol. 56:427–456.

Chadwick, D., and Marsh, J., eds. 1993. *Crop Protection and Sustainable Agriculture*. Chichester, UK: John Wiley & Sons.

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

Cheatham, M. R., Rouse, M. N., Esker, P. D., Ignacio, S., Pradel, W., Raymundo, R., et al. 2009. Beyond yield: plant disease in the context of ecosystem services. Phytopathology 99:1228-1236.

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. Wallingford, UK: CABI.

Connor, D. J. 2008. Organic agriculture cannot feed the world. Field Crops Research 106(2):187.

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.

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. 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):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. USA 116:7371-7376. doi: 10.1073/pnas.1810767116.

Fan, J., Yang, J., Wang, Y.-Q., et al. 2016. Current understanding on *Villosiclava virens*, a unique flower – infecting fungus causing rice false smut disease: A profile on the rice false smut pathogen. Mol. Plant Pathol. 17:1321–1330. https://doi.org/10.1111/mpp.12362

Garrett, K. A., Forbes, G. A., Savary, S., Skelsey, P., Sparks, A. H., Valdivia, C., et al. 2011. Complexity in climate-change impacts: an analytical framework for effects mediated by plant disease: Complexity in climate-change impacts. 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. Doi: 10.1111/j.1439-0329.2010.00654.x

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. W. E., Koch, E., & Schaffrath, U. 2010. *Phakopsora pachyrhizi*, the causal agent of Asian soybean rust. Mol. Plant Pathol. 11:169-177.

GPHA 2022a. 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. Willocquet, L., Singh, M., Sah, S., Bove, F., Savary, S., Yuen, J. (Eds.) First Edition, epub. ISBN: 978-91-988233-0-1. Available at:https://www.isppweb.org/about_gpha.asp

GPHA 2022b. 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. Willocquet, L., Singh, M., Sah, S., Bove, F., Savary, S., Yuen, J. (Eds.) First Edition, pdf. ISBN: 978-91-988233-1-8. Available at: 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(3859):1243-1248.

Heesterbeek, J. A. P. and Zadoks, J. C., 1987. Modelling pandemics of quarantine pests and diseases: problems and perspectives. Crop Prot. 6(4):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., and Hansen, J.G. 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(3):402-411.

Hyatt-Twynam, S. R., Parnell, S., Stutt, R. O., Gottwald, T. R., Gilligan, C. A., and Cunniffe, N. J. 2017. Risk-based management of invading plant disease. New Phytol. 214(3):1317-1329.

Van Ittersum, M. K., van Bussel, L. G. J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., et al. 2016. Can sub-Saharan Africa feed itself? Proc. Natl. Acad. Sci. U.S.A. 113:14964–14969.

Jeger M. J. 2022. The impact of climate change on disease in wild plant populations and communities. Plant Pathol. 71:111–130. https: //doi.org/10.1111/ppa.134

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

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., 2012. *On Systems Analysis and Simulation of Ecological Processes with Examples in CSMP and FORTRAN* (Vol. 1). Berlin, Heidelberg: Springer Science & Business Media.

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., and Kumar, P. L. 2015. Maize lethal necrosis (MLN), an emerging threat to maize-based food security in sub-Saharan Africa. Phytopathology 105(7):956-965.

MEA – Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-being: Synthesis*. Washington, DC, USA: Island Press.

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(1):1-13.

Myers, N., Mittermeier, R.A., Mittermeier, C.G., Da Fonseca, G.A. and Kent, J., 2000. Biodiversity hotspots for conservation priorities. Nature 403(6772):853-858.

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

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., et al. 2020. Disease-mediated ecosystem services: Pathogens, plants, and people. Tr. 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., and Mazzoni, V., 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.* Mexico: CIMMYT.

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 Crop. Res. 120(2):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., Klain, S., Levine, J., and Tam, J. 2013. Humans and nature: how knowing and experiencing nature affect well-being. Annu. Rev. Envir. Res. 38:473-502.

Savary, S. 2014. The roots of crop health: cropping practices and disease management. Food Secur. 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(12):1001-1009.

Savary, S., Teng, P. S., Willocquet, L., and Nutter, Jr, F. W. 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 Crop. 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. 1467

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.

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. Retrieved 9 April 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.

Saunders, D. G., Pretorius, Z. A. and Hovmøller, M. S., 2019. Tackling the re-emergence of wheat stem rust in Western Europe. Communications Biology 2(1):51.

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. 1874 https://doi.org/10.3389/fpls.2020.601009

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.

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. Rome: FAO. https://doi.org/10.4060/cc0639en

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*. Cambridge, USA: Belknap Press of Harvard University Press.

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

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

Zadoks, J. C., and Schein, R. D. 1979. *Epidemiology and Plant Disease Management*. New York, USA: Oxford University Press.

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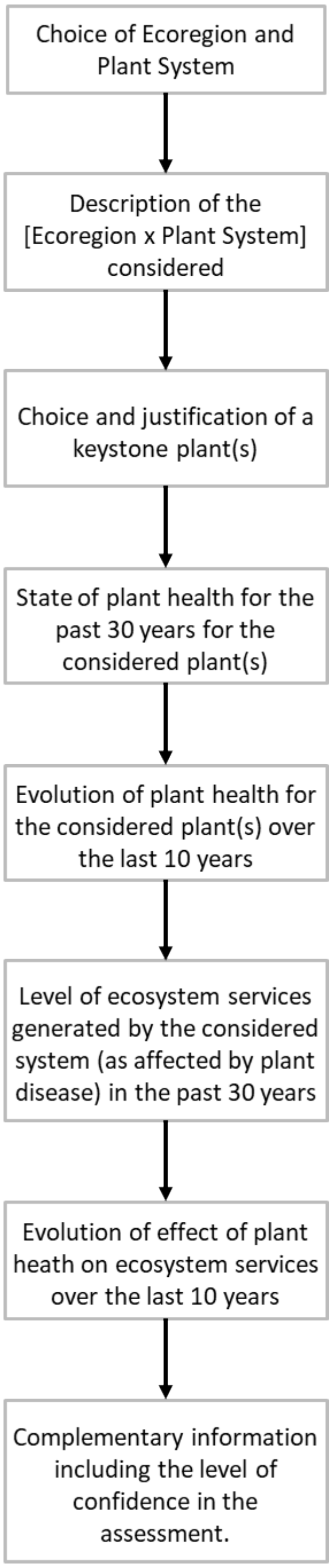
Sidebar 1


Choice of Ecoregion and Plant System
Description of the [Ecoregion x Plant System] considered
Choice and justification of a keystone plant(s)
State of plant health for the past 30 years for the considered plant(s)
Evolution of plant health for the considered plant(s) over the last 10 years
Level of ecosystem services generated by the considered system (as affected by plant disease) in the past 30 years
Evolution of effect of plant heath on ecosystem services over the last 10 years
Complementary information including the level of confidence in the assessment.

Sidebar 2

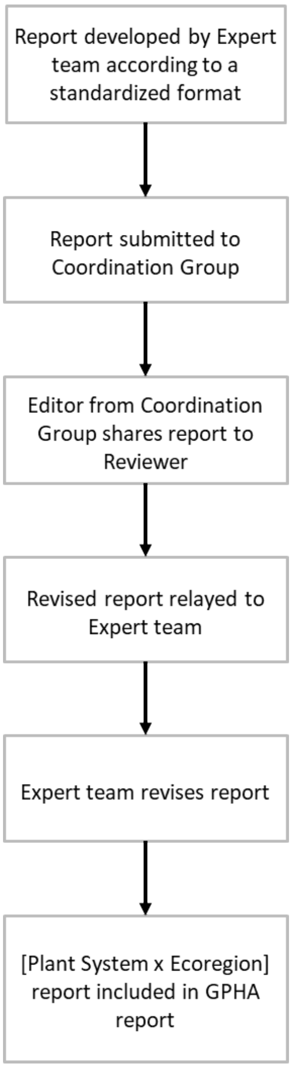
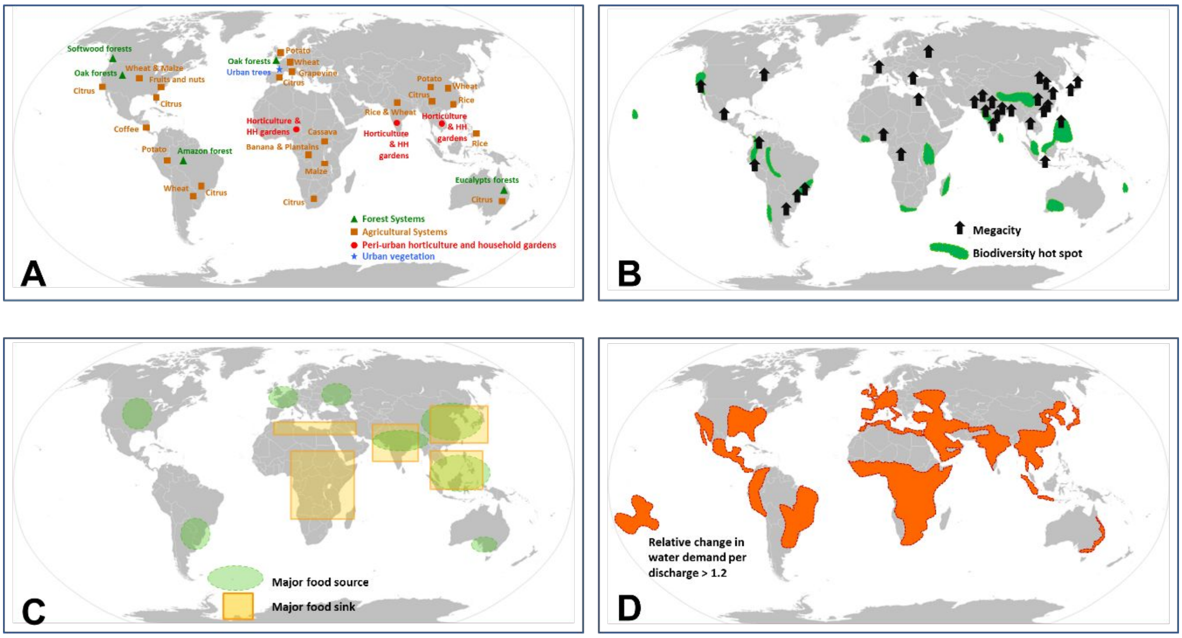

Report developed by Expert team according to a standardized format
Report submitted to Coordination Group
Editor from Coordination Group shares report to Reviewer
Revised report relayed to Expert team
Expert team revises report
[Plant System x Ecoregion] report included in GPHA report

Figure 1. Distribution of [Plant System x Ecoregion] systems considered in the Global Plant Health Assessment, megacities, biodiversity hotspots, sources and sinks of food, and water resource



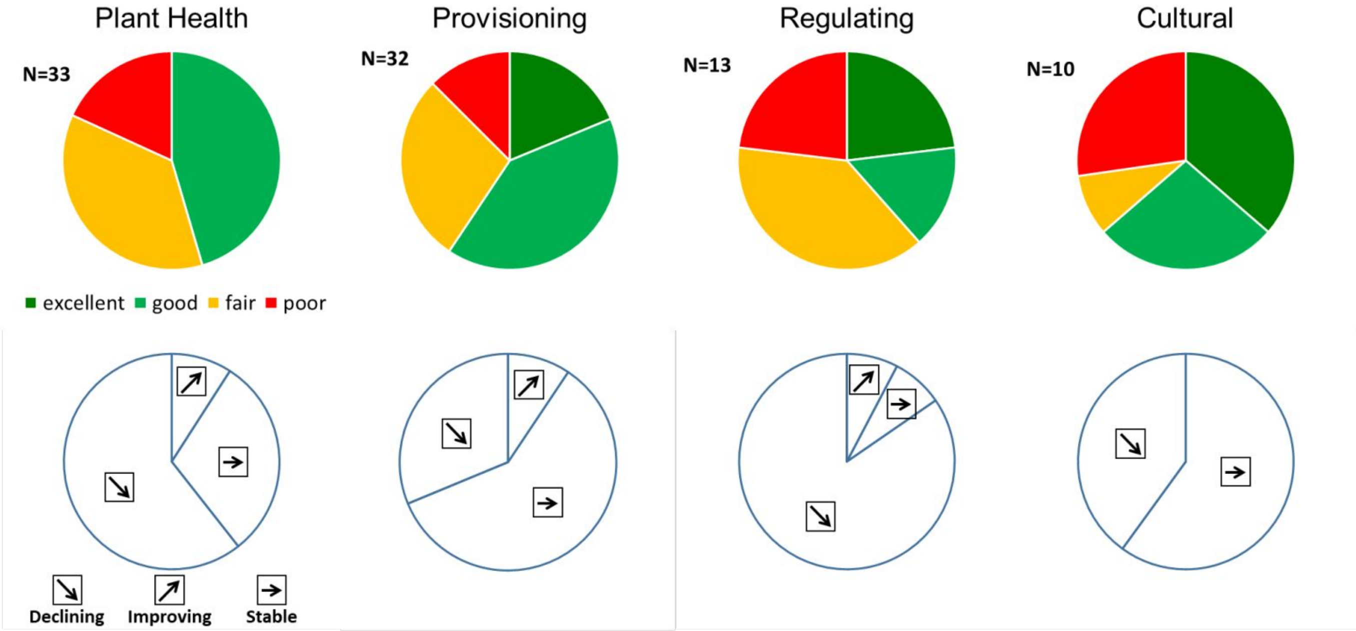
A: Approximate locations of the [Plant System x Ecoregion] systems considered in the Global Plant Health Assessment.

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.

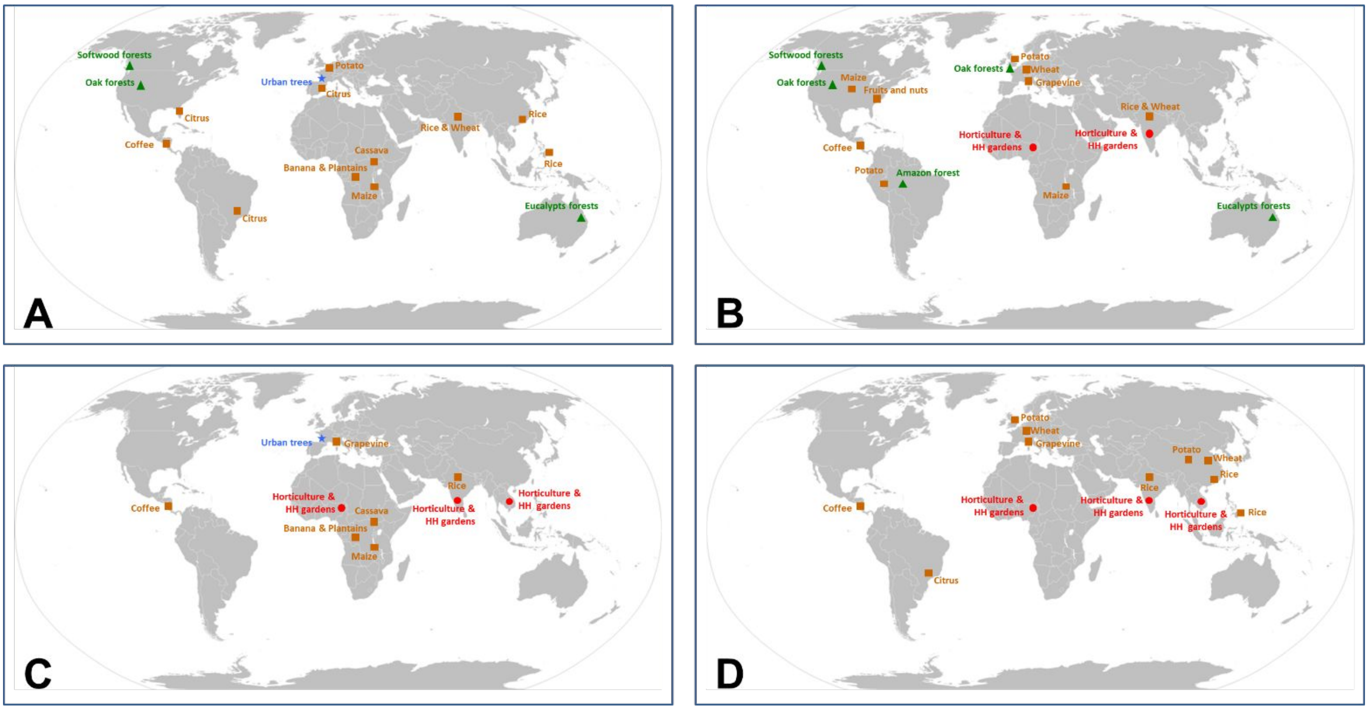
D: Water discharge based on climate change and population. Approximately redrawn from Vörösmarty et al. (2000).

Figure 2. 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 cultural services) considered. Entries indicate the number of [Ecoregion × Plant System] considered.

Fig. 3. Distribution of key challenges associated with plant health as reported in the Global Plant Health Assessment



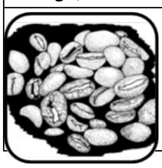
A. Pathogen invasions. Large scale polyetic disease expansions (i.e., pandemics, Heesterbeek and Zadoks, 1987) are reported in several forest systems (oak and softwood forests in North America; eucalypt forests in Australia), with potentially severe consequences on biodiversity. Perennial plant systems (urban trees, citrus plantations in the New World and Europe) are also concerned. 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 South East Asia appears to have been associated with that of hybrid rice cultivation. In the recent decades, a coupled regional climate - disease system has established yearly in South-East Asia (where vectors multiply and acquire viruses) and East Asia (to which viruliferous vectors are transported as the summer monsoon progresses northwards; see details in text and Supplementary File C).

B. Climate change. The increased frequency of extended droughts and excessive rains is reported in the Global Plant Health Assessment, 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 (Fig. 3A). Vegetable production in peri-urban systems of sub-Saharan Africa and South Asia are also concerned, as a result of increased pathogen vector activity.

C. Inspiration of nature in human-made and -managed plant systems. Perennial, complex, and multiple 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 inter-specific diversity prevails in many annual field crop systems of sub-Saharan Africa. Diseased plane trees are replaced by non-susceptible 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, and South-East Asia.

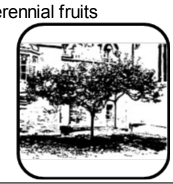
D. Pesticide usage. An array of issues concerns the use of pesticides. Pesticide usage may be: (1) insufficient and/or inadequate (e.g., coffee, Central America); (2) the sole alternative to disease control, leading to over-reliance (e.g., potato, Western Europe), (3) inadequate for lack of chemical innovation in new compounds (e.g., grapevine, Western Europe), (4) challenged by pathogen adaptation (e.g., wheat, Western Europe), (5) 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 South-east Asia), (6) associated with the use of banned pesticides, or pesticides that are dangerous to human health (vegetables, sub-Saharan Africa).

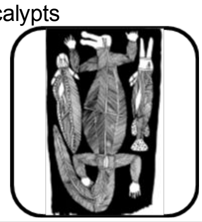
Table 1. List of selected Plant Systems and Ecoregions: importance and challenges

Plant Systems and their meaning (society, cultural)	Importance of ecosystem services	Known challenges of plant systems, including plant diseases	Ecoregions selected
 **Wheat** *Line drawing: Demeter, goddess of harvest and agriculture, on a silver coin, 4th century BC, 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 creating yield ceilings.	WE, NAm, SAm, EA, SA
 **Rice** *Line drawing: Ifugao Sculpture, Philippines. The Louvre.*	Rice is the icon of world's food crops. All of it is intended for human food, not for animal feed, biofuel, or industrial purpose. Most of the world's rice is produced and consumed in Asia, home to four billion humans and of 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** *Line drawing: Maya maize god. He also is the patron of scribal arts, which he invented. Classic Period (200-900 AD).*	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, especially in SSA where several pandemics have occurred and disease emergences are threatening.	NAm, SSA
 **Potato** *Line drawing: 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 producing 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** *Line drawing: Head from Ife (Nigeria): 14th-15th century AD, bronze.*	*Manihot esculenta*, a 16th century introduction of slave traders from the Amazon to Africa, is critical to food security in SSA.	Cassava has a chronically poor productivity everywhere in SSA. Plant diseases are known as major bottleneck to productivity. Several pandemics have occurred in the past 30 years.	SSA
 **Banana and plantains** *Line drawing: 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 new, grave, diseases have developed recently.	SSA
 **Grapevine** *Line drawing: Dionysos in a ship, sailing among dolphins. Attic kylix, ca. 53 BC. Vulci, Italy.*	Grapevine is at the heart of Western culture. Spain, France and Italy are the world 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** *Line drawing: 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** *Line drawing: Sidamo coffee (Coffea arabica).*	Arabica coffee (*Coffea arabica*) is one of the most traded agricultural products in the world. Coffee cultivation is especially	The coffee-shade tree system, the largest agroforestry system of CA, is threatened by new practices, new plant material (*C. robusta*). The coffee rust	CA

Coffee originates from Ethiopia and the southern tip of Arabia.	important in CAM, economically and environmentally.	crisis caused loss of income of many farm and field workers, aggravating poverty and food insecurity, and prompting migrations.	
 **Citrus** *Line drawing: O Meu Pé de Laranja Lima (My sweet Orange Tree), by José Moro 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
 **Peri-Urban Horticulture and Household gardens** *Line drawing: 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 challenges of meeting 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** *Line drawing: The Pulitzer Fountain, a fountain at Manhattan's Grand Army Plaza, New York, USA.*	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 2000 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 the Dutch Elm Disease (*Ophiostoma novo-ulmi*) in Europe.	WE
 **Oak forests** *Line drawing: 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 the Congress of the USA as 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** *Line drawing: 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	Large effects of climate change on the sustainability of softwood forest. Some species threatened of extinction by diseases. Complex biotic-abiotic interactions.	NAm
 **Amazon Forest** *Line drawing: 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** *Line drawing: 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

Abbreviations: WE: Western Europe; Nam: North America; Sam: South America; East Asia: EA; South Asia: SA; SEA: South-East Asia; sub-Saharan Africa: SSA; Central America: CA; Mediterranean: MED; Australasia: AUS. Line-drawings prepared from public domain sources (Wikipedia) and reprinted with permission from the GPHA, 2022.

Plant System	World Eco-region	Overall state of plant health	Level of confidence in assessment: Plant health	Main ecosystem services			Level of confidence in assessment: Services
				Provi-sioning	Regu-lating	Culture	
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 	South-East 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
	West 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
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
	South-East Asia	G ↘	reasonably confident	G →	F ↘	E →	uncertain to reasonably confident
Urban Trees 	Europe	P ↘	reasonably confident		P ↘	P ↘	reasonably confident
Oak forests 	West 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

Caption of Table 2

Overall state of plant health: color of boxes (green, yellow, orange) and letters (G, F, P, E) refer to three levels of plant health over the past 30 years: "good", "fair", "poor", or “excellent”. 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.

A global assessment of the state of plant health

Supplementary file A

reprinted with permission from the GPHA, 2022b

Standardized procedure to develop the reports: approach and methods, and report template

Approach and methods of the Global Plant Health Assessment

Aim of the Global Plant Health Assessment

The GPHA aims to provide a first ever overall assessment of plant health in both natural and human-made ecosystems of the world. Plant health is assessed through the functions that plants ensure in ecosystems: ecosystem services (MEA 2005). The GPHA assesses plant health on the basis of published, science- and fact-based, expert evaluations. While the GPHA considers plant health from the angle of infectious diseases, it also addresses plant health as a whole. Its goal is to generate an overview of the current status and trends in plant health, and their outcomes on ecosystem services: provisioning (food, fiber, and material), regulating (climate, water, and soils), and cultural (re-creation, spiritual, and beauty). Policies must be grounded on scientific evidence: with the GPHA, we aim to produce material that will help developing policies to ensure sustainability of plant health globally and locally. The GPHA addresses some of the main broad types of the World's plant-systems. Each system in each ecoregion has been addressed by a small team composed of a Lead Expert with a group of 2-3 Experts. The initiative involved over 80 scientists across the world.

Overall principles and organization of the Assessment

Some key features of the GPHA are:

- Any terrestrial ecosystem in the world may be considered. These are referred to as Plant Systems, which can be human-made (e.g., agriculture) or not (e.g., ecosystems where human perturbations are limited).
- Among the human-made ecosystems, we considered (1) agrosystems, (2) peri-urban horticulture (3) household (kitchen) gardens, and (4) urban vegetation. The Assessment also considers a range of forest systems around the world.
- In this assessment, plant health is seen through the lens of infectious plant diseases. Because plant health is not restricted to infectious diseases, attention was also paid when relevant to 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). Abiotic diseases thus were not addressed *per se*; but biotic and abiotic factors were considered as factors of infectious diseases and their consequences. The GPHA therefore concentrated on viruses, bacteria, phytoplasma, fungi, oomycetes, nematodes, as well as on organisms (e.g., parasitic plants) behaving (e.g., dispersal, survival, specialization, adaptation) as plant pathogens. Pathogen vectors were also considered.
- The GPHA is entirely based on volunteered time from experts in plant pathology and associated fields.
- GPHA participants contribute 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.
- The GPHA is coordinated by a team of Scientists with different expertise: Geography, Climatology, Sociology, Environmental Sciences, Economy, Systems Sciences, and, in Plant Pathology: Forest Pathology, Field crop pathology, Integrated Pest Management, Molecular Plant-Pathogen

Interactions, Epidemiology, and Crop Loss Analysis. Members of the coordination group come from different parts of the world.
- The project is templated on the MEA (2005): A series of ecoregions of the world are selected; in each of these, key Plant Systems are identified.
- For each [Plant System × Ecoregion] combination, teams were established, with a Lead Expert mobilizing a few (2 or 3) Experts.
- Each team produces a report on the state of plant health in its chosen [Plant System x Ecoregion]. These reports are standardized in format and size (Supplementary file A) with a specified set of questions. Standardization of reports is a critical way to: (1) minimize the volunteered time inputs of Lead Experts and Experts; (2) produce homogeneous reports in their formats and sizes, which (3) enables comparisons: for similar plant systems across ecoregions, and across plant systems within ecoregions.
- Each report is grounded on 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 are identified by each team, as indicated below and in Supplementary file C.

The assessment thus does not attempt to address all plant species of the biosphere. It considers a set keystone plant species (Bond 1994) distributed over ecoregions, the status of keystone being assigned to plants that play a critical role in natural (including managed) ecosystems or in human-made argrosystems. As a result, each report focuses on the overall state of health of a given (set of) keystone plant species in a chosen plant system.

Recognizing that plant health is an abstraction which cannot be quantitatively measured, GPHA reports (1) are designed to produce qualitative assessments based on verifiable, published data, and (2) focus on the consequences of plant health on ecosystem services (provisioning, regulating, and cultural), because these can be quantified or qualified. GPHA [Plant System × Ecoregion] reports were developed (Figure 1), on: (1) cereal systems; (2) roots and tubers, banana and plantain systems; (3) fruit trees and grapes; (4) peri-urban horticultural systems and household gardens; (5) urban vegetation; and (6) forest systems.

Steps of the Global Plant Health Assessment

The GPHA included three sets of steps, which are summarized below.

Steps to select [Ecoregion × Plant System] components

Communications and an e-conference were organized to enable the following steps: (1) a preliminary list of [Ecoregion × Plant System] combinations; (2) the selection of key ecoregions (Bailey 1996) in the world, based on their ecological relevance and diversity, and their role toward human population and societies; (3) the choice of plant systems on the basis of their importance (economic, social, cultural, and ecological) to human societies; (4) the selection of critically important [Ecoregion × Plant System] combinations from the ecological, biodiversity, and agricultural (global food security) standpoints; and (5) within each prioritized [Plant System × Ecoregion] combination, the identification of a keystone (set of) plant(s) on which plant health is to be assessed.

Assessment procedure by each team on their target [Ecoregion x Plant System]

The procedure is based on each team assembling information according to eight sections arranged in successive boxes (Supplementary file A): Box 1 - General information ([Ecoregion × Plant System] chosen; names, affiliations and email addresses of Lead Expert and Experts); Box 2 - Background information (description of the [Ecoregion × Plant System] considered); Box 3 - Choice and justification of the keystone plant(s) in the chosen [Ecoregion x Plant System]; Box 4 - Question 1: "*How do you describe the state of plant health in the past 30 years for the considered plant(s)?*"; Box 5 - Question 2: "*How has plant health evolved for the considered plant(s) over the recent 10 years?*"; Box 6 - Question 3: "*What has been the level of ecosystem services generated by the considered system (as affected by plant disease) in the past 30 years?*"; Box 7 - Question 4 "*How has the effect of plant health on the generation of the considered Ecosystem Services evolved over the recent 10 years?*"; and Box 8 - Complementary information, including the level of confidence in the assessment produced.

Boxes 4 to 7 (i.e., Questions 1 to 4) constitute the core of the expert information sought. In order to achieve standardization across reports, answers to these questions were scaled. Questions pertaining to system states (Questions 1 and 3) are to be answered on a five-point scale: "Excellent", "Good", "Fair", "Poor", Bad". These classes correspond to a series of colors from dark green to red (Supplementary file A). Questions pertaining to trends in states (Questions 2 and 4) are to be answered on a three-point scale: "declining", "improving", or "stable". These classes correspond to arrows pointing, down, up, or level. Questions 3 and 4 may address each of the different types of ecosystem services, provisioning, regulating, or cultural. Any report may provide a set of four combinations of two responses: plant health (state and trend), provisioning (state and trend), regulating (state and trend), and cultural (state and trend). Each of these pairs is represented by a colored box (state) with an arrow (trend) as shown in Supplementary file A.

Internal peer-review and revisions of reports

As in the Millennium Ecosystem Assessment (MEA, 2005), the information gathered had to be verified internally. Each member of the Coordination Group acted as an Editor for a given report, and had the report reviewed by one other Reviewer. Lead Experts revised their reports based on the comments of the Reviewer and Editor.

References

Bailey R (1996) *Ecosystem Geography*. New York: Springer

Bond WJ (1994) Keystone Species. In: Schulze ED, Mooney HA (eds) Biodiversity and Ecosystem Function. Praktische Zahnmedizin Odonto-Stomatologie Pratique Practical Dental Medicine, vol 99. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-58001-7_11

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

Report template of the Global Plant Health Assessment

The following document is derived from the description of a report template which was sent to Lead Scientists in order to guide them to develop the reports.

About this report - General instructions

This template is intended to all Lead Scientists of the Global Plant Health Assessment. We provide this template to save your time, to guide your work as Lead Scientists, so that you only need to follow the suggestions we make. This template is also meant to ensure uniformity across reports. Lastly, we want to make sure that each report addresses four specific questions. All reports will be reviewed and discussed among the participants of the Global Plant Health Assessment, and a synthesis of reports will be made.

Your report is not meant to be comprehensive. It is not a review. Instead, this report should be seen as the *view* of a Lead Scientist, along with a few Experts, on the state of plant health in a given Plant System, in a chosen Ecoregion of the world. The guidelines in each of the following sections (in grey) should help you in preparing this report.

This view from a team of scientists (Lead Scientist + Experts) must be supported by references. A minimum of three references* per report is required; a maximum of 15 references is possible.

All participants to the Global Plant Health Assessment will be associated with any reporting or publication of this work. This is why we ask your *complete affiliation details* along with your *name and email*.

We estimate that the preparation of the report should not involve more than three working days (accumulated time) for each Lead Scientist. This includes the time that each Lead Scientist would take to share information and drafts of the report with Experts of her/his choice.

We shall be glad to help and answer queries. Please finalise and send your report **before July 31, 2020**. When completed, please sent the report to Serge Savary with copy to Paul Esker.

* Suggested reference format:

Smith J, Jones M Jr, Houghton L et al (1999) Future of health insurance. N Engl J Med 965:325–329

1. General information

[Ecoregion x PlantSystem]: example: South Asia x Peri-Urban Horticultural Systems and Household Gardens

Lead Scientist: please provide: (1) First name (middle name) Last name; (2) email; (3) Complete affiliation

Expert 1: please provide: (1) First name (middle name) Last name; (2) email; (3) Complete affiliation

Expert 2: please provide: (1) First name (middle name) Last name; (2) email; (3) Complete affiliation

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Expert n: please provide: (1) First name (middle name) Last name; (2) email; (3) Complete affiliation

To Lead Scientists: Please involve a limited number of Experts. Three Experts is usually enough. In some cases, more Experts may be needed - but keep this number small. Note: each expert MUST have contributed to the report.

2. Background information: Please describe the [Ecoregion x PlantSystem] considered in the present report

suggested length: 10-15 lines

Each report deals with one [Ecoregion x PlantSystem]. Please describe in a few sentences the [Ecoregion x PlantSystem] which is considered in the present report. What are its main characteristics? What are its main features? What makes this [Ecoregion x PlantSystem], considered in the present report, **special**? *Examples*: there will be reports on *grapevine in Europe (grapevine and wine making are a major economic activity, with very important cultural roots and meaning)*, on *wheat and maize in North America (cereal production in North America is a major economic activity and a vital component of global food security)*, on *forests in the Amazonas (the Amazon plays an essential role in climate regulation, is a vital repository of biological diversity)*.

Please explain why this [Ecoregion x PlantSystem] is important. What is its role in terms of Provisioning (food, fibre, materials), in terms of Regulation (climate, soils, water), or in terms of Culture (beauty, spiritual value, cultural value)? A brief description of these will explain which **Ecosystem Service** is considered in the report.

Please provide a few references.

Please specify which of the following groups of Ecosystem Services you have decided to report on in this Report (see the Table annexed at the end of this document):

1. **Provisioning Services**: food, fibre, materials

2. **Regulating Services**: climate, soils, water

3. **Cultural Services**: culture, spiritual, beauty

3. Please specify the PlantSystem considered in the report

suggested length: 10-15 lines

This section **explains which plant or plants are considered in the report**. These plant or plants may be cultivated or not, they may be annual plants or perennial plants. The choice of plants should, essentially, be based on their **contribution to** the **ecosystem services** that they provide (Provisioning, Regulating, Culture) - that is to say the "importance" the chosen plants have towards these services.

Choice of plants in some **agricultural systems** is relatively easy: wheat for [Europe x Cereals], potato for [South America x Roots and Tubers], for example.

The choice is more difficult in **complex cultivated systems**: [Peri-Urban Horticulture and Household Gardens x Southeast Asia], for example. In this case, selecting some of the most frequent components of such systems is suggested, for example: leafy vegetables, solanaceae, crucifers. This kind of choice will allow comparison with other analogous PlantSystems in different Ecoregions, for example: [Peri-Urban Horticulture and Household Gardens x South Asia], or [... x sub-Saharan Africa].

The choice is perhaps even harder for **non-cultivated complex systems**: [Forest x Amazon], for example, where biological diversity is a key feature - which we want to address if possible. Considering **keystone species** is then advised. For this report on plant health assessment, two standpoints exist in the choice of keystone species. One is the frequency/importance of a given species in the PlantSystem considered; another is the existence of major disease problems. Although the prevalence of disease may be a reason to select a plant species as keystone, it perhaps is more advisable to prioritise the first criterion (frequency/importance of a given species).

The choice of plants considered is entirely that of the Lead Scientist and Experts. It may be that several species, or a group of species, are considered.

Please provide reference(s) to support these choices.

4. Question 1: How do you describe the state of plant health in the past 30 years for the considered plant(s)? suggested length: 10-20 lines

This section needs to provide information on the **overall state of health** of the considered Plant System, within a given Ecoregion. The state of health must refer to the keystone species (one or several), which have been specified in the previous section.

Broadly - the question is: Are there major diseases on this (these) keystone species? Please provide some background on why these diseases are important, in terms of their spread in plant populations, or in terms of their effects on plant populations.

Please provide reference(s).

Please summarise your answer to this question on a 5-point scale (Excellent / Good / Fair / Poor / Bad) using one of the coloured squares below.

Notes: (1) the notion of trend over time is addressed in Question 2; (2) the notion of effects on Ecosystem Services is addressed in Questions 3 and 4.

5. Question 2: How has plant health evolved for the considered plant(s) over the recent 10 years?

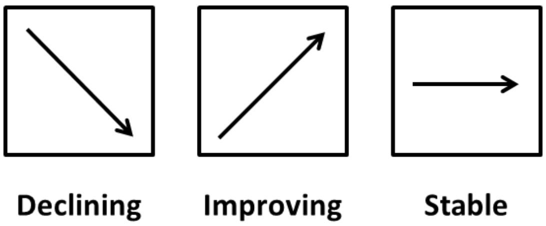
suggested length: 10-20 lines

This section complements the answer to question 1, with a **trend in plant health** over a shorter time-frame. We suggest 10 years as a reference period, but the time horizon may be expanded if relevant -- as long as the past 10 years are included.

Broadly - the question is: Has there been an increase in frequency of the major diseases indicated in answering Question 1? Have they been decreasing? Please provide some background on these changes over time.

Please provide reference(s).

Please summarise your answer to this question on a 3-point scale (Improving / Stable / Declining) using one of the arrows below.



Note: the notions of effects on Ecosystem Services are addressed in Questions 3 and 4.

6. Question 3: What has been the level of ecosystem services generated by the considered system (as affected by plant disease) in the past 30 years?

suggested length: 10-20 lines

This question shifts to the notion of **performance of plant systems under disease**. Performance is **scaled on the three types of Ecosystem Services**.

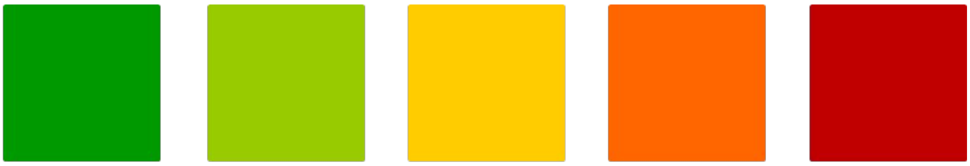
To address this question, each Lead Scientist needs to consider the Ecosystem Services which are generated by the considered system. **Please see the table** at the end of this template. **For some PlantSystems**, **only one Service** needs to be considered; **for others, two services** need to be considered (**and two responses** are requested for this question).

For each Ecosystem Service considered, the question asked amounts to the following: "How has this Ecosystem Service, as affected by plant health, been performing in the past 30 years?"

This question concerns the levels: (1) of **Provisioning Services**, (2) of **Regulating Services**, and (3) of **Cultural Services,** as affected by plant health

Please provide reference(s).

Please summarise your answers to this question (**one per each ecosystem service considered**) on a 5-point scale (Excellent / Good / Fair / Poor / Bad) using the coloured squares below.



Excellent **Good** **Fair** **Poor** **Bad**

Notes: the notions of trend over time for each Service are addressed in Question 4.

7. Question 4: How has the effect of plant health on the generation of the considered Ecosystem Services evolved over the recent 10 years?

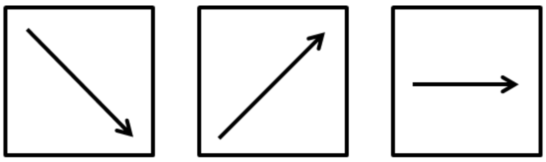
suggested length: 10-15 lines

This last question complements the previous one in providing **trend(s)** over a ten year period.

For each of the Services reported in the previous Question 3, a trend is requested: has the generation of the considered service, as affected by plant health, been "Improving" / "Stable" / "Declining"?

Please provide references.

Please summarise your answers to this question (**one answer per each ecosystem service considered**) on a 3-point scale (Improving / Stable / Declining) using one of the arrows below.



Declining **Improving** **Stable**

8. Complementary information

suggested length: 10-15 lines

This is an open section, where each team (Lead Scientist and Experts) wants to complement information given in the report. This information pertains to critical aspects that are overlooked in answering in a simplistic way the questions of the report. These aspects may pertain, for example, to:

- the physical environment: climate change may be associated with (1) changes in the frequency / intensity of disease. The physical environment includes droughts, fires, and any element of the physical environment considered appropriate by the team.

- the biological environment: plant diseases may be related to the biological environment in many ways. In forest systems or urban systems, pathogens and insects may for instance be associated with tree decline; or, micro-organisms that are antagonists to pathogens may also be affected by a given dynamics/process. Please note that vectors of pathogens (arthropods, nematodes) are integral part of "disease" as addressed in Question 1.

- the social or economic environment: major shifts in systems are the results of social or economic changes. This may change (1) the disease status, (2) the level-importance of Ecosystem Services. This can be included, as appropriate.

Lastly, and importantly, please provide **your own assessment of the findings of the present report** -- how confident are you in your findings in this report. This can be scaled as follow:

1. very confident: many studies, publications, support your views. There are only few gaps in the literature.

2. reasonably confident: a number of studies, publications, support your views. There are gaps in the literature.

3. uncertain: there are very few studies, publications, to support your views. There are major gaps in the literature.

This section may prove to be extremely valuable for the Global Plant Health Assessment, in developing its conclusions. Any insight is useful.

Please provide references.

Annex: Suggested Ecosystem Services to consider by [Ecoregion x PlantSystem]

These are **only suggestions** towards Lead Scientists, who ultimately have to decide. It is very important to consider more than one group of Ecosystems Services whenever this makes sense, ***irrespective*** of the literature.

The diversity of Ecosystem Services is a main feature of the Assessment.

PlantSystem	World Eco-region	Main Ecosystem Service			Key Plant(s)/Crop
		P provisioning	R regulating	C culture	
Cereal systems	NW Europe	P			Wheat
	N. America	P			Wheat and Maize
	S. America	P			Wheat
	South Asia	P			Rice and Wheat
	East Asia	P			Wheat
	East Asia	P			Rice
	SE Asia	P			Rice
	SS Africa	P			Maize
	Australasia	P			Wheat
Roots & Tubers	South Asia	P			Potato
	East Asia	P			Potato
	SS Africa	P			Cassava
	NW Europe	P			Potato
	S. America	P			Potato
Banana & Plantains	SS Africa	P			Banana and Plantains
Fruit trees & Grape	NW Europe	P		C	Grapevine
	SE Asia	P			Mango
	N. America 1	P			Fruits and nuts
	N. America 2	P			Grapevine and almond
Horticultural Systems	South Asia	P		C	Multiple
	SE Asia	P		C	Multiple
	SS Africa	P		C	Multiple
Urban Vegetation	NW Europe		R	C	Plane tree
Forests	Amazon		R	C	Multiple
	Australasia		R	C	Eucalypts
	Europe	P	R	C	Oaks
	North Europe	P	R		Multiple
	N. America 1	P	R		Multiple
	N. America 2	P	R		Oaks

Global Plant Health Assessment

Supplementary file B - List of pathogens and diseases by keystone plant

Keystone plant	Disease (pest) common name(s)	Acronym	Scientific name of pathogen (pest)	Remarks and references
Wheat (*Triticum aestivum*)				
	Stripe (yellow) rust		*Puccinia striiformis*	
	Stem (black) rust		*Puccinia graminis* f. sp. *tritici*	
	Leaf (brown) rust		*Puccinia triticina*	
	Septoria tritici blotch		*Zymoseptoria tritici*	
	Stagnospora tritici blotch		*Phaeosphaeria nodorum (previously Stagonospora nodorum)*	
	Fusarium head blight (scab)	FHB	Several *Fusarium* species (anamorph and teleomorph forms)	
	Tan spot		*Pyrenophora tritici-repentis*	
	powdery mildew	PM	*Blumeria graminis*	
	Leaf blight (complex)		*Bipolaris sorokiniana, Pyrenophora tritici-repentis,* and *Alternaria triticina*	Duveiller et al., 1997; Sharma et al., 2007
	Spot blotch		*Bipolaris sorokiniana* (teleomorph = *Cochliobolus sativus)*	
	Root and foot rot		*Bipolaris sorokiniana* (teleomorph = *Cochliobolus sativus)*	
	Take-all		*Gaeumannomyces tritici (previously G. graminis* var. *tritici)*	
	Common bunt		*Tilletia caries*	
	Flag smut		*Urocystis agropyri*	
	Sharp-eye spot		*Rhizoctonia cerealis*	
	Wheat blast		*Pyricularia graminis-tritici*	Ceresini et al., 2018
	Wheat bacterial leaf streak	WBLS	*Xanthomonas translucens* pv *undulosa*	
	Wheat streak mosaic	WSM	Wheat streak mosaic virus	Vector: wheat curl mite *Aceria tosichella*
	Barley yellow dwarf	BYD	Several species of Barley Yellow Dwarf Viruses	Vectors: several Aphid species
	Wheat spindle streak mosaic	WSSM	Wheat spindle streak mosaic virus	Vector: *Polymyxa graminis*
Rice (*Oryza sativa*)				
	Bakanae	BK	*Gibberella fujikuroi*	
	Rice blast	BL	*Pyricularia oryzae*	
	Brown spot	BS	*Bipolaris oryzae*	
	False smut	FSM	*Ustilaginoidea virens*	
	Narrow brown spot	NBS	*Cercospora oryzae*	
	Sheath blight	SHB	*Rhizoctonia solani*	
	Bacterial blight	BLB	*Xanthomonas oryzae* pathovar *oryzae*	
	Bacterial leaf streak	BLS	*Xanthomonas oryzae* pv. *oryzicola*	
	Rice black streaked dwarf disease	RBSD	Rice Black Streaked Dwarf Virus	Fang et al., 2001
	Rice grassy stunt disease	RGSD	Rice Grassy Stunt Virus	
	Rice ragged stunt disease	RRSD	Rice Ragged Stunt Virus	
	Rice stripe disease	RSD	Rice Stripe Virus	
	Rice tungro disease	RTD	Rice Tungro Bacilliform Virus; Rice Tungro Spherical Virus	Infection by both virus required for full symptoms
	Rice Orange Leaf Disease	ROLD	rice orange leaf phytoplasma	Ou, 1987
	Brown planthopper	BPH	*Nilaparvata lugens*	Vector for RSD and RGSD
	Green leafhopper	GLH	*Nephotettix cincticeps*	Vector of the ROLD phytoplasma (Li et al., 2015)
	Small brown planthopper	SBPH	*Laodelphax striatellus*	Wang et al., 2008; Cho et al., 2015
	White-back plant hopper	WBPH	*Sogatella furcifera*	Vector of RBSDV; Zhou et al., 2013

Maize				
	Grey leafspot	GLS	*Cercospora zeae-maydis*	Mueller et al. 2016; White DG, 1999; Aboukhaddour et al., 2020; Bandyopadhyay, 2019a
	Northern corn leaf blight	NCBL	*Setosphaeria turcica (Exserohilum turcicum)*	
	Southern corn leaf blight		*Bipolaris maydis*	
	Common rust		*Puccinia sorghi*	
	Southern rust		*Puccinia polysora*	
	Ear rots and stalk rots		*Fusarium subglutinans (F. moniliforme); F. graminearum; Fusarium* spp.	
	Tropical stalk and ear rots		*Fusarium verticillioides; Diplodia macrospora*	
	Kernel and ear rots		*Fusarium* spp.; *Aspergillus flavus*; *Aspergillus* spp.	
	Tar spot		*Phyllachora maydis*	
	Corn bacterial leaf streak		*Xanthomonas vasicola* pv.*vasculorum*	
	Pythium root rot		*Pythium* spp.; *P. arrhenomanes; P. graminicola*	
	Downy mildew		*Peronosclerospora sorghi*	
	Stewart's wilt		*Pantoea stewartii*	
	Gross's wilt		*Clavibacter michiganensis*	
	Eyespot		*Aureobasidium zeae (Kabatiella zeae)*	
	Maize streak virus disease	MSV	Maize Streak Virus	Martin and Shepherd 2009
	Maize lethal necrosis	MLN	co-infection of Maize chlorotic mottle virus, MCMV, with sugarcane mosaic virus (SCMV) or other potyviruses	Mahuku et al., 2015
	Striga		*Striga hermonthica; S. asiatica*	Runo and Keria, 2018
	Fall armyworm	FAW	*Spodoptera frugiperda*	Goergen et al., 2016
Potato (*Solanum tuberosum*)				
	Potato late blight	PLB	*Phytophthora infestans*	
	Black scurf	PBS	*Rhizoctonia solani*	
	Powdery scab	PPS	*Spongospora subterranea*	
	Early blight	PEB	*Alternaria solani*	
	Verticillium wilt	PVW	*Verticillium dahliae*	
	Fusarium wilt		*Fusarium solani*	
	Fusarium wilt		*Fusarium oxysporum*	
	Bacterial wilt, brown rot	PBW	*Ralstonia solanacearum*	
	Blackleg, Black shank, and bacterial soft rot	PBL	*Pectobacterium carotovorum* subsp. *Carotovorum, Pectobacterium atrosepticum*	*P. atrosepticum*: formerly *Erwinia carotovora* subsp. *atroseptica*
	Stolbur phytoplasma	PSP	*Candidatus* Phytoplasma solani	vector: leafhoppers
	Purple top		Potato purple-top wilt phytoplasma: Candidatus *Phytoplasma aurantifolia*	Caicedo et al 2015; Vectors: *Macrosteles* and *Hyalesthes* spp.
	Zebra chip		*Candidatus* Liberibacter solanacearum	Castillo Carrillo et al., 2019; Vector: Psyllids
	Wart		*Synchytrium endobioticum*	
	cyst nematode	PCN	*Globodera rostochiensis*	
	cyst nematode	PCN	*Globodera pallida*	
	Root knot nematode		*Meloidogyne* spp.	
	Potato Virus Y	PVY	genus Potyvirus, Potato virus Y	transmission: grafting, aphids
	Potato virus X	PVX	genus Potexvirus, Potato virus X	mechanical transmission
	Potato virus S	PVS	genus Carlavirus, Potato virus S	some aphid transmission
	Potato virus A	PVA	genus Potyvirus, Potato virus A	transmission: aphids
	Potato leaf roll	PLRV	genus Polerovirus, Potato leafroll virus	vector: *Myzus persicae*
Cassava *(Manihot esculenta)*				
	Cassava anthracnose disease	CAD	*Colletotrichum gloeosporioides* f. sp. *manihotis*	
	Cassava brown leaf spot	CBLS	*Cercosporidium henningsii*	
	Cassava bacterial blight	CBB	*Xanthomonas axonopodis* pv. *manihotis*	
	Cassava mosaic disease	CMD	Cassava mosaic begomoviruses	
	Cassava brown streak disease	CBSD	Cassava brown streak ipomoviruses	
	Cassava mealybug	CM	*Phenacoccus manihoti*	
	African root and tuber scale	ARTS	*Stictococcus vayssierei*	
	Cassava green mite	CGM	*Mononychellus tanajoa*	
Banana and plantain (*Musa* spp.)				

	Banana fusarium wilt	BFW	*Fusarium oxysporum* f.sp. *cubense*	Hauser et al., 2019
	Banana yellow sigatoka	BYS	*Mycosphaerella musicola*	
	Banana black sigatoka	BBS	*Mycosphaerella fijiensis*	
	Banana Pseudomonas wilt	BPW	*Ralstonia solanacearum (Pseudomonas solanacearum)* (race 1)	Safni et al., 2014
	Banana Xanthomonas wilt	BXW	*Xanthomonas vasicola* pv. *musacearum*	
	Banana bunchy top virus disease	BBTD	Banana bunchy top virus	transmission: *Pentalonia nigronervosa* (banana aphid)
	Banana nematodes		*Radopholus similis*; *Meloidogyne* spp.; *Pratylenchus* spp.; *Helicotylenchus multicinctus*	
	Banana weevil		*Cosmopolites sordidus*	
Grapevine (*Vitis vinifera)*				
	Downy mildew	GDM	*Plasmopara viticola*	
	Powdery mildew	GPM	*Erysiphe necator*	
	Botrytis bunch rot	GBBR	*Botrytis cinerea*	
	Black-rot	GBR	*Guignardia bidwelii*	
	Phomopsis cane and leaf spot	GPC	*Diaporthe ampelina,*	syn. *Phomopsis viticola*
	Grapevine trunk diseases	GTDs	several ascomycetes and basidiomycetes	Includes Petri, Black foot, Eutypa, Botryosphaeria diebacks, and Esca
	Grapevine yellows	GYs		Phloem-limited bacteria: Bois noir; Flavescence dorée
	Leaf roll	GLR		Closteroviridae
	Corky rugose wood-like syndrome	GCR		Betaflexiviridae
Apple (*Malus domestica)*				
	Fire blight	AFB	*Erwinia amylovora*	
	Apple scab	ASC	*Venturia inaequalis*	
Pecan (*Carya illinoinensis)*				
	Pecan scab	PSC	*Venturia effusa*	
	Pecan bacterial leaf scorch	PBLS	*Xylella fastidiosa*	
Coffee (*Coffea Arabica*)				
	Coffee leaf rust	CLR	*Hemileia vastatrix*	
	American leaf spot disease	ALSD	*Mycena citricolor*	
	Coffee leaf scorch	CLS	*Xylella fastidiosa*	
	Coffee berry borer	CBB	*Hypothenemus hampei*	
Citrus				
	Citrus black spot	CBS	*Phyllosticta citricarpa*	Martínez-Minaya et al., 2015
	Citrus Greening - Huanglongbing	CG-HLB	*Candidatus* Liberibacter asiaticus *(*CLas*);*	Vector: *Diaphorina citri* Gottwald, 2010.
	African Greening	CG-AG	*Candidatus* Liberibacter africanus (CLaf)	Vector: *Tryoza erytreae* Gottwald, 2010.
	Citrus canker	CCk	*X. axonopodis (*syns. *X. campestris, X. citri)*: *X. axonopodis* pv. *citri*; X. *axonopodis* pv. *Aurantifolii)*	Asiatic citrus canker (Canker A): *X. axonopodis* pv. *citri* Cancrosis B: *X. axonopodis* pv. *aurantifolii*
	Citrus variegated chlorosis	CVC	*Xylella fastidiosa* subsp. *pauca*	Vectors: sharpshooter leafhoppers and spittlebugs Coletta-Filho et al., 2020; Roy et al 2015; Liu, 2020.
	Citrus tristeza	CTV disease	CTV virus	Vector: several Aphid species; Lee 2015.
	Citrus leprosis	CLep	CiLV-N; CiLV-C; CiLV-C2	Vector: mites (*Brevipalpus* spp.)
	Citrus yellow vein clearing disease	CYVC	CYVC virus	Vector: whiteflies (*Dialeurodes citri*); Liu et al 2020
	Mediterranean fruit fly		*Ceratitis capitata*	Urbaneja et al., 2020
	Oriental fruit fly		*Bactrocera dorsalis*	
	Citrus leafminer		*Phyllocnistis citrella*	
	California red scale		*Aonidiella aurantii*	
	citrus mealybug		*Planococcus citri*	
	citrus red mite		*Panonychus citri*	

	Asian citrus psyllid		*Diaphorina citri*	
	African citrus psyllid		*Tryoza erytreae*	
	Citrus fruit borer		*Gymnandrosoma aurantianum*	
Tomato (*Solanum lycopersicum*)				
	Damping off		*Pythium* spp.; *Rhizoctonia* spp.	
	Early blight - Alternaria leaf blights	PEB	*Alternaria alternata*; *A. solani*	
	Late blight	PLB	*Phytophthora infestans*	
	Gray mold	TGM	*Botrytis cinerea*	
	Southern blight		*Sclerotium rolfsii*	
	Tomato yellow leaf curl	TYLC	one or a mixture from many different strains and species of Begomovirus (*Geminiviridae*)	transmission: whitefly, *Bemisia tabaci*
	Fusarium wilt		*Fusarium oxysporum* f. sp. *lycopersici*	
	Verticillium wilt			
	Bacterial wilt, brown rot	RSSC	*Ralstonia solanacearum* species complex	
	Bacterial spot		*Xanthomonas vesicatoria* spp.	
	Root-knot nematodes	RKN	*Meloidogyne* spp.	
	Potato Virus Y	PVY	genus Potyvirus, Potato virus Y	transmission: grafting, aphids
	Tomato chlorosis virus disease	TCV	Tomato chlorosis virus Crinivirus	
	Peanut bud necrosis virus disease	PBNV	Peanut bud necrosis virus	transmission: thrips
	Tomato spotted wilt virus disease	TSWV	Tomato spotted wilt virus	transmission: thrips
African eggplant (*Solanum macrocarpon*)				
	Bacterial wilt, brown rot	RSSC	*Ralstonia solanacearum* species complex	
	Tomato yellow leaf curl	TYLC	one or a mixture from many different strains and species of Begomovirus (*Geminiviridae*)	transmission: whitefly, *Bemisia tabaci*
	Root-knot nematodes	RKN	*Meloidogyne* spp.	
African nightshades (*Solanum* spp.)				
	Fusarium wilt		*Fusarium oxysporum* f.sp. *lycopersici*	
	Verticillium wilt		*Verticillium albo-atrum; V. dahliae*	
	Bacterial wilt, brown rot	RSSC	*Ralstonia solanacearum* species complex	
	Yellow leaf curl	Begomo	one or a mixture from many different strains and species of Begomovirus (*Geminiviridae*))	transmission: whitefly, *Bemisia tabaci*
	Root-knot nematodes	RKN	*Meloidogyne* spp.	
Okra (*Abelmoschus esculentus*)				
	Choaneophora leaf and fruit rot	CLFR	*Choanephora cucurbitarum*	
	Vascular wilt		*Fusarium oxysporum*	Ariyo and Olasatan 2009
	Bacterial wilt	PBW	*Ralstonia solanacearum*	
	Okra leaf curl disease	OLC	one or a mixture from many different strains and species of Begomovirus (*Geminiviridae*)	
	Root-knot nematodes	RKN	*Meloidogyne* spp.	
Amaranth (*Amaranthus tricolor*)				
	Damping off		*Pythium aphanidermatum*	
	Leaf (web) blight		*Rhizoctonia solani*	Uppala et al., 2010
	Stem decay		*Fusarium* sp.	
	leaf and stem rot	CLFR	*Choanephora cucurbitarum*	Teri and Mlasani, 1994; Mnzava et al. 1999, Blodgett et al. 1998
	Capsicum chlorosis virus		CaCV	transmission: thrips
	Root-knot nematode	RKN	*Meloidogyne* spp.	Coyne et al 2018
French bean (*Phaseolus vulgaris*)				
	Anthracnose	FBA	*Colletotrichum lindemuthianum*	Chowdappa, 2013; CABI, 2019a; Mishra et al., 2019
	Gray mold	TGM	*Botrytis cinerea*	
	Leaf spot		*Cercospora canescens*	
	Powdery mildew		*Erysiphe polygoni*	
	Leaf rust		*Uromyces* spp.	
	Fusarium wilt		*Fusarium solani*	
Yard-long bean (*Vigna unguiculata* ssp. *sesquipedalis*)				
	Anthracnose		*Colletotrichum lindemuthianum*	
	Rust		*Uromyces vignae*	
	Cercospora leaf spot		*Pseudocercospora cruenta*	
	Yellow mosaic diseases		one or a mixture from several different strains and species of Begomovirus (*Geminiviridae*)	

Cauliflower (*Brassica oleracea)*				
	Damping off		*Pythium* spp.; *Rhizoctonia* spp.	
	Alternaria leaf blights		*Alternaria brassicae*; *A. brassicicola*	
	Downy mildew		*Peronospora parasitica*	
	powdery mildew		*Erysiphe cruciferarum*	
	Club root		Plasmodiophora brassicae	Bhattacharya et al., 2014
	Black rot	XBR	*Xanthomonas campestris* pv. *campestris*	Chowdappa, 2013; CABI, 2019b
Bitter gourd (*Momordica charantia)*				
	Powdery mildew		Podosphaera xanthii	Ali et al., 2010; Raj et al., 2010
	Downy mildew		Pseudoperonospora cubensis	
	Bitter gourd mosaic		Cucumber Mosaic Virus; Papaya Ringspot Virus; Bitter gourd Distortion Mosaic Virus	
	Bitter gourd leaf curl		one or a mixture from many different strains and species of Begomovirus (*Geminiviridae*) and satellite DNAs	
Leafy brassicas (pak choy; *Brassica rapa subsp. chinensis*)				
	Black rot	XBR	*Xanthomonas campestris*	
	Damping-off		*Pythium* spp.	
Kang kong (*Ipomea aquatica)*				
	White rust - White blister		*Albugo ipomoeae-panduratae*	
	Leaf spot		*Cercospora ipomoeae*	
Chilli peppers (*Capsicum* spp.)				
	Anthracnose		*Colletotrichum* spp.	
	Phytophthora blight		*Phytophthora infestans*	
	Bacterial spot		*Xanthomonas* sp.	
	Pepper yellow leaf curl	PYLC	one or a mixture from many different strains and species of Begomovirus (*Geminiviridae*)	Kenyon et al., 2014
Multiple Cucurbitaceous species				
	Fusarium wilt		*Fusarium solani*	
	Squash leaf curl	Begomo	one or a mixture from many different strains and species of Begomovirus (*Geminiviridae*)	transmission: whitefly, *Bemisia tabaci*
	Aphid-borne yellows	Polero	one or a mixture from several different strains and species of Polerovirus (*Geminiviridae*)	transmission: aphids
	Cucurbit yellows	Crini	cucurbit yellows criniviruses	transmission: whitefly, *Bemisia tabaci*
	Gummy stem blight	GSB	*Didymella* spp.	
Plane tree (*Platanus orientalis*, *Platanus × acerifolia*)				
	Canker stain disease (Plane wilt)	PCSD	*Ceratocystis platani*	Observatree, 2016; Ferrari & Pichenot 1974; Tsopelas et al., 2017
	powdery mildew		*Erysiphe platani*	
	anthracnose		*Apiognomonia veneta*	
	Massaria disease		*Splanchnonema platani*	
	trunk canker		*Fomitiporia* sp.	
Oaks - Europe: Pedunculate oak (*Quercus robur*); Sessile oak (*Q. petraea*); Downy oak (*Q. pubescens*); Turkey oak (*Q. cerris*); Holm oak (*Q. ilex*); Cork oak (*Q. suber*) - North America: White oak (*Quercus alba*); Northern red oak (*Q. rubra*); Coast live oak (*Q. agrifolia*); and Tanoak (*Notholithocarpus densiflorus*)				
	Sudden oak death	SOD	*Phytophthora ramorum*	Cobb et al 2020
	Oak wilt disease		*Bretziella fagacearum (Ceratocystis fagacearum)*	
	Root pathogens		*Armillaria* spp. *and Gymnopus (Collybia) fusipes*	
	Powdery mildew		*Erysiphe alphitoides*	
	Emerging bacterial pathogens (Europe)		*Brenneria goodwinii, Lonsdalea quercina and Gibbsiella quercinecans*	
Loblolly pine (Southern pine; *Pinus taeda*)				
	Heterobasidion root disease		*Heterobasidion irregulare*	
			Armillaria spp.	
			Phytopthora cinnamomi	
			Leptographium spp.	
	Brown spot needle blight		*Lecanosticta acicola*	
Douglas-fir (*Pseudotsuga menziesii*)				
	Laminated root rot		*Phellinus sulphurascens*	Hansen and Goheen, 2000
	Armillaria root disease		*Armillaria ostoyae*	

	Swiss needle cast		*Nothophaeocryptopus gaeumannii*	
Lodgepole pine (*Pinus contorta* var. *latifolia*)				
	Dothistroma needle blight		*Dothistroma septosporum*	Woods et al 2005; Woods et al 2017
	Hard pine rusts		*Cronartium harknessii; C. comandrae; C. coleosporoides*	
Eastern white pine (*Pinus strobus*)				
	Brown spot needle disease		*Lecanosticta acicola*	
	Dothistroma needle blight		*Dothistroma septosporum*	
	Caliciopsis canker		*Caliciopsi pinea*	
	Armillaria root disease		*Armillaria* spp.	
	White pine blister rust	WPBR	*Cronartium ribicola*	WPBR was introduced to the New World by 1900
Red spruce and white spruce (*Picea* spp.)				
	Armillaria root rot		*Armillaria* spp.	Price et al. 2013
	Tomentosus root disease		*Onnia tomentosa*	
Cocoa *(Theobroma cacao)*				
	Moniliophthora pod rot; frosty pod		*Moniliophthora roreri*	Ploetz, 2016
	Witch's broom		*Moniliophthora perniciosa*	
	Black pod disease; Phytophthora pod rot		*Phytophthora megakarya; Phytophthora* spp.	
	Vascular streak dieback		*Ceratobasidium theobromae*	
Rubber tree *(Hevea brasiliensis)*				
	South American leaf blight	SALB	*Microcyclus ulei*	Lieberei, 2007; Ploetz, 2016
Australasian Forests (Eucalypts): three main genera: *Eucalyptus*, *Corymbia*, *Angophora*.				
	Phytophthora dieback	PDB	*Phytophthora cinnamomi*	Paap et al. 2017; Keane et al. 2000; Cahill et al. 2008; Carnegie & Pegg, 2018
	Root and butt rot		*Armillaria luteobubalina*	
	Myrtle rust		*Austropuccinia psidii*	
	Marri canker		*Quambalaria coyrecup*	
	Leaf and shoot blight		*Quambalaria pitereka*	
	Leaf diseases		*Teratosphaeria* spp., *Aulographina eucalypti*	

Aboukhaddour R, Fetch T, McCallum BD, et al (2020) Wheat diseases on the prairies: A Canadian story. Plant Pathol 69:418–432

Ali I, Malik AH, Malik AH, Mansoor S (2010) First report of Tomato leaf curl Palampur virus on bitter gourd in Pakistan. Plant Dis 94:276

Ariyo OJ, Olasantan FO (2009) Good agriculture practices for Okra in Sub-Saharan Africa. In: Nono-Womdim R, et al (eds) Good Agricultural Practices for African indigenous vegetables. Proceedings of a technical Consultation Workshop held in Arusha, Tanzania, 7 – 9 Dec 2009. Pp 159 – 180. ISBN 978 90 6605 694 7, *Scripta Horticulturae* Number 15

Bandyopadhyay R, Cardwell KF, Ortega-Beltran A, et al (2019a) Identifying and managing plant health risks for key African crops: maize. In: Neuenschwander, Tamò (eds) Critical Issues in Plant Health: 50 years of Research in African Agriculture. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 173-212

Bhattacharya I, Dutta S, Mondal S et al (2014) Clubroot disease on Brassica crops in India. Can J Plant Pathol 36:154–160

Blodgett JT, Swart WJ, Louw S (1998) First Report of *Fusarium sambucinum, F. oxysporum, and F. subglutinans* associated with Stem Decay of *Amaranthus Hybridus* in South Africa. Plant Dis 82:1062-1062

CABI (2019a). *Colletotrichum lindemuthianum* (anthracnose of bean). Invasive Species Compendium. https://www.cabi.org/isc/datasheet/14918

CABI (2019b). *Xanthomonas campestris* pv. *campestris* (black rot). Invasive Species Compendium. https://www.cabi.org/isc/datasheet/56919

Cahill DM, Rookes JE, Wilson BA, et al (2008) *Phytophthora cinnamomi* and Australia's biodiversity: impacts, predictions and progress towards control. Aust J Bot 56:279

Caicedo J, Crizón M, Pozo A, et al (2015) First report of '*Candidatus* Phytoplasma aurantifolia' (16SrII) associated with potato purple top in San Gabriel-Carchi, Ecuador. New Dis Rep 32:20–20

Carnegie AJ, Pegg GS (2018) Lessons from the incursion of myrtle rust in Australia. Annu Rev Phytopathol 56:457–478.

Castillo Carrillo C, Fu Z, Burckhardt D (2019) First record of the tomato potato psyllid *Bactericera cockerelli* from South America. Bull Insectol 72:85–91

Ceresini PC, Castroagudín VL, Rodrigues FÁ, et al (2018) Wheat blast: past, present, and future. Annu Rev Phytopathol 56:427–456

Cho S-Y, Jeong R-D, Yoon Y-N, et al (2015) A nationwide survey and genetic analysis of rice stripe virus in South Korea during 2012–2013. J Gen Plant Pathol 81:390–398

Chowdappa P (2013) Disease management in urban and peri-urban horticulture. In: Sumangala HP, Malhotra SK, Chowdappa P (eds) Urban and Peri-urban Horticulture-A perspective. Confederation of Horticulture Associations of India, New Delhi, pp 35–42

Cobb RC, Haas SE, Kruskamp N, Whalen WD, Swiecki TJ, Rizzo DM, Frankel SJ, Meentemeyer RK (2020) The magnitude of regional-scale tree mortality caused by the invasive pathogen *Phytophthora ramorum.* Earth's Future e2020EF001500

Coletta-Filho HD, Castillo AI, Laranjeira FF, et al (2020) Citrus variegated chlorosis: an overview of 30 years of research and disease management. Trop Plant Pathol 45:175–191

Coyne DL, Cortada L, Dalzell JJ et al (2018) Plant-Parasitic Nematodes and Food Security in Sub-Saharan Africa. Annu Rev Phytopathol 56:381–403

Duveiller E, Dubin E, Reeves H, McNab A (1997) Helminthosporium Blights of Wheat: Spot Blotch and Tan Spot. Proceedings of an International Workshop; El Batan, Texcoco (Mexico); 9-14 Feb 1997. CIMMYT, Mexico

Fang S, Yu J, Feng J, et al (2001) Identification of rice black-streaked dwarf fijivirus in maize with rough dwarf disease in China. Arch Virol 146:167–170

Ferrari JP, Pichenot M (1974) *Ceratocystis fimbriata* Ellis et Halsted f. *platani* (Walter), responsable d'une grave maladie du platane en France : « la tache chancreuse ». C R Acad Sci Paris D 278:2787-2789

Gottwald TR (2010) Current epidemiological understanding of citrus huanglongbing. Annu Rev Phytopathol 48:119–139

Goergen G, Kumar PL, Sankung SB, et al (2016) First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), a new alien invasive pest in West and Central Africa. PLoS ONE 11(10), e0165632

Hansen EM, Goheen EM (2000) *Phellinus weirii* and other native root pathogens as determinants of forest structure and process in western North America. Annu Rev Phytopathol 38:515-39

Hauser S, Gold C, Pasberg-Gauhl C et al (2019) Identifying and managing plant health risks for key African crops: banana and plantain. In: Neuenschwander, Tamò (eds) Critical Issues in Plant Health: 50 years of Research in African Agriculture. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 229–258

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

Kenyon L, Tsai W-S, Shih S-L, Lee L-M (2014) Emergence and diversity of begomoviruses infecting solanaceous crops in East and Southeast Asia. Virus Res 186:104-113

Lieberei R (2007) South American leaf blight of the rubber tree (Hevea spp.): new steps in plant domestication using physiological features and molecular markers. Ann Bot 100:1125–1142. https://doi.org/10.1093/aob/mcm133

Liu C, Liu H, Hurst J, Timko MP, Zhou C (2020) Recent advances on citrus yellow vein clearing virus in citrus. Hortic Plant J 6:216–222

Mahuku G, Lockhart BEL, Wanjala B, et al (2015) Maize lethal necrosis, an emerging threat to maize-based food security in sub-Saharan Africa. Phytopathology 105:956-965

Martin DP, Shepherd DM (2009) The epidemiology, economic impact and control of maize streak disease. Food Secur 1:305–315

Martínez-Blay V, Pérez-Rodríguez J, Tena A, Soto A (2018) Density and phenology of the invasive mealybug *Delottococcus aberiae* on citrus: implications for integrated pest management. J Pest Sci 91:625–637

Mishra RK, Parihar AK, Basvaraj T et al (2019) Identification of new sources of resistance in Rajmash (*Phaseolus vulgaris* L.) against powdery mildew (*Erysiphe polygoni*) and stem rot (*Sclerotinia sclerotiorum*) diseases. Legume Res 42:430–433

Mnzava, NM, Dearing JA, Guarino L, Chweya JA, (compilers), de Koeijer H (ed) (1999) Bibliography of the genetic resources of traditional African vegetables. Neglected leafy green vegetable crops in Africa Vol. 2. International Plant Genetic Resources Institute, Rome, Italy

Mueller DS, Wise KA, Sisson AJ, et al (2016) Corn yield loss estimates due to diseases in the United States and Ontario, Canada from 2012 to 2015. Plant Health Prog 17:211–222. https://doi.org/10.1094/PHP-RS-16-0030

Observatree (2016) Field Identification Guide - Plane wilt. Online resource retrieved from www.observatree.org.uk

Ou, SH (1987) Rice Diseases. Second Edition. Farnham Royal: CAB International

Paap T, Burgess TI, Calver M, et al (2017) A thirteen-year study on the impact of a severe canker disease of *Corymbia calophylla* , a keystone tree in Mediterranean-type forests. For Pathol 47: e12292

Ploetz RC (2016) The Impact of Diseases on Cacao Production: A Global Overview. In: Bailey BA, Meinhardt LW (eds) Cacao Diseases: A History of Old Enemies and New Encounters. Springer International Publishing, Cham, pp 33–59

Price DT, Alfaro RI, Brown KJ et al (2013) Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environ Rev 21:322-365

Raj SK, Snehi SK, Khan MS et al (2010) First report of *Pepper leaf curl Bangladesh virus* strain associated with bitter gourd (*Momordica charantia* L.) yellow mosaic disease in India. Australas Plant Dis Notes 5:14–16

Roy A, Hartung JS, Schneider WL, et al (2015) Role bending: complex relationships between viruses, hosts, and vectors related to citrus leprosis, an emerging disease. Phytopathology 105:1013–1025

Runo S, Kuria EK (2018) Habits of a highly successful cereal killer, Striga. PLoS Pathogens 14:e1006731

Safni, I., Cleenwerck, I., De Vos, P., Fegan, M., Sly, L. and Kappler, U., 2014. Polyphasic taxonomic revision of the *Ralstonia solanacearum* species complex: proposal to emend the descriptions of *Ralstonia solanacearum* and *Ralstonia syzygii* and reclassify current *R. syzygii* strains as *Ralstonia syzygii* subsp. *syzygii* subsp. nov., *R. solanacearum phylotype* IV strains as *Ralstonia syzygii* subsp. *indonesiensis* subsp. nov., banana blood disease bacterium strains as *Ralstonia syzygii* subsp. *celebesensis* subsp. nov. and *R. solanacearum* phylotype I and III strains as *Ralstonia pseudosolanacearum* sp. nov. International Journal of Systematic and Evolutionary Microbiology, 64(Pt_9) :3087-3103.

Sharma RC, Duveiller E, 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 Crop Res 103:109–118

Teri JM, Mlasani DK (1994) Choanephora blight and alternaria leaf spot of Amaranth in Tanzania. Plant Pathol 43:228-229

Tsopelas P, Santini A, Wingfield MJ, de Beer ZW (2017) Canker stain: a lethal disease destroying iconic plane trees. Plant Dis 101:645-658

Uppala S, Beena S, Chapala M et al (2010) Bioefficacy of endophytes in the management of leaf blight disease of amaranth. In: Reddy MS, Desai S, Sayyed RZ et al (eds) Plant Growth Promotion by Rhizobacteria for Sustainable Agriculture. Scientific Publishers, India, pp 524-530

Urbaneja A, Grout T, Gravena S, et al (2020) Citrus pests in a global world. In: Talon M, Caruso M, Gmitter F (eds) The Genus Citrus. Woodhead Publishing, Duxford, UK, pp 333–348

Wang H-D, Chen J-P, Zhang H-M, et al (2008) Recent rice stripe virus epidemics in Zhejiang Province, China, and experiments on sowing date, disease–yield loss relationships, and seedling susceptibility. Plant Dis 92:1190–1196

White DG (ed) (1999) Compendium of Corn Diseases, 3rd ed. The American Phytopathological Society, St Paul, MN

Woods A, Coates KD, Hamann A (2005) Is an unprecedented Dothistroma needle blight epidemic related to climate change? BioScience 55:761-769

Woods AJ, Coates KD, Watts M et al (2017) Warning signals of adverse Interactions between climate change and native stressors in British Columbia forests. Forests 8:280

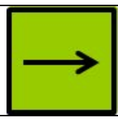
Zhou C (2020) The status of citrus Huanglongbing in China. Trop Plant Pathol 45:279–284

A global assessment of the state of plant health

Supplementary file C - State and evolution of plant health and service by key-stone plant species

Supplementary file C - Table 1. State and evolution of plant health and services - Wheat

Plant health

Ecoregion	*State of plant health*	*State assess-ment*	*Evolution of plant health*	*Evolution assess-ment*	*Summary*	*Level of assessment confidence*	*References*
Western Europe	Many different diseases, mostly under reasonable control through pesticides, host plant resistance, and cropping practices.	Good	Emergence of new pathogen races (stripe rust); re-invasion risks (stem rust); increasing FHB threat; and persistent difficulties in managing septoria tritici blotch.	Declining		very confident	CABI, 2020; Figueroa et al., 2018; Hovmøller et al., 2016; Jørgensen et al., 2014; Kahiluoto et al., 2019; Savary et al., 2017; 2019; Singh et al., 2016; Willocquet et al., 2020
North America	Several main disease problems: FHB, rusts, and foliage necrotrophs. Most diseases under reasonable control.	Good	Emerging challenges include further control of FHB, virus diseases, and emerging pathogen races (stripe rust).	Stable		very confident	Aboukhaddour et al. 2020; Brar et al. 2019; McMullen et al. 2012
South America	Several important diseases with occasionally very serious epidemics (leaf rust, stripe rust, FHB). Reasonable control achieved through breeding and chemicals.	Good	Persistent and growing issues associated with the maize - no-till production system (viral diseases, FHB). Occasional wheat blast outbreaks in Brazil's Cerrado.	Stable		very confident	Carmona et al. 1999; 2006; Ceresini et al., 2018; Reis and Carmona, 2013
East Asia (China)	Numerous and very diverse, serious plant pathogens.	Fair	Many different diseases: massive, networked efforts: breeding, monitoring, forecasting systems. Considerable improvement through modern technology. Strong reliance on pesticides.	Improving		reasonably confident	Cock et al. 2016; Guo et al., 2019
South Asia (Indo-Gangetic Plains)	Several chronic diseases (leaf blight) over very large acreages; frequent epidemics (rusts).	Fair	Climate change (heat waves) documented to increase disease (leaf blight). Persistent epidemic threats (rusts).	Declining		reasonably confident	Duveiller et al., 1997; 2007; Sharma et al., 2007

Impacts of plant health on ecosystem services

Ecoregion	*Nature and state of services generated*		*Evolution of services generated*	*Evolution assess-ment*	*Summary*	*Level of assessment confidence*	*References*
Western Europe	**Food production**: Major wheat producer and exporter. Yield stagnation related to climate change.	Good	High and stable yield and production, despite wheat health decline.	Stable		reasonably confident	Brisson et al., 2010; Savary et al., 2019
North America	**Food production**: Major wheat producer and exporter. Yield variability related to disease and management effort.	Fair	Many challenges to manage diseases because of their diversity, and because the major diseases impact both production quantity and quality.	Declining		reasonably confident	Willyerd et al., 2015
South America	**Food production**: Important wheat producer and exporter. Yield variability related to climate variability (ENSO) and diseases.	Good	Increasing concerns over plant health: leaf rust, wheat blast. Concerns over sustainability of production and management; and over environmental footprint.	Declining		reasonably confident	Cruppe et al., 2020; Germán et al., 2011
East Asia (China)	**Food production**: Major wheat production center for regional food security. Massive progress over 30 years.	Good	Many different diseases; increasing concerns over quality (FHB). Production is not directly threatened *per se*, but its environmental cost is a concern.	Stable		reasonably confident	FAOSTAT, 2020
South Asia (Indo-Gangetic Plains)	**Food production**: Major wheat production center for regional food security. Steady progress over 30 years.	Fair	Emerging concerns on climate change -driven disease (wheat blight); on the sustainability of the system with a clear role of diseases.	Stable		reasonably confident	Chauhan et al., 2012

References

Aboukhaddour R, Fetch T, McCallum BD, et al (2020) Wheat diseases on the prairies: A Canadian story. Plant Pathol 69:418–432

Brar GS, Fetch T, McCallum BD, et al (2019) Virulence dynamics and breeding for resistance to stripe, stem, and leaf rust in Canada since 2000. Plant Dis 103:2981–2995

Brisson N, Gate P, Gouache D, Charmet G, Oury FX, Huard F (2010) Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Res 119:201–212

CABI (2020) Crop Protection Compendium, https://www.cabi.org/cpc

Carmona M, Ferrazini M, Barreto D (2006) Tan spot of wheat caused by *Drechslera tritici-repentis* : Detection, transmission, and control in wheat seed. Cereal Res Commun 34:1043–1049

Carmona M, Reis E, Cortese P (1999) Mancha Amarilla y Septoriosis de la Hoja. Diagnóstico, Epidemiología y Nuevos Criterios para el Manejo. ISBN987-43-1253-X

Ceresini PC, Castroagudín VL, Rodrigues FÁ, et al (2018) Wheat blast: past, present, and future. Annu Rev Phytopathol 56:427–456

Chauhan BS, Mahajan G, Sardana V, et al (2012) Productivity and sustainability of the rice–wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent. Adv Agron 117:315–369

Cock MJW, Tang, R, Liu Z, Wang H (2016) The main agricultural insect and disease pests of China and implications for the use of remote sensing for their management. CAB Rev 11:No. 014

Cruppe G, Cruz CD, Peterson G, et al (2020) Novel sources of wheat head blast resistance in modern breeding lines and wheat wild relatives. Plant Dis 104:35–43

Duveiller E, Dubin E, Reeves H, McNab A (1997) Helminthosporium Blights of Wheat: Spot Blotch and Tan Spot. Proceedings of an International Workshop; El Batan, Texcoco (Mexico); 9-14 Feb 1997. CIMMYT, Mexico

Duveiller E, Singh RP, Nicol JM (2007) The challenges of maintaining wheat productivity: pests, diseases, and potential epidemics. Euphytica 157:417–430

FAOSTAT (2020) http://www.fao.org/faostat

Figueroa M, Hammond-Kosack KE, Solomon PS (2018) A review of wheat diseases—a field perspective. Molec Plant Pathol 19:1523-1536

Germán S, Chaves M, Campos P, et al (2011) Challenges in controlling leaf rust in the Southern Cone region of South America. 2011 BGRI Technical Workshop. https://www.globalrust.org/sites/default/files/posters/german_2011.pdf

Guo L-M, HE J, Li J, Chen J-P, Zhang H-M (2019) Chinese wheat mosaic virus: A long-term threat to wheat in China. J Integr Agri 18:821-829

Hovmøller MS, Walter S, Bayles RA et al (2016) Replacement of the European wheat yellow rust population by new races from the centre of diversity in the near-Himalayan region. Plant Pathol 65:402-11

Jørgensen LN, Hovmøller MS, Hansen JG et al (2014) IPM Strategies and their dilemmas including an introduction to www.eurowheat.org. J Integr Agric 13:265-281

Kahiluoto H, Kaseva J, Balek J et al (2019) Decline in climate resilience of European wheat. Proc Nat Acad Sci 116:123-8

McMullen M, Bergstrom G, De Wolf E, et al (2012) A unified effort to fight an enemy of wheat and barley: Fusarium head blight. Plant Dis 96:1712–1728

Reis E, Carmona MA (2013) Integrated disease management of fusarium head blight. In: Aconada T, Chulze S (eds) Fusarium Head Bligh in Latin America. Springer, Dordrecht, pp 159–173

Sharma RC, Duveiller E, 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 Crop Res 103:109–118

Savary S, Djurle A, Yuen J et al (2017) A white paper on global wheat health based on scenario development and analysis. Phytopathology 107:1109-1122

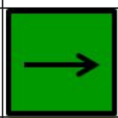
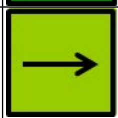
Savary S, Willocquet L, Pethybridge SJ, Esker P, McRoberts N, Nelson A (2019) The global burden of pathogens and pests on major food crops. Nature Ecol Evol 3:430-439

Singh RP, Singh PK, Rutkoski J et al (2016) Disease impact on wheat yield potential and prospects of genetic control. Annu Rev Phytopathol 54:303-322

Willocquet L, Meza WR, Dumont B et al (2021). An outlook on wheat health in Europe based on a network of field experiments. Crop Prot 139: 105335.

Willyerd KT, Bradley CA, Chapara V, et al (2015) Revisiting fungicide-based management guidelines for leaf blotch diseases in soft red winter wheat. Plant Dis 99:1434–1444

Supplementary file C - Table 2. State and evolution of plant health and services - Rice

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
South-East Asia	Many diseases - viral, bacterial and fungal. These have been brought under acceptable control mainly through host plant resistance.	Good	A strong dynamics between production contexts and disease patterns has taken place. Overall, rice health has been sustained.	Stable		reasonably confident	Cabauatan et al., 2009; Cuong et al., 1997; Savary et al., 2000; 2022; Willocquet et al., 2000
East Asia	Two dominant diseases, blast and bacterial blight have long dominated rice health, and been controlled through host plant resistance. Rice sheath blight has become more serious.	Good	Major new issues have emerged. A monsoon-driven regional epidemic system has established enabling long-distance spread of grave virus diseases	Declining		reasonably confident	Cho et al., 2015; Fang et al., 2001; Huang et al., 2011; Li et al., 2015; Matsumura and Sanada-Morimura, 2010; Otuka, 2013; Savary and Mew, 1996; Wang et al., 2008;; Zhou et al., 2013
South Asia (Indo-Gangetic Plains)	As in East Asia, two dominant diseases, blast and bacterial blight have been controlled through host plant resistance. Brown spot remains a major unresolved challenge.	Fair	False smut has become a serious concern, both in terms of yield quantity and quality (mycotoxins). Climate change enhances brown spot epidemics.	Declining		reasonably confident	Barnwal et al., 2013; Fan et al., 2016; Gnanamanickam et al., 1999; Han et al., 2020; Nagarajan, 1989; 1994; Reddy et al., 2011
Impacts of plant health on ecosystem services							
	Nature and state of services generated		***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
South-East Asia	**Food production**: Excellent progress of rice production across the region despite disease losses.	Excellent	Stabilization of food production at the cost of a drop in total factor productivity, and serious environmental costs.	Stable		reasonably confident	Savary et al., 2014
East Asia	**Food production**: Major productivity achievements have been performed through science. This has ensured the nutrition of one of the most populated ecoregion of the world.	Good	Crop performances are maintained and food production, as a service, remains stable. Major challenges will have to be addressed in the future, which will involve plant diseases.	Stable		reasonably confident	Hu et al., 2016; Peng et al., 2009; 2010
South Asia (Indo-Gangetic Plains)	**Food production**: Rice production has progressively increased, averting a major food crisis. Rice diseases are a clear reducer of systems performances, but not a cause for system disruption.	Good	Climate change, insufficient use of IPM, challenges in training and education, bring about an actual impact of plant diseases. Sustaining the performances of the Rice Wheat system will become even more challenging.	Declining		reasonably confident	Barnwal et al., 2013; Chauhan et al., 2012; Erenstein and Thorpe, 2011; Sharma et al., 2007; Timsina and Connor, 2001

References

Barnwal MK, Kotasthane A, Magculia N, et al (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

Cabauatan P, Cabunagan R, Choi I (2009) Rice viruses transmitted by the brown planthopper Nilaparvata lugens Stål. In: Heong K, Hardy B (eds) Planthoppers: New threats to the sustainability of intensive rice production systems in Asia. IRRI, Los Baños, pp 357–368

Chauhan BS, Mahajan G, Sardana V, et al (2012) Productivity and sustainability of the rice–wheat cropping system in the Indo-Gangetic Plains of the Indian subcontinent. Adv Agron 117:315–369

Cho S-Y, Jeong R-D, Yoon Y-N, et al (2015) A nationwide survey and genetic analysis of rice stripe virus in South Korea during 2012–2013. J Gen Plant Pathol 81:390–398

Cuong NL, Ben PT, Phuong LT, et al (1997) Effect of host plant resistance and insecticide on brown planthopper Nilaparvata lugens (Stål) and predator population development in the Mekong Delta, Vietnam. Crop Prot 16:707–715

Erenstein O, Thorpe W (2011) Livelihoods and agro-ecological gradients: A meso-level analysis in the Indo-Gangetic Plains, India. Agric Syst 104:42–53

Fan J, Yang J, Wang Y-Q, et al (2016) Current understanding on *Villosiclava virens*, a unique flower-infecting fungus causing rice false smut disease: A profile on the rice false smut pathogen. Mol Plant Pathol 17:1321–1330

Fang S, Yu J, Feng J, et al (2001) Identification of rice black-streaked dwarf fijivirus in maize with rough dwarf disease in China. Arch Virol 146:167–170

Gnanamanickam S, Priyadarisini V, Narayanan N, et al (1999) An overview of bacterial blight disease of rice and strategies for its management. Curr Sci 77:1435–1444

Han Y, Li D, Yang J, et al (2020) Mapping quantitative trait loci for disease resistance to false smut of rice. Phytopathol Res 2:20

Hu X-F, Cheng C, Luo F, et al (2016) Effects of different fertilization practices on the incidence of rice pests and diseases: A three-year case study in Shanghai, in subtropical southeastern China. Field Crop Res 196:33–50

Huang S-W, Wang L, Liu L-M, et al (2011) Rice spikelet rot disease in China – 1. Characterization of fungi associated with the disease. Crop Prot 30:1–9

Li S, Hao W, Lu G, et al (2015) Occurrence and identification of a new vector of Rice Orange Leaf Phytoplasma in South China. Plant Dis 99:1483–1487

Matsumura M, Sanada-Morimura S (2010) Recent status of insecticide resistance in Asian rice planthoppers. JARQ 44:225–230

Nagarajan S (1989) Plant protection problems in rice-wheat rotation system-a perspective. Oryza 26:329–333

Nagarajan S (1994) Rice pest management in India. In: Teng P, Heong K, Moody K (eds) Rice Pest Science and Management: Selected Papers from the International Rice Research Conference. IRRI, Los Baños, pp 43-52

Otuka A (2013) Migration of rice planthoppers and their vectored re-emerging and novel rice viruses in East Asia. Front Microbiol 4:309

Peng S, Buresh RJ, Huang J, et al (2010) Improving nitrogen fertilization in rice by sitespecific N management. A review. Agron Sustain Dev 30:649–656

Peng S, Tang Q, Zou Y (2009) Current status and challenges of rice production in China. Plant Prod Sci 12:3–8

Reddy CS, Laha GS, Prasad MS, et al (2011) Characterizing multiple linkages between individual diseases, crop health syndromes, germplasm deployment, and rice production situations in India. Field Crop Res 120:241–253

Savary S, Mew T (1996) Analyzing crop losses due to *Rhizoctonia solani*: rice sheath blight, a case study. In: Baruch S, Jabaji-Hare S, Neate S, Dijst G (eds) Rhizoctonia Species: Taxonomy, Molecular Biology, Ecology, Pathology and Disease Control. Springer, Dordrecht, pp 237–245

Savary S, Willocquet L, Castilla N, et al (2022) Whither rice health in the lowlands of Asia: Shifts in production situations, injury profiles, and yields. Plant Pathol 71:55–85

Savary S, Willocquet L, Elazegui FA, et al (2000) Rice pest constraints in tropical Asia: characterization of injury profiles in relation to production situations. Plant Dis 84:341–356

Sharma RC, Duveiller E, 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 Crop Res 103:109–118

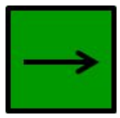
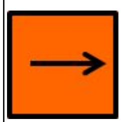
Timsina J, Connor DJ (2001) Productivity and management of rice–wheat cropping systems: issues and challenges. Field Crop Res 69:93–132

Wang H-D, Chen J-P, Zhang H-M, et al (2008) Recent rice stripe virus epidemics in Zhejiang Province, China, and experiments on sowing date, disease–yield loss relationships, and seedling susceptibility. Plant Dis 92:1190–1196

Willocquet L, Fernandez L, Savary S (2000) Effect of various crop establishment methods practised by Asian farmers on epidemics of rice sheath blight caused by *Rhizoctonia solani*. Plant Pathol 49:346-354

Zhou G, Xu D, Xu D, Zhang M (2013) Southern rice black-streaked dwarf virus: a white-backed planthopper-transmitted fijivirus threatening rice production in Asia. Front Microbiol 4: 10.3389/fmicb.2013.00270

Supplementary file C - Table 3. State and evolution of plant health and services - Maize

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
North America	Many diseases may affect maize; the most important ones are under satisfactory control, especially through host plant resistance.	Good	There has been little change of disease patterns. Some diseases, once a concerned, have been brought under control. New diseases are developing and expanding, especially as a consequence of climate change.	Stable		Reasonably confident	Garrett et al. 2021; Mallowa et al., 2015; Ortiz-Castro et al., 2020
Sub-Saharan Africa	Many diseases, affecting crop stands and harvests, and causing quantitative and qualitative losses. Mycotoxin contaminations are recurrent, very serious, and dangerous. Very heavy losses.	Poor	The challenges to maize health in SSA are massive. SSA has been victim of two major invasions: a virus involved in causing maize lethal necrosis (MLN) and the invasion by the fall armyworm (FAW)	Declining		Reasonably confident	Bandyopadhyay et al., 2019; Boddupalli et al., 2020; Goergen et al., 2016; Mahuku et al., 2015; Martin and Shepherd 2009; Runo and Kuria, 2018
Impacts of plant health on ecosystem services							
Ecoregion	***Nature and state of services generated***		***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
North America	**Food, feed, and biomass production**: North America, a major world granary, produces 50 to 60 million tons of maize yearly. The many diseases are under control through host plant resistance and integrated disease management.	Excellent	The general disease profile has not dramatically changed; management options do exist, especially through host plant resistance.	Stable		Reasonably confident	Esker et al., 2018
Sub-Saharan Africa	**Food production**: overall, yields are low, in the range of 1-2 ton.ha-1. The low average maize yields of SSA owe much to plant health problems.	Poor	Tremendous challenges are to be faced, with new pathogen and pest invasions vs poor infrastructure and resources, in a context of rapid population increase and climate change. Yet yield losses do not appear to have increased.	Stable		Reasonably confident	FAOSTAT, 2022; Kumar et al., 2019

References

Bandyopadhyay R, Cardwell KF, Ortega-Beltran A, et al (2019a) Identifying and managing plant health risks for key African crops: maize. In: Neuenschwander, Tamò (eds) Critical Issues in Plant Health: 50 years of Research in African Agriculture. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 173-212

Boddupalli P, Suresh, LM, Mwatuni F, et al (2020) Maize lethal necrosis (MLN): efforts toward containing the spread and impact of a devastating transboundary disease in sub-Saharan Africa. Virus Res 282:197943

Esker PD, Shah DA, Bradley CA, et al (2018) Perceptions of Midwestern crop advisors and growers on foliar fungicide adoption and use in maize. Phytopathology 108:1078–1088

FAOSTAT (2022) http://www.fao.org/faostat

Garrett KA, Nita M, De Wolf ED, et al (2021) Plant pathogens as indicators of climate change, third Edition. In: Letcher TM (ed) Climate Change. Elsevier, Switzerland, pp 499–513

Goergen G, Kumar PL, Sankung SB, et al (2016) First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), a new alien invasive pest in West and Central Africa. PLoS ONE 11(10), e0165632

Kumar PL, Legg JP, Ayodele M, Mahuku G, Ortega-Beltran A, Bandyopadhyay R (2019) Disease surveillance, diagnostics and germplasm health in crop protection. In: Watson D (ed) Achieving Sustainable Cultivation of Maize. Volume 2: Cultivation Techniques, Pest and Disease Control. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 41-73

Mahuku G, Lockhart BEL, Wanjala B, et al (2015) Maize lethal necrosis, an emerging threat to maize-based food security in sub-Saharan Africa. Phytopathology 105:956-965

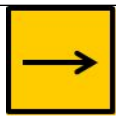
Mallowa SO, Esker PD, Paul PA, et al (2015) Effect of maize hybrid and foliar fungicides on yield under low foliar disease severity conditions. Phytopathology 105:1080–1089

Martin DP, Shepherd DM (2009) The epidemiology, economic impact and control of maize streak disease. Food Secur 1:305–315

Ortiz-Castro M, Hartman T, Coutinho T, et al (2020) Current understanding of the history, global spread, ecology, evolution, and management of the corn bacterial leaf streak pathogen, *Xanthomonas vasicola* pv. *vasculorum*. Phytopathology 110):1124-1131

Runo S, Kuria EK (2018) Habits of a highly successful cereal killer, Striga. PLoS Pathogens 14:e1006731

Supplementary file C - Table 4. State and evolution of plant health and services - Potato

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
South America	A diverse spectrum of many plant diseases, many of which hard to manage. Dominating problems with PLB, cyst nematodes, and several viruses.	Good	New threats caused by bacteria (Candidatus *Phytoplasma aurantifolia* and Candidatus *Liberibacter solanacearum*), fungi, and viruses	Stable		reasonably confident	Caicedo et al., 2015; Castillo Carillo et al., 2019; Kreuze et al., 2020; Lindqvist-Kreuze et al., 2020; Thomas-Sharma et al., 2016;
East Asia	Main yield reducers are PEB, PLB, PBSh and bacterial and fungal wilts. Control is difficult under shortage of healthy seed, fragmented and poor farms, absence of rotations.	Poor	Demand drives susceptible varieties. Access to resource (seed) and knowledge to manage disease is difficult. Pesticides are a main recourse. Plans to strengthen R&D are underway.	Declining		reasonably confident	Huang and Liu, 2016a; 2016b; Jing et al., 2018
Europe	PLB is the main disease, along with viruses (PLRV, PVY, and PSP), bacterial rot (PBL) and nematodes (*Globodera* spp., *Meloidogyne* spp. Good seed and decision support systems enable good control.	Good	Emergence of new *Phytopthora* lineages through sexual recombination, overcoming host resistances and chemicals. Increased ELB with climate change's warmer and drier summers.	Declining		very confident	Andersson et al., 1998; Andrivon et al., 2006; Drenth et al., 1995; Odilbekov et al., 2019; Thevenoux et al., 2020
Impacts of plant health on ecosystem services							
	Nature and state of services generated		***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
South America	**Food production**: major food source with heterogeneous productivity. The traditional Andean systems make use of little/no pesticides for low yields.	Fair	Potato remains a main staple in South America despite the plant health challenges, and remains a major source of livelihoods for many small farmers.	Declining		reasonably confident	Devaux et al., 2020; Lindqvist-Kreuze et al., 2020
South America	**Regulating:** Safeguarding natural ecosystems. Potato seed production at higher elevations is compromised; cultivation in the highlands threatens mountain wildlands.	Poor	In the Andes: encroachment of montane ecosystems to escape disease and increasing (climate change) temperature. Increasing insecticide use and residues.	Declining		reasonably confident	Navarrete et al., 2017; Thomas-Sharma et al., 2016
East Asia	**Food production**: China is the first potato producer in the world despite insufficient R&D investment in potato health for poor, fragmented, farming systems.	Fair	Steps are being taken to improve plant health: improved seed health, healthy seed multiplication, consideration of soil-borne pathogens and rotations.	Stable		reasonably confident	FAOSTAT, 2022
Europe	**Food production**: Potato production has declining by 30% in the past 30 years as a result of shifting diets and the phasing out of potato as feed. The crop is increasingly specialized and costly, especially because of PLB.	Poor	Production is harder and riskier with phased-out chemicals, climate change and extremes. *P. infestans* evolves at an alarming rate. 25 treatments per season are frequent.	Declining		very confident	FAOSTAT, 2022; Haverkort et al., 2008

References

Andersson B, Sandström M, Strömberg A (1998) Indications of soil borne inoculum of *Phytophthora infestans*. Potato Res 41:305-310

Andrivon D, Pellé R, Ellissèche D (2006) Assessing resistance types and levels to epidemic diseases from the analysis of disease progress curves: Principles and application to potato late blight. Am J Pot Res 83:455–461

Caicedo J, Crizón M, Pozo A, et al (2015) First report of '*Candidatus* Phytoplasma aurantifolia' (16SrII) associated with potato purple top in San Gabriel-Carchi, Ecuador. New Dis Rep 32:20–20

Castillo Carrillo C, Fu Z, Burckhardt D (2019) First record of the tomato potato psyllid *Bactericera cockerelli* from South America. Bull Insectol 72:85–91

Devaux A, Goffart J, Petsakos A, et al (2020) Global food security, contributions from sustainable potato agri-food systems. In: Campos H, Ortiz O (eds) The Potato Crop: Its Agricultural, Nutritional and Social Contribution to Humankind. Springer International Publishing, Cham, pp 3–36

Drenth A, Janssen EM, Govers F (1995) Formation and survival of oospores of *Phytophthora infestans* under natural conditions. Plant Pathol 44:86-94

FAO (2022) http://www.fao.org/faostat

Haverkort AJ, Boonekamp PM, Hutten R. et al (2008) Societal costs of late blight in potato and prospects of durable resistance through cisgenic modification. Potato Res 51:47–57

Huang C, Liu W (2016a) Occurrence characteristics and monitoring advice of potato late blight in China in recent years. Plant Prot 42:142-147 (In Chinese)

Huang C, Liu W (2016b) Occurrence characteristics and monitoring strategies of potato diseases and pests. China Plant Prot 36:48-52 (In Chinese)

Jing R, Li H, Hu X, Shang W, Shen R, Guo C, Guo Q, Subbarao KV (2018) Verticillium wilt caused by *Verticillium dahliae* and *V. nonalfalfa*e in potato in Northern China. Plant Dis 102:1958-1964

Kreuze J, Souza-Dias J, Jeevalatha A, et al (2020) Viral diseases in potato. In: Campos H, Ortiz O (eds) The Potato Crop: Its Agricultural, Nutritional and Social Contribution to Humankind. Springer International Publishing, Cham, pp 389–430

Lindqvist-Kreuze H, Gamboa S, Izarra M, et al (2020) Population structure and host range of the potato late blight pathogen *Phytophthora infestans* in Peru spanning two decades. Plant Pathol 69:334–346

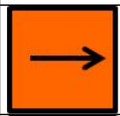
Navarrete I, Panchi N, Andrade-Piedra J (2017) Potato crop health quality and yield losses in Ecuador. Rev Latinoamericana Papa 21:69–88

Odilbekov F, Edin E, Mostafanezhad H. et al. (2019) Within-season changes in *Alternaria solani* populations in potato in response to fungicide application strategies. Eur J Plant Pathol 155:953–965

Thevenoux R, Folcher L, Esquibet M, et al (2020) The hidden diversity of the potato cyst nematode *Globodera pallida* in the south of Peru. Evol Appl 13:727–737

Thomas-Sharma S, Abdurahman A, Ali S, et al (2016) Seed degeneration in potato: the need for an integrated seed health strategy to mitigate the problem in developing countries. Plant Pathol 65:3–16

Supplementary file C - Table 5. State and evolution of plant health and services - Cassava

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Sub-Saharan Africa	Although past threats (cassava mealybug and green mite) have been brought under (biological) control, major virus epidemics (cassava mosaic and brown streak) cause massive losses against a backdrop of diverse chronic diseases.	Poor	The ecology of the African root and tuber scale, a major pest, is largely unknown. Epidemics of cassava brown streak continue unabated as resistance levels available for breeding are insufficient.	Declining		reasonably confident	Alicai et al., 2007; Dixon et al 2003; Legg et al., 2006; 2011
Impacts of plant health on ecosystem services							
	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Sub-Saharan Africa	**Food production**: cassava production has kept pace with population growth despite 30-40% losses and stagnating yields.	Poor	Losses to some diseases have declined (CMD) while others have increased (CBSD)	Stable		reasonably confident	Legg et al., 2006
Sub-Saharan Africa	**Regulating:** cassava production is traditionally part of agrosystems in balance with natural ecosystems providing key resources (water, carbon storage, materials, food, spiritual)	Fair	Production increase has been at the expense of increasing encroachment on natural ecosystems.	Declining		reasonably confident	Aregbesola et al., 2020

References

Alicai T, Omongo CA, Maruthi MN et al (2007) Re-emergence of cassava brown streak disease in Uganda. Plant Dis 91:24–29

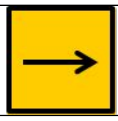
Aregbesola OZ, Legg JP, Lund OS et al (2020) Life history and temperature-dependence of cassava-colonising populations of *Bemisia tabaci*. J Pest Sci. 93:1225-1241

Dixon AGO, Bandyopadhyay R, Coyne D et al (2003) Cassava: from a poor farmer's crop to a pacesetter of African rural development. Chron Hortic 43:8–14

Legg JP, Jeremiah SC, Obiero H et al (2011) Comparing the regional epidemiology of the cassava mosaic and cassava brown streak pandemics in Africa. Virus Res 159:161–170

Legg JP, Owor B, Sseruwagi P et al (2006) Cassava mosaic virus disease in East and Central Africa: Epidemiology and management of a regional pandemic. Adv Virus Res 67:355–418

Supplementary file C Table 6. State and evolution of plant health and services - Banana and plantain in sub-Saharan Africa

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Sub-Saharan Africa	Bananas in SSA are exposed to a range of major, severe diseases affecting the vascular system, fruit production, or systemic. These diseases, fungal, viral, or bacterial, are extremely hard to control.	Poor	Disease emergences and expansions are underway: BXW in East Africa, BBTV in Southern and Western Africa, and BFW-TR4 in Mozambique. The severity of established diseases (black sigatoka) is increasing.	Declining		very confident	Abele and Pillay, 2007; Hauser et al., 2019; Kimunye et al., 2020; Tripathi et al., 2009; Zadoks and Schein, 1979
Impacts of plant health on ecosystem services							
	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Sub-Saharan Africa	**Food production**: Major staple and source of income (local trade and exports)	Fair	Maintained approximately at a par with population growth.	Stable		very confident	
Sub-Saharan Africa	**Regulating:** biodiversity, carbon storage, water, soil, and climate.	Fair	Strong reduction of regulating services as a result of plantation abandonment and encroachment of agriculture in natural systems.	Declining		reasonably confident	

References

Abele S, Pillay M (2007) Bacterial wilt and drought stresses in banana production and their impact on economic welfare in Uganda: Implications for banana research in East African highlands. J Crop Improve 19:173–191

Drenth A, and Kema G (2021) The vulnerability of bananas to globally emerging disease threats. Phytopathology 111:2146-2161

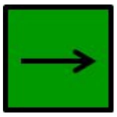
Hauser S, Gold C, Pasberg-Gauhl C et al (2019) Identifying and managing plant health risks for key African crops: banana and plantain. In: Neuenschwander, Tamò (eds) Critical Issues in Plant Health: 50 years of Research in African Agriculture. Burleigh Dodds Science Publishing Limited, Cambridge, UK, pp 229–258

Kimunye JN, Were E, Mussa F et al (2020) Distribution of *Pseudocercospora* species causing Sigatoka leaf diseases of banana in Uganda and Tanzania. Plant Pathol 69:50-59

Tripathi L, Mwangi M, Abele S et al (2009) Xanthomonas wilt: a threat to banana production in east and central Africa. Plant Dis 93:440–451

Zadoks JC and Schein RD (1979) Epidemiology and Plant Disease Management. New York: Oxford University Press

Supplementary file C - Table 7. State and evolution of plant health and services - Grapevine in Western Europe

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Western Europe	Many fungal, oomycete, virus, phytoplasma and bacterial diseases occur in Europe. However management has been effective through decision support systems and crop management.	Good	Grapevine trunk diseases with complex ætiologies have become pressing issues. Viral diseases have expanded or been introduced. The use and efficiency of chemical pesticides have declined.	Declining		reasonably confident	Bois et al., 2017; Gambino et al., 2014; Gramaje et al., 2018; Maliogka et al., 2015; Mondello et al., 2018
Impacts of plant health on ecosystem services							
	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Western Europe	**Provisioning**: high (collective, individual) revenues generated by trade and export.	Excelle nt	Constant technological progress leading to regular quality improvement. Digital technology and IPM are offsetting the pesticide- and disease-related challenges.	Stable		reasonably confident	Eurostat, 2018
Western Europe	**Regulating**: grapevine contributes to climate regulation (CO2 storage), water regulation, erosion control, and biodiversity.	Excelle nt	These services have been negatively affected by the decline in plant health.	Declining		reasonably confident	
Western Europe	**Cultural**: Grapevine has a major contribution to recreation, heritage, aesthetic experience and landscape beauty.	Excelle nt	These services have been negatively affected by the decline in plant health, in particular with the dying grapevine plants. This impact is hard to assess.	Declining		reasonably confident	

References

Bois B, Zito S, Calonnec A (2017) Climate vs grapevine pests and diseases worldwide: the first results of a global survey. OENO One 51:133

Eurostat (2018) https://ec.europa.eu/eurostat/statistics-explained/index.php/Vineyards_in_the_EU_-_statistics#General_overview

Gambino G, Navarro B, Torchetti EM, et al (2014) Survey on viroids infecting grapevine in Italy: identification and characterization of Australian grapevine viroid and Grapevine yellow speckle viroid 2. Eur J Plant Pathol 140:199–205

Gramaje D, Úrbez-Torres JR, Sosnowski MR (2018) Managing grapevine trunk diseases with respect to etiology and epidemiology: current strategies and future prospects. Plant Dis 102:12–39

Maliogka VI, Martelli GP, Fuchs M, Katis NI (2015) Control of viruses infecting grapevine. In: Advances in Virus Research. Academic Press, San Diego, CA, pp 175–227

Mondello V, Larignon P, Armengol J, et al (2018) Management of grapevine trunk diseases: knowledge transfer, current strategies and innovative strategies adopted in Europe. Phytopathol Medit 57:369-383

Supplementary file C - Table 8. State and evolution of plant health and services - Fruits and nuts in North America

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
North America	Apple scab and fire blight are very serious issues in apples, but are satisfactorily managed through crop management and chemicals. Pecan scab follows a similar pattern.	Good	Climate change combined with pathogen introductions may bring about new concerns. Perennial fruits are notoriously difficult to breed for disease resistances.	Stable	→	reasonably confident	Bock et al., 2017; 2018; Cox, 2015; Dewdney et al., 2003; 2007
Impacts of plant health on ecosystem services							
	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
North America	**Provisioning**: the available management instruments, especially chemicals, are providing adequate control to prevent disruption of supply.	Good	Climate change brought about fire blight and apple scab epidemics, along with emerging diseases. While the present is stable, the future is uncertain.	Stable	→	reasonably confident	USDA, 2020
North America	**Cultural**: Diseases have had limited impact on the cultural celebration of apple and pecan.	Good	No threat is envisioned on the cultural values of these trees.	Stable	→	reasonably confident	Wells, 2017

References

Bock CH, Brenneman TB, Wood BW et al (2017) Challenges of managing disease in tall orchard trees – pecan scab, a case study. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 12, 008: 1-18

Bock CH, Oliver JE, Che, C, et al (2018) Pecan bacterial leaf scorch, caused by *Xylella fastidiosa*, is endemic in Georgia pecan orchards. Plant Health Prog 19: 284-287

Cox KD (2015) Fungicide resistance in *Venturia inaequalis*, the causal agent of apple scab in the United States. In: Ishii H, Hollomon D (eds) Fungicide Resistance in Plant Pathogens: Principles and a Guide to Practical Management. Springer Japan, pp 433-447

Dewdney MM, Bigg, AR, Turechek WW (2007) A statistical comparison of the blossom blight forecasts of MARYBLYT and Cougarblight with receiver operating characteristic curve analysis. Phytopathology 97:1164-1176

Dewdney MM, Charest J, Paulitz TC et al (2003) Multivariate analysis of apple cultivar susceptibility to *Venturia inaequalis* under greenhouse conditions. Can J Plant Pathol 25:387-400

USDA-NASS (2020) United States Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/. Accessed 27 May 2020

Wells L (2017) Pecan: America's Native Nut Tree. The University of Alabama Press, Tuscaloosa, AL

Supplementary file C - Table 9. State and evolution of plant health and services - Coffee in Central America

Plant health

Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Central America	Very strong epidemics of plant diseases at the national and regional scales.	Poor	Amplification of epidemics with interacting changing climate, shifts in economical logics, and changes in changes in crop management and purposes.	Declining		Very confident	Avelino and Anzueto 2020; Avelino et al. 2015; Harvey et al. 2021; McCook and Vandermeer 2015; Rodriguez et al. 2001; Staver et al. 2001

Impacts of plant health on ecosystem services

Central America	***Nature and state of services generated***	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Central America	**Provisioning**: Very large contribution to small-holder livelihoods via a range of products (coffee, wood, tourism).	Fair	Large impacts of plant diseases on livelihoods.	Declining		Very confident	Avelino et al., 2015; DeClerck et al. 2010; Harvey et al. 2021; Jha et al. 2014
Central America	**Regulating**: Very large contribution of agroforestry systems to multiple regulating services (carbon sequestration, soil conservation, water regulation, biodiversity conservation)	Good	Threats are developing against agroforestry systems with renewed intensification and short-term logics.	Declining		Very confident	DeClerck et al. 2010; Harvey et al., 2021; Jha et al. 2014

References

Avelino J, Cristancho M, Georgiou S, et al (2015) The coffee rust crises in Colombia and Central America (2008–2013): impacts, plausible causes and proposed solutions. Food Secur 7:303–321

Avelino J, Anzueto F (2020) Coffee rust epidemics in Central America: chronicle of a resistance breakdown following the great epidemics of 2012 and 2013. In: Ristaino J, Records A (eds) Emerging Plant Diseases and Global Food Security. APS Press, St Paul, MN, pp 185–198

DeClerck FAJ, Chazdon R, Holl KD, et al (2010) Biodiversity conservation in human-modified landscapes of Mesoamerica: Past, present and future. Biol Conserv 143:2301–2313

Harvey CA, Pritts AA, Zwetsloot MJ, et al (2021) Transformation of coffee-growing landscapes across Latin America. A review. Agron Sustain Dev 41:62

Jha S, Bacon CM, Philpott SM, et al (2014) Shade coffee: update on a disappearing refuge for biodiversity. BioScience 64:416–428

McCook S, Vandermeer J (2015) The big rust and the red queen: Long-term perspectives on coffee rust research. Phytopathology 105:1164–1173

Rodríguez CM, Obando JJ, Villalobos W, Moreira, L, Rivera C (2001) First report of *Xylella fastidiosa* infecting coffee in Costa Rica. Plant Dis 85:1027–1027

Staver C, Guharay F, Monterroso D, Muschler RG (2001) Designing pest-suppressive multistrata perennial crop systems: Shade-grown coffee in Central America. Agrofor Syst 53:151–170

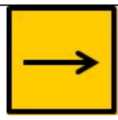
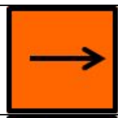
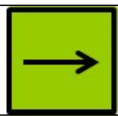
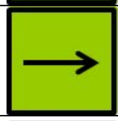
Supplementary file C - Table 10. State and evolution of plant health and services - Citrus (Global)

Plant health

Ecoregion	*State of plant health*	*State assess-ment*	*Evolution of plant health*	*Evolution assess-ment*	*Summary*	*Level of assessment confidence*	*References*
Global	Tristeza (CTV) has long dominated the concerns over citrus health. Most diseases were under acceptable control through (virus) certification and IPM.	Fair	Multiple major epidemics caused by introduced pathogens, many of them vectored, have occurred worldwide. Several are extremely hard to manage.	Declining		Reasonably confident	Bové, 2006; Garcia-Figuera et al., 2021; Gottwald, 2010; Gottwald et al., 2002; Lee, 2015; Liu et al., 2020; Martínez-Blay et al., 2018; Roy et al., 2015; Urbaneja et al., 2020; Zhou, 2020
East Asia (China)	HLB is of major concern but is spread is checked by several nation-wide measures.	Fair	Virus epidemics have occurred, with limited impacts, or have been brought under control.	Stable		Reasonably confident	Sun et al., 2009
South America (Brazil)	Some regions of Brazil have been spared, but major epidemics (CVC, CCk, CBS, Clep, and HLB) had grave impacts in the states of São Paulo, Minas Gerais and Paraná.	Fair	CCk and HLB have led to a declined of citrus health in São Paulo State.	Declining		Reasonably confident	Coletta-Filho et al., 2020
North America (USA)	Citrus production in Florida has been severely impacted in by CCk and by HLB, while California was spared.	Fair	In the last 10 years, citrus health in the USA has sharply declined in Florida, declined in some states, while California is threatened.	Declining		Reasonably confident	Gochez et al., 2020; Graham et al., 2020; McRoberts et al., 2019; Sétamou et al., 2020; USDA-NASS, 2020
Mediterranean	Except for localized epidemics citrus health has been good. Control of Tristeza has overall been effective.	Good	Invasive diseases are threatening Citrus health in Spain and the Mediterranean.	Declining		Reasonably confident	Ruíz-Rivero et al., 2021
Australasia (Australia)	Citrus health has been good and stable.	Good	Threats exist, but nation-wide policies and means are established.	Stable		Reasonably confident	
Sub-Saharan Afric (South Africa)	Citrus health has been good and stable.	Good	Many of major citrus diseases are absent in South Africa. Tristeza is under control. African Greening is localized, with limited impact. CBS hampers access to the EU market. Improvements are based on diagnostic tools and post-entry quarantine.	Improving		Reasonably confident	Ajene et al., 2020; Carstens et al., 2012; Cook et al., 2019

Impacts of plant health on ecosystem services

	Nature and state of services generated	*State assess-ment*	*Evolution of services generated*	*Evolution assess-ment*	*Summary*	*Level of assessment confidence*	*References*
Global	• **Provisioning:** Global citrus production has increased in the past 30 years.	Good	Marked decline in citrus health has triggered a decline in provisioning services in some regions	Decline		Reasonably confident	
	• **Cultural:** Citrus trees are commonly found in gardens, streets and small orchards worldwide.	Good	Decline in the generation of cultural services in some regions	Decline		Reasonably confident	
East Asia (China)	• **Provisioning:** China is the world largest producer of citrus.	Good	The citrus industry has grown even faster in the past decade.	Improving		Reasonably confident	

South America (Brazil)	• **Provisioning:** level of provisioning services has been good, however at increased (disease-related) costs.	Fair	While the cultivated area has declined (to disease), employment levels have been stable.	Stable		Reasonably confident	Bassanezi et al 2020
	• **Cultural:** these services have declined with the removal of trees.	Poor	These services have not improved.	Stable		Reasonably confident	
North America (USA)	• **Provisioning:** only fair with the succession of epidemics in Florida.	Fair	These services have declined. In Florida: production reduced by 74%, and production costs increased by 283%	Declining		Reasonably confident	Grafton-Cardwell, 2020; Singerman et al 2018
	• **Cultural:** over the years, many trees have been removed from private and public spaces.	Poor	The HLB epidemics is causing further decline.	Declining		Reasonably confident	
Mediterranean	• **Provisioning:** has been good, despite some yield reductions due to pests and quality (cosmetic) damage on fruits.	Good	level declining due to introductions of invasive pests causing cosmetic damage on fruits.	Declining		Reasonably confident	DG AGRI, 2020; 2021.
	• **Cultural:** good and stable leve.	Good		Stable		Reasonably confident	
Australasia (Australia)	• **Provisioning:** good despite threats of invasions, e.g., citrus canker and HLB.	Good		Stable		Reasonably confident	
Sub-Saharan Afric (South Africa)	• **Provisioning:** excellent.	Excellent	Sustained growth (66%) and exports (34%).	Improving		Reasonably confident	

References

Ajene IJ, Khamis FM, van Asch B, et al (2020) Distribution of *Candidatus* Liberibacter species in Eastern Africa, and the first report of *Candidatus* Liberibacter asiaticus in Kenya. Sci Rep 10:3919

Bassanezi RB, Lopes SA, de Miranda MP, Wulff NA, Volpe HXL, Ayres AJ (2020) Overview of citrus huanglongbing spread and management strategies in Brazil. Trop Plant Pathol 45:251–264

Bové JM (2006) Huanglongbing: a destructive, newly-emerging, century-old disease of citrus. Journal of Plant Pathology 88:7–37

Carstens E, Le Roux HF, Van Rooyen L, et al (2012) Citrus Black Spot does not occur in the Western Cape, Northern Cape and Free State provinces of South Africa. S Afr J Sci 108:56-61

Coletta-Filho HD, Castillo AI, Laranjeira FF, et al (2020) Citrus variegated chlorosis: an overview of 30 years of research and disease management. Trop Plant Pathol 45:175–191

Cook G, Kirkman W, Clase R, et al (2019) Orchid fleck virus associated with the first case of citrus leprosis-N in South Africa. Eur J Plant Pathol 155:1373–1379

DG AGRI (2020) The citrus market in the EU: production, areas and yields. European Commission, Directorate General for Agriculture and Rural Development

DG AGRI (2021) Monthly imports of oranges to the EU. European Commission, Directorate General for Agriculture and Rural Development

Garcia-Figuera S, Grafton-Cardwell EE, Babcock BA, et al (2021) Institutional approaches for plant health provision as a collective action problem. Food Secur 13:273–290

Gochez AM, Behlau F, Singh R, et al (2020) Panorama of citrus canker in the United States. Trop Plant Pathol 45:192–199

Gottwald TR (2010) Current epidemiological understanding of citrus huanglongbing. Annu Rev Phytopathol 48:119–139

Gottwald TR, Graham JH, Schubert TS (2002) Citrus canker: The pathogen and its impact. Online. Plant Health Progress doi:10.1094/PHP-2002-0812-01-RV

Grafton-Cardwell E (2020) Management of Asian citrus psyllid in California. In: Qureshi J, Stansly P (eds) Asian Citrus Psyllid: Biology, Ecology and Management of the Huanglongbing Vector. CAB International, Wallingford, UK, pp 250–257

Graham J, Gottwald T, Setamou M (2020) Status of huanglongbing (HLB) outbreaks in Florida, California and Texas. Trop Plant Pathol 45:265–278

Lee R (2015) Control of virus diseases of citrus. In: Loebenstein G, Katis N (eds) Advances in Virus Research. Academic Press, San Diego, CA, pp 143–173

Liu C, Liu H, Hurst J, Timko MP, Zhou C (2020) Recent advances on citrus yellow vein clearing virus in citrus. Hortic Plant J 6:216–222

Martínez-Blay V, Pérez-Rodríguez J, Tena A, Soto A (2018) Density and phenology of the invasive mealybug *Delottococcus aberiae* on citrus: implications for integrated pest management. J Pest Sci 91:625–637

McRoberts N, Figuera SG, Olkowski S, et al (2019) Using models to provide rapid programme support for California's efforts to suppress Huanglongbing disease of citrus. Phil Trans R Soc B 374:20180281

Roy A, Hartung JS, Schneider WL, et al (2015) Role bending: complex relationships between viruses, hosts, and vectors related to citrus leprosis, an emerging disease. Phytopathology 105:1013–1025

Ruíz-Rivero O, Garcia-Lor A, Rojas-Panadero B, et al (2021) Insights into the origin of the invasive populations of *Trioza erytreae* in Europe using microsatellite markers and mtDNA barcoding approaches. Sci Rep 11:18651

Sétamou M, Alabi OJ, Kunta M, et al (2020) Distribution of *Candidatus* Liberibacter asiaticus in citrus and the asian citrus psyllid in Texas over a decade. Plant Dis 104:1118–1126

Singerman A, Burani-Arouca M, Futch SH (2018) The profitability of new citrus plantings in Florida in the era of huanglongbing. Hortsci 53:1655–1663

Sun X, Zhou C, Qing L, Yang S (2009) Advances in research on citrus tatter leaf virus. J Fruit Sci 26:213-216

Urbaneja A, Grout T, Gravena S, et al (2020) Citrus pests in a global world. In: Talon M, Caruso M, Gmitter F (eds) The Genus Citrus. Woodhead Publishing, Duxford, UK, pp 333–348

USDA-NASS (2020) Citrus Fruits 2020 Summary. United States Department of Agriculture, National Agricultural Statistics Service. https://www.nass.usda.gov/Publications/Todays_Reports/reports/cfrt0820.pdf

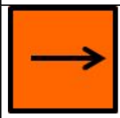
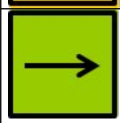
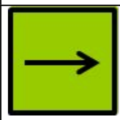
Zhou C (2020) The status of citrus Huanglongbing in China. Trop Plant Pathol 45:279–284

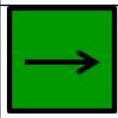
Supplementary file C - Table 11. State and evolution of plant health and services - Peri-urban horticultural systems and household gardens

Plant health

Ecoregion	*State of plant health*	*State assess-ment*	*Evolution of plant health*	*Evolution assess-ment*	*Summary*	*Level of assessment confidence*	*References*
Sub-Saharan Africa	Many diseases in diverse systems. Introduced plants (tomato) severely diseased. Very high losses.	Fair	Some diseases have decreased in importance, but many have increased. Climate change-induced temperatures enhancing virus transmissions.	Declining		Reasonably confident	Blodgett et al., 1998; CABI, 2019a; 2019b; Coyne et al., 2018; FAOSTAT, 2018; Jones, 2009; Mnzava et al., 1999; Teri and Mlasani, 1994
South Asia	Many diseases in very diverse systems. Introduced plants (tomato) severely diseased. Large differences in vulnerability among crops.	Fair	Climate change-induced temperatures enhancing virus transmissions. Effective breeding programs (host plant resistance), microbial biological control, grafting, and chemical pesticides.	Improving		Reasonably confident	Ali et al., 2010; Bhattacharya et al. 2014; Chowdappa, 2013; Gautam et al., 2013;Nagendran et al., 2019; Raj et al., 2010
South-East Asia	Many diseases in extremely diverse systems. Many different production systems involving a range of technologies. Large differences in vulnerability among crops.	Good	Major (soil borne) diseases still prevail. New races existing pathogens, better adapted, more aggressive, or with expanding ranges. Inoculum build-up (soil), and poor seed health.	Declining		Reasonably confident	Jansen et al., 1995; Kenyon et al., 2014; Mishra et al., 2019; Schreinemachers et al., 2012

Impacts of plant health on ecosystem services

	Nature and state of services generated	*State assess-ment*	*Evolution of services generated*	*Evolution assess-ment*	*Summary*	*Level of assessment confidence*	*References*
Sub-Saharan Africa	**Provisioning**: very high losses deplete provision flows. The very low consumption of vegetables in SSA is attributable at least in part to such losses.	Poor	Limited progress achieved.	Stable		Reasonably confident	FAOSTAT, 2018; Levasseur et al. 2007; Schreinemachers et al., 2018
Sub-Saharan Africa	**Regulating**: excessive pesticide use, with health risks and destruction of natural (microbiological) enemies of pathogens and pests.	Poor	Major health direct risks from the over-use of banned pesticides. Expanding agricultural area.	Declining		Reasonably confident	Levasseur et al. 2007
South Asia	**Provisioning**: despite the exploding urban population, sustained food provisioning. This is attributable at least in part to dynamic plant breeding progress against diseases.	Good	Innovative breeding (bio) biotechnology leading to disease resistant plant material; bio-pesticides deployment.	Improving		Reasonably confident	Chowdappa, 2013; Mishra et al., 2019; Uppala et al., 2010 ; Schreinemachers et al., 2018
South Asia	**Regulating**: water and land challenges in a dynamic context. Pesticide use and over-use frequent.	Fair	Pesticide use and resource depletion in part compensated by better and more efficient technology.	Improving		Reasonably confident	
South Asia	**Cultural** (pertains to household gardens): food provisioning and the associated cultural and social roles maintained.	Good	No indication of decline.	Stable		Little or indirect evidence	
South-East Asia	**Provisioning**: despite pressure, food provisioning has grown apace with that of South-East Asia's cities.	Good	As for South Asia: innovative breeding (bio) biotechnology leading to disease resistant plant material; bio-pesticides deployment.	Stable		Reasonably confident	Schreinemachers et al., 2012; Schreinemachers et al., 2018

South-East Asia	**Regulating**: pesticide use is a concern and so is the (over-)use of resources: land, water, and energy (synthetic fertilizers).	Fair	As elsewhere, but to a higher extent, systems under pressures. Very high pesticide use and not decelerating. Biological and chemical degradation of soils. Growing pressure on water and energy.	Declining		Reasonably confident	
South-East Asia	**Cultural** (pertains to household gardens): food provisioning and the associated very high cultural and social roles maintained.	Excellent	No indication of decline.	Stable		Little or indirect evidence	

References

Ali I, Malik AH, Malik AH, Mansoor S (2010) First report of Tomato leaf curl Palampur virus on bitter gourd in Pakistan. Plant Dis 94:276

Bhattacharya I, Dutta S, Mondal S et al (2014) Clubroot disease on Brassica crops in India. Can J Plant Pathol 36:154–160

Blodgett JT, Swart WJ, Louw S (1998) First Report of *Fusarium sambucinum, F. oxysporum, and F. subglutinans* associated with Stem Decay of *Amaranthus Hybridus* in South Africa. Plant Dis 82:1062-1062

CABI (2019a). *Colletotrichum lindemuthianum* (anthracnose of bean). Invasive Species Compendium. https://www.cabi.org/isc/datasheet/14918

CABI (2019b). *Xanthomonas campestris* pv. *campestris* (black rot). Invasive Species Compendium. https://www.cabi.org/isc/datasheet/56919

Chowdappa P (2013) Disease management in urban and peri-urban horticulture. In: Sumangala HP, Malhotra SK, Chowdappa P (eds) Urban and Peri-urban Horticulture-A perspective. Confederation of Horticulture Associations of India, New Delhi, pp 35–42

Coyne DL, Cortada L, Dalzell JJ et al (2018) Plant-Parasitic Nematodes and Food Security in Sub-Saharan Africa. Annu Rev Phytopathol 56:381–403

FAOSTAT (2018) http://www.fao.org/faostat/en/#data/QC

Gautam HR, Bhardwaj ML, Kumar R (2013) Climate change and its impact on plant diseases. Curr Sci 105:1685–1691

Jansen HGP, Midmore DJ, Binh PT, Valasayya S, Tru LC (1995) Peri-urban vegetable production in Ho Chi Minh city, Vietnam (AVRDC, Shanhua, Tainan). http://worldveg.tind.io/record/23547/files/eb0171.pdf

Jones RAC (2009) Plant virus emergence and evolution: Origins, new encounter scenarios, factors driving emergence, effects of changing world conditions, and prospects for control. Virus Res 141:113–130

Kenyon L, Tsai W-S, Shih S-L, Lee L-M (2014) Emergence and diversity of begomoviruses infecting solanaceous crops in East and Southeast Asia. Virus Res 186:104-113

Levasseur V, Pasquini MW, Kouamé C, Temple L (2007) A review of urban and peri-yrban vegetable production in West Africa. Acta Hort. 762. https://doi.org/10.17660/ActaHortic.2007.762.23

Mishra RK, Parihar AK, Basvaraj T et al (2019) Identification of new sources of resistance in Rajmash (*Phaseolus vulgaris* L.) against powdery mildew (*Erysiphe polygoni*) and stem rot (*Sclerotinia sclerotiorum*) diseases. Legume Res 42:430–433

Mnzava, NM, Dearing JA, Guarino L, Chweya JA, (compilers), de Koeijer H (ed) (1999) Bibliography of the genetic resources of traditional African vegetables. Neglected leafy green vegetable crops in Africa Vol. 2. International Plant Genetic Resources Institute, Rome, Italy

Nagendran K, Venkataravanappa V, Chauhan NS et al (2019) Viral diseases: a threat for tomato cultivation in Indo-Gangetic eastern plains of India. J Plant Pathol 101:15–22

Raj SK, Snehi SK, Khan MS et al (2010) First report of *Pepper leaf curl Bangladesh virus* strain associated with bitter gourd (*Momordica charantia* L.) yellow mosaic disease in India. Australas Plant Dis Notes 5:14–16

Schreinemachers P, Schad I, Tipraqsa P et al (2012) Can public GAP standards reduce agricultural pesticide use? The case of fruit and vegetable farming in northern Thailand. Agric Human Values 29:519-529. https://doi.org/10.1007/s10460-012-9378-6

Schreinemachers P, Simmons EB, Wopereis MCS (2018) Tapping the economic and nutritional power of vegetables. Glob Food Sec 16:36-45

Teri JM, Mlasani DK (1994) Choanephora blight and alternaria leaf spot of Amaranth in Tanzania. Plant Pathol 43:228-229

Uppala S, Beena S, Chapala M et al (2010) Bioefficacy of endophytes in the management of leaf blight disease of amaranth. In: Reddy MS, Desai S, Sayyed RZ et al (eds) Plant Growth Promotion by Rhizobacteria for Sustainable Agriculture. Scientific Publishers, India, pp 524-530

Supplementary file C - Table 12. State and evolution of plant health and services - Urban trees in Western Europe: Plane tree

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Western Europe	Oriental and London plane trees: Health status very heterogeneous, poor in southern Europe, and threatened in other parts of Europe. PCSD (Table 1) of plane trees is a major disease.	Poor	PCSD progresses across Europe. Plane trees of World Heritage Canal du Midi are condemned.	Declining		reasonably confident	Ferrari and Pichenot, 1974; Observatree, 2016; Panconesi, 1999; Tsopelas et al., 2017; VNF, 2019
Impacts of plant health on ecosystem services							
	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Western Europe	**Regulating**: Many decades are required to restore the regulating services ensure d by diseased urban trees.	Poor	PCSD is threatening these regulating services rapidly.	Declining		reasonably confident	Livesley et al., 2016
Western Europe	**Cultural**: The Oriental plane was sacred in ancient Egypt, Greece and Persia. Both Oriental and London planes have a strong historical, cultural, and social roles and values.	Poor	PCSD has killed many Oriental planes in Southern Europe. Tens of thousands of London planes are being lost to PCSD in Western Europe.	Declining		reasonably confident	Tsopelas et al., 2017; Turner-Skoff and Cavender, 2019

References

Ferrari JP, Pichenot M (1974) *Ceratocystis fimbriata* Ellis et Halsted f. *platani* (Walter), responsable d'une grave maladie du platane en France : « la tache chancreuse ». C R Acad Sci Paris D 278:2787-2789

Livesley SJ, McPherson EG, Calfapietra C (2016) The urban forest and ecosystem services: impacts on urban water, heat, and pollution cycles at the tree, street, and city scale. J Environ Qual 45:119-124

Observatree (2016) Field Identification Guide - Plane wilt. Online resource retrieved from www.observatree.org.uk

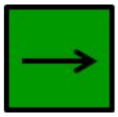
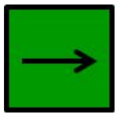
Panconesi A (1999) Canker stain of plane trees: a serious danger to urban plantings in Europe. J Plant Pathol 81:3-15

Tsopelas P, Santini A, Wingfield MJ, de Beer ZW (2017) Canker stain: a lethal disease destroying iconic plane trees. Plant Dis 101:645-658

Turner-Skoff JB, Cavender N (2019) The benefits of trees for livable and sustainable communities. Plants People Planet 1:323-335

VNF (2019). Voies Navigables de France. VNF poursuit la lutte contre le chancre coloré du platane. Online report retrieved from http://www.sudouest.vnf.fr/vnf-poursuit-la-lutte-contre-le-chancre-colore-du-a432.html

Supplementary file C - Table 13. State and evolution of plant health and services - Oaks in Western Europe and North America

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Western Europe	Poor crown condition - tree decline - has increased in evergreen and deciduous temperate oaks. Oak declines involve severe drought stress interacting with biotic agents, including pathogens. *Phytophthora* spp. have been emphasized in some cases. Acute oak decline (AOD) is associated with bacteria interacting with the bark beetles in the UK.	Fair	A significant tree decline has been reported in evergreen Mediterranean oaks. Newly described, emerging, pathogenic bacteria have been associated with Acute oak Decline and reported in England, Spain and Portugal.	Declining		reasonably confident	Brady et al., 2017; Camilho-Alves et al., 2013; Delatour, 1983; Desprez-Loustau et al., 2006; Jung et al., 2018; Manion and Lachance 1992; Marçais and Desprez-Loustau 2014; Michel et al., 2018
North America	North American oaks have become less abundant, particularly in the eastern USA. Multiple studies indicate that oak sapling mortality and lack of regeneration present a doubtful future for oak forests	Fair	Despite the prevalence of oaks across the northern U.S., multiple studies indicate that oak sapling mortality and lack of regeneration present a doubtful future for oak forests.	Declining		reasonably confident	Cobb et al., 2020; Conrad et al., 2020; Grünwald et al., 2019; Jensen-Tracy 2009; Juzwik et al., 2011; Navarro et al., 2020; Oak et al., 1996
Impacts of plant health on ecosystem services							
	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Western Europe	**Provisioning**: Oaks produce high quality timber. France alone produces over 12 million m³ of timber annually. Southern Europe cork oak forests account for 90% of the world's cork oak production.	Excellent	Provisioning services are affected by oak decline and diseases.	Stable		reasonably confident	Bugalho et al., 2018
Western Europe	**Regulating**: Oak forests ensure long-term carbon storage (400 Mt C in France alone); host a large biodiversity.	Excellent	Regulating services are affected by oak decline and diseases.	Declining		reasonably confident	McGrath et al., 2015; Mitchell et al., 2019
Western Europe	**Cultural**: The oak tree is a symbol of longevity, stability, strength (Leroy et al., 2020). Oak forests offer recreational and tourism services.	Excellent	Cultural services are threatened by oak decline and diseases.	Stable		reasonably confident	Boyd et al., 2013
North America	**Provisioning**: Oaks large quantities of hardwood lumber. Acorns are an important food source for indigenous peoples. Oak forests support hunted or collected food.	Excellent	Provisioning services are affected by oak decline and diseases.	Declining		reasonably confident	McShea and Healy 2002
North America	**Regulating**: Oaks forests host a large biodiversity; regulate biomass, carbon sequestration, soil formation, nutrient fluxes, energy flows; purify water and regulate water dynamics.	Excellent	Regulating services are affected by oak decline and diseases.	Declining		reasonably confident	Cavender-Bares 2019
North America	**Cultural**: Majestic oaks have enormous importance to human culture and meaning.	Excellent	Cultural services are affected by oak decline and diseases.	Declining		reasonably confident	Boyd et al., 2013

References

Brady C, Arnold D, McDonald J, Denman S (2017) Taxonomy and identification of bacteria associated with acute oak decline. World J Microbiol Biotechnol 33: 143

Boyd IL, Freer-Smith PH, Gilligan CA, Godfray HCJ (2013) The consequence of tree pests and diseases for ecosystem services. Science 342(6160):1235773

Bugalho MN, Pinto-Correia T, PulIdo F (2018) Human use of natural capital generates cultural and other ecosystem services in montado and dehesa oak woodlands. In: Paracchini ML, Zingari PC, Blasi C (eds) Reconnecting Natural and Cultural Capital. Publication Office of the European Union, Luxembourg, pp 115-123

Camilho-Alves da Clara MIE, de Almeida Ribeiro NMC (2013) Decline of Mediterranean oak trees and its association with *Phytophthora cinnamomi*: a review. Eur J For Res 132: 411-432

Cavender-Bares J (2019) Diversification, adaptation, and community assembly of the American oaks (*Quercus*), a model clade for integrating ecology and evolution. New Phytol 221:669– 692

Cobb RC, Haas SE, Kruskamp N, Whalen WD, Swiecki TJ, Rizzo DM, Frankel SJ, Meentemeyer RK (2020) The magnitude of regional-scale tree mortality caused by the invasive pathogen *Phytophthora ramorum.* Earth's Future e2020EF001500

Conrad AO, Crocker EV, Li X, Thomas WR, Ochuodho TO, Holmes TP, Nelson CD (2020) Threats to oaks in the eastern United States: perceptions and expectations of experts. J For 118:14-27

Delatour C (1983) Les dépérissements de chênes en Europe. Rev For Fran 5:265-282

Desprez-Loustau ML, Marçais B, Nageleisen LM, Piou D, Vannini A (2006) Interactive effects of drought and pathogens in forest trees. Ann For Sci 63: 597-612

Grünwald NJ, LeBoldus JM, Hamelin RC (2019) Ecology and evolution of the sudden oak death pathogen *Phytophthora ramorum*. Annu Rev Phytopathol 57:301-321

Jensen-Tracy S, Kenaley S, Hudler G, Harrington T, Logue C (2009) First report of the oak wilt fungus, *Ceratocystis fagacearum*, in New York State. Plant Dis 93:428

Jung T, Pérez-Sierra A, Durán A et al (2018) Canker and decline diseases caused by soil- and airborne *Phytophthora* species in forests and woodlands. Persoonia 40:182–220

Juzwik J, Appel DN, MacDonald WL, Burks S (2011) Challenges and successes in managing oak wilt in the United States. Plant Dis 95:888-900

Manion PD, Lachance D (1992) Forest Decline Concepts. APS Press, St Paul, MN, USA

Marçais B, Desprez-Loustau ML (2014) European oak powdery mildew: impact on trees, effects of environmental factors, and potential effects of climate change. Ann For Sci 71:633-642

McGrath MJ, Luyssaert S, Meyfroidt P et al (2015) Reconstructing European forest management from 1600 to 2010. Biogeosciences 12:4291-4316

McShea WJ, Healy WM (2002) Oak Forest Ecosystems Ecology and Management for Wildlife. Johns Hopkins University Press, Baltimore, MD

Michel A, Seidling W, Prescher AK (2018). Forest Condition in Europe: 2018 Technical Report of ICP Forests, Austrian Research Centre for Forests, Vienna

Mitchell RJ, Bellamy PE, Ellis CJ et al (2019). Collapsing foundations: The ecology of the British oak, implications of its decline and mitigation options. Biol Conserv 233:316-327

Navarro S, Wiese R, Nichols C et al E (2020) Slowing the Spread of Sudden Oak Death in Oregon Forests, 2001-2018. In: Frankel SJ, Alexander JM (eds) Proceedings of the seventh sudden oak death science and management symposium: healthy plants in a world with *Phytophthora*. PSW-GTR-268. Department of Agriculture, Forest Service, Pacific Southwest Research Station Albany, CA, USA, pp 2-3

Oak S, Tainter F, Williams J, Starkey D (1996) Oak decline risk rating for the southeastern United States. Ann For Sci 53:721-730

Supplementary file C - Table 14. State and evolution of plant health and services - Managed softwood forests of North America

Plant health

Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
North America	Overall, and despite some serious diseases, the state of health of actively managed softwood forests (AMSFs) may be considered fair. The concerns associated with the white pine blister rust, *Cronartium ribicola* is very serious	fair	Health of the five managed forest types considered has much declined. Pathogen impacts have increased in response to increased precipitation variations (excess and shortage), leading to stress-initiated declines and associated diseases.	declining		reasonably confident	Agne et al., 2018; Costanza et al., 2018; Coyle et al., 2015; 2019; Geils et al., 2010; Kliejunas et al., 2009; Hansen and Goheen, 2000; Kurz et al., 2008; Mildrexler et al., 2019; Woods et al., 2005; 2017

Impacts of plant health on ecosystem services

	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
North America	**Provisioning**: AMSFs across North America have produced a wide range of products over the last 30 years. Timber losses to plant disease have been relatively small. But those related to atmospheric and water regulation, have not been quantified: this is a global information gap.	good	Provisioning of services have declined. Timber volume and value have diminished; fewer healthy trees contribute to the carbon and water cycles. The recent decline of tree health might have far-reaching consequences, which cannot be quantified here.	declining		reasonably confident	Aitken et al., 2008; Allen et al., 2010; Flewelling and Monserud, 2002; McDowell et al., 2015; Metsaranta et al., 2011; Millar and Stephenson, 2015; Price et al., 2013; Spittlehouse and Stewart, 2003; Russell et al., 2015; Woods and Watts, 2019

References

Agne MC, Beedlow PA, Shaw DC, et al (2018) Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. For Ecol Manage 409:317-332

Aitken SN, Yeaman S, Holliday JA, et al (2008) Adaptation, migration or extirpation: climate change outcomes for tree populations. Evol Applic 1:95–111

Allen CD, Macalady AK, Chenchouni H, et al (2010) A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. For Ecol Manage 259:660-684

Constanza KL, Whitney TD, McIntire CD et al (2018) A synthesis of emerging health issues of eastern white pine (*Pinus strobus*) in eastern North America. For Ecol Manage 423: 3-17.

Coyle DR, Barnes BF, Klepzig KD, et al (2019) Abiotic and biotic factors affecting loblolly pine health in the Southeastern United States. For Sci 66:145–156

Coyle DR, Klepzig KD, Koch FH et al (2015) A review of southern pine decline in North America. For Ecol Manage 349:134-148

Flewelling JW, Monserud RA (2002) Comparing methods for modelling tree mortality. In: Crookston NL, Havis RN (eds) Second Forest Vegetation Simulator Conference. USDA, Forest Service, Rocky Mountain Research Station, Proc. RMRS-P-25., Ogden, UT, pp 168-177

Geils BW, Hummer KE, Hunt RS (2010) White pines, *Ribes*, and blister rust : A review and synthesis. For Pathol 40:147-185

Hansen EM, Goheen EM (2000) *Phellinus weirii* and other native root pathogens as determinants of forest structure and process in western North America. Annu Rev Phytopathol 38:515-39

Kliejunas JT, Geils BW, Glaeser JM et al (2009) General Technical Report PSW-GTR-225. Pacific Southwest Research Station, USDA Forest Service; Albany, California: 2009. Review of literature on climate change and forest diseases of western North America.

Kurz W, Dymond C, Stinson G et al (2008) Mountain pine beetle and forest carbon feedback to climate change. Nature 452:987–990

McDowell NG, Coops NC, Beck PS et al (2015) Global satellite monitoring of climate-induced vegetation disturbances. Trends Plant Sci 20:114–123

Metsaranta JM, Dymond CD, Kurz WA, Spittlehouse DL (2011) Uncertainty of 21st century growing stocks and GHG balance of forest in British Columbia, Canada resulting from potential climate change impacts on ecosystem processes. For Ecol Manage 262:827-837

Mildrexler DJ, Shaw DC, Cohen WB (2019) Short-term climate trends and the Swiss needle cast epidemic in Oregon's public and private coastal forestlands. For Ecol Manage 432:501-513

Millar CI, Stephenson NL (2015) Temperate forest health in an era of emerging megadisturbance. Science 349:823-826

Price DT, Alfaro RI, Brown KJ et al (2013) Anticipating the consequences of climate change for Canada's boreal forest ecosystems. Environ Rev 21:322-365

Russell MB, D'Amato AW, Albers MA et al (2015) Performance of the Forest Vegetation Simulator in managed white spruce plantations influenced by eastern spruce budworm in northern Minnesota For Sci 61:723-730

Spittlehouse DL, Stewart RB (2003) Adaptation to climate change in forest management. J Ecosyst Manage 4:1-11

Woods A, Coates KD, Hamann A (2005) Is an unprecedented Dothistroma needle blight epidemic related to climate change? BioScience 55:761-769

Woods AJ, Coates KD, Watts M et al (2017) Warning signals of adverse Interactions between climate change and native stressors in British Columbia forests. Forests 8:280

Woods AJ, Watts M (2019) The extent to which an unforeseen biotic disturbance agent can challenge timber objectives. For Ecol Manage 453

Supplementary file C - Table 15. State and evolution of plant health and services - Rubber tree and Cacao in the Amazon Forest

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Amazon (Cocoa and Rubber Tree)	Many pathogens of Cocoa and Rubber tree are present. Yet plant diseases are not reported to cause epidemics.	***Good***	The health status of populations in the wild has likely not changed over the past 10 years.	***Stable***		***reasonably confident***	Gazis and Chaverri, 2015; Gilbert and Hubbell, 1996; Ploetz, 2016; ter Steege et al., 2013
Impacts of plant health on ecosystem services							
	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Amazon (Cocoa and Rubber Tree)	**Provisioning:** Unaffected by diseases	Good	No reports of decline.	Stable		uncertain	Gazis and Chaverri, 2015
Amazon (Cocoa and Rubber Tree)	**Regulating**: Carbon storage, climate regulation, biodiversity conservation, cannot possibly be affected by the health status of just two species.	Good	No disease-related decline in regulating services.	Stable		reasonably confident	Gomes et al., 2019; Lovejoy and Nobre, 2019

References

Gazis R, Chaverri P (2015) Wild trees in the Amazon basin harbor a great diversity of beneficial endosymbiotic fungi: is this evidence of protective mutualism? Fungal Ecol 17:18–29

Gilbert GS, Hubbell SP (1996) Plant diseases and the conservation of tropical forests. BioScience 46:98–106

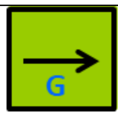
Gomes VHF, Vieira ICG, Salomão RP, ter Steege H (2019) Amazonian tree species threatened by deforestation and climate change. Nat Clim Chang 9:547–553

Lovejoy TE, Nobre C (2019) Amazon tipping point: Last chance for action. Sci Adv 5:eaba2949

Ploetz RC (2016) The Impact of Diseases on Cacao Production: A Global Overview. In: Bailey BA, Meinhardt LW (eds) Cacao Diseases: A History of Old Enemies and New Encounters. Springer International Publishing, Cham, pp 33–59

ter Steege H, Pitman NCA, Sabatier D, et al (2013) Hyperdominance in the Amazonian Tree Flora. Science 342:1243092

Supplementary file C - Table 16. State and evolution of plant health and services - Australian Forests (Eucalypts)

Plant health							
Ecoregion	***State of plant health***	***State assess-ment***	***Evolution of plant health***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Australian Forests (Eucalypts)	Many pathogens affect Eucalypts, especially *Phytophthora cinnamomi.* Despite this and numerous other causes for poor health, the state of eucalypt health is rated as good	good	Tree declines involving pathogens and multiple other causes (drought, fire, insects) are on the rise. Pathogen invasions have occurred.	declining		reasonably confident	ABARES, 2018; Cahill et al., 2008; Carnegie and Pegg, 2018; Keane et al., 2000; Paap et al., 2008; 2017;
Impacts of plant health on ecosystem services							
	Nature and state of services generated	***State assess-ment***	***Evolution of services generated***	***Evolution assess-ment***	***Summary***	***Level of assessment confidence***	***References***
Australian Forests (Eucalypts)	**Provisioning:** Several eucalypt species account for most of the timber harvesting in Australia representing over AU$ 8.5 billion of its GDP.	good	The economic benefits for the timber industry has been stable despite the true impact of diseases being unknown.	stable		reasonably confident	ABARES, 2018; McLeod, 2005
Australian Forests (Eucalypts)	**Regulating**: regulation of water supply; soil formation and conservation; carbon storage and sequestration.	good	Pathogens - *Phytophthora cinnamomi* - is a major threat to biodiversity.	declining		reasonably confident	Cahill et al., 2008; Garkaklis et al., 2004
Australian Forests (Eucalypts)	**Cultural:** recreation, and Indigenous and non-Indigenous cultural values.	good	Increase of eucalypt declines bring about a decline in cultural services.	declining		reasonably confident	ABARES, 2018;

References

ABARES (2018) Montreal Process Implementation Group for Australia and National Forest Inventory Steering Committee, 2018, Australia's State of the Forests Report 2018. ABABES, Canberra. https://www.agriculture.gov.au/abares/forestsaustralia/sofr/sofr-2018

Cahill DM, Rookes JE, Wilson BA, et al (2008) *Phytophthora cinnamomi* and Australia's biodiversity: impacts, predictions and progress towards control. Aust J Bot 56:279

Carnegie AJ, Pegg GS (2018) Lessons from the incursion of myrtle rust in Australia. Annu Rev Phytopathol 56:457–478

Garkaklis M, Calver M, Wilson B, Hardy Ges (2004) Habitat alteration caused by an introduced plant disease, *Phytophthora cinnamomi*: a potential threat to the conservation of Australian forest fauna. In: Lunney D (ed) Conservation of Australia's Forest Fauna, Second Edition. Royal Zoological Society of New South Wales, Mosman, NSW, Australia, pp 899–913

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

McLeod P (2005) Business Case for Phytophthora Research Funding. Commissioned by the Murdoch University Centre for Phytophthora Science and Management

Paap T, Burgess TI, Calver M, et al (2017) A thirteen-year study on the impact of a severe canker disease of *Corymbia calophylla* , a keystone tree in Mediterranean-type forests. For Pathol 47: e12292

Paap T, Burgess TI, McComb JA, Shearer BL, Hardy GESJ (2008) *Quambalaria* species, including *Q. coyrecup* sp. nov., implicated in canker and shoot blight diseases causing decline of Corymbia species in the southwest of Western Australia. Mycol Res 112:57–69