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Crop health and its global impacts on the components of food security

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Abstract The literature on the importance of plant pathogens sometimes emphasizes their possible role in historical food shortages and even in famines. Aside from such major crises, plant pathogens should also be seen as important reducers of crop performances, with impacts on system sustainability, from the ecological, agronomical, social, and economic standpoints – all contributing ultimately to affecting food security. These views need reconciliation in order to produce a clearer picture of the multidimensional effects of plant disease epidemics. Such a picture is needed for disease management today, but would also be useful for future policies. This article attempts to develop a framework that would enable assessment of the impacts of plant diseases, referred collectively to as crop health, on food security via its components. We have combined three different existing definitions of food security in order to develop a framework consisting of the following six components: (1) Availability. Primary production; (2) Availability. Import - Stockpiles; (3) Access. Physical and supply chain; (4) Access. Economic; (5) Stability of food availability; (6) Utility-Safety-Quality-Nutritive value. In this framework, components of food security are combined with three attributes of production situations: the nature of the considered crop (i.e. food- or non-food), the structure of farms (i.e. subsistence or commercial),

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and the structure of markets (i.e. weakly organized and local, to strongly organized and globalized). The resulting matrix: [Food security components] × [Attributes of production situations] provides a framework where the impacts of chronic, acute, and emerging plant disease epidemics on food security can be examined. We propose that, given the number of components and interactions at play, a systems modelling approach is required to address the functioning of food systems exposed to plant disease risks. This approach would have application in both the management of the current attrition of crop performances by plant diseases, and also of possible disease-induced shocks. Such an approach would also enable quantifying shifts in disease vulnerability of production situations, and therefore, of food systems, as a result of climate change, globalization, and evolving crop health.

Keywords Plant disease epidemics · Epidemiology · Crop losses · Chronic epidemics · Acute epidemics · Emerging epidemics

Introduction

Food security has been defined as "[a condition] when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO 1996). This definition suggests successive stages or steps through which food security may be achieved at a given geographical location, in a given socio-economic context: first the availability of sufficient food; second, physical access to food; third, food that is safe and nutritious; and fourth, food that satisfies dietary, cultural, and health requirements (Teng and Escaler 2010). The definition also entails a temporal dimension, as it indicates that food security must be achieved "at all times". Thus, the above definition invites the identification of components of food security – elements that constitute food security, and also elements of a process, that is, steps towards food security.

The phrase "crop health" is sometimes used in a loose manner, to refer to any harmful factor, biological, chemical, or physical, that may affect plant physiology and crop performances. Several approaches to the use of this phrase have been proposed (Döring et al. 2012); the meaning of "crop health" in the present article is limited to the harmful effects associated with plant pathogens. The present analysis discusses a limited series of crop-pathogen examples, from different angles. One of these angles is the spatiotemporal characteristics of disease progress, which determines the local extent, the geographical range, and the temporal pattern of disease injury caused to crop plants, and therefore, of damage. Some plant diseases develop very suddenly, causing severe epidemics with massive damage within a given area; others are, seemingly, omnipresent, recurrent, affecting very wide areas, but seldom causing complete loss. Such extreme epidemiological patterns can have very different consequences. These differences in impacts may be first associated with the shape of epidemiological patterns, which have recently been defined as chronic, acute, or emerging (Savary et al. 2011). But the differences in impact may owe much to the overall context where the epidemics take place. In this work, we refer to this overall context, with its ecological, social, economic, and technological dimensions, as a production situation (Breman and De Wit 1983; Rabbinge and De Wit 1989). A production situation is the nexus where agricultural production takes place, where crops develop within a given ecological, cultural, social, and technological context, and where agricultural produce finds its way to consumption by societies in a given economic setting (Rabbinge and De Wit 1989). Plant disease epidemics also take place in this production situation nexus; and their possible consequences, in terms of losses in quantity or quality, as well as in terms of loss of environmental resources, depend on the production situation (Savary et al. 2016).

Plant disease represents a threat to global food security (Strange and Scott 2005). This threat takes many different forms, depending on the considered disease, crop, and production situation (Savary et al. 2006). This makes risk analysis difficult, and hard to share and explain to policy makers. Furthermore, global change, including climate change, influences the type of disease threats (Gregory et al. 2009; Chakraborty and Newton 2011; Gustafson 2011), their possible consequences, and the approaches to relieve them. A framework of analysis is needed, to which this article contributes.

This article addresses the structure of the complex relations between food security and its components, on the one hand, plant disease epidemics and their patterns, on the other, within production situations. It is organized in five sections, each with successive objectives. In the first section different definitions of food security components are compared, and a set of components that appear suitable for assessing impacts of plant disease on food security is chosen. The second section consists of short narratives on a few major plant disease epidemics, where we highlight impacts and some elements of socio-economic contexts from a limited set of selected references. These examples have been chosen to both suggest typical food system attributes influencing plant disease impacts on food security, and also to illustrate patterns of impacts on food security components. In the third section, we then consider attributes of production situations (i.e., of food systems) that determine plant disease impacts. In the fourth section, we analyse the impacts of plant disease epidemics on food security components in the selected plant disease examples. And in the fifth and last section, we develop a tentative synthesis of plant disease epidemic impacts on food security components, depending on the nature of the crop and the characteristics of production situations.

Food security and its components

Several lists of components of food security have been proposed. A simple set of four components has been proposed by the FAO (2006): Food availability, Food access, Utilization, and Stability (Fig. 1). These four components provide a fair synthesis of the 1996 definition, but perhaps do not emphasize enough the multiple dimensions – physical, economic, social – of "food availability"; they do not propose much insight into the nutritional value of food either. The set of indicators proposed later on by FAO, IFAD, and WFP (2013) is organized in two broad categories, static and dynamic determinants, and outcomes. Among the static and dynamic determinants, groups of indicators are proposed pertaining to: the availability of food, its physical access, its economic access, its utilization, its vulnerability, and the existence of food shocks. Two groups again are formed under the outcomes of food security, which reflect the access to and the utilization of food. This other characterization of food security in eight components (Fig. 1) appears much more detailed. It incorporates the economic dimension of food access, and it offers a number of indicators for the nutritional dimensions of food. Yet, this second characterisation lacks the critical component of sustainable food provisioning by agro-ecosystems. Desker et al. (2013) proposed a third set of components of food security. This set (Fig. 1) includes two components for food availability, one pertaining to food provisioning, and the other to the existence of means to store and release food in social systems. This third set includes two components for access as well, a first one addressing the physical access to food, such as the existence of markets or stores, and their accessibility, and the second one addressing the economic access to food, including, e.g. a purchasing power that suffices to purchase food. This third set also includes a fifth component, food utility, which integrates elements pertaining to the nutritional value of food.

In this article, we combine these three approaches to the definition of components of food security (Fig. 1). A first component is "availability generated by primary agricultural production". This component refers to the first ecosystem service generated by agro-ecosystems, food provisioning (Millennium Ecosystem Assessment 2005), and is centred on the ability of agriculture to produce food for societies. A second component also concerns the availability of food, but is centred on the critical role of infrastructures that enable the storing of food and its progressive release to consumers. A third component concerns the physical access to food, its distribution, which is made possible by transportation systems. Transportation infrastructures entail costs: cost of construction, and cost for maintenance, which are borne by societies or economic groups. The fourth component also deals with access to food, but from the economic standpoint: here we refer to the purchasing power of people to buy food. This fourth component therefore refers to consumers' incomes, to food prices, and to fraction of income allocated to food purchase. Food production can be partly, or completely, disrupted by various events; the fifth component therefore pertains to the time dimension of food provisioning to societies, and refers to availability of food over time (time of the year and successive years). The sixth component concerns the intrinsic value of food as nourishment. Food value may be partly or completely eliminated (or even become negative) in the case of poor cooking quality, or of inadequate balance of nutrients. Pesticide residues, contaminants, or toxins may even make food unsafe for consumption.

We propose these six components for food security as an acceptable synthesis of earlier definitions. This set of components also constitutes a suitable basis to examine the multiple impacts – technical, economic, and social – of crop health on food security.

Examples of impacts of plant diseases

The social and economic impacts of plant disease are hard to assess, in part because so many elements can simultaneously affect societies. Even in the best-documented historical examples, much caution is required not to overstate, or under-estimate, causes and effects (Zadoks 2008). Another reason is that losses caused by plant diseases are so seldom quantified. A third reason is that plant diseases have so many possible consequences (Zadoks 2008) on the components of food security: a framework for analysis is necessary, which this article may contribute to developing. The following section presents some examples of plant disease impacts, indicating when necessary where caution is required. These examples were chosen because they fulfil two criteria: (1) the reported impacts on components of food security are well documented, and (2) the chosen examples collectively allow examination of possible impacts of plant diseases on the six components of Fig. 1: (1) Availability and primary food production, (2) Availability through reliable import and storage, (3) Access through the existence of reliable physical structure enabling food distribution, (4) Access to food by consumers through sufficient purchasing power, (5) Stability of food production over crop growing seasons and over successive years, (6) Production of safe, nutritious food that meets desirable quality standards.

What follows is a series of crop-pathogen examples, which are addressed in a narrative way in the first stage. In the second

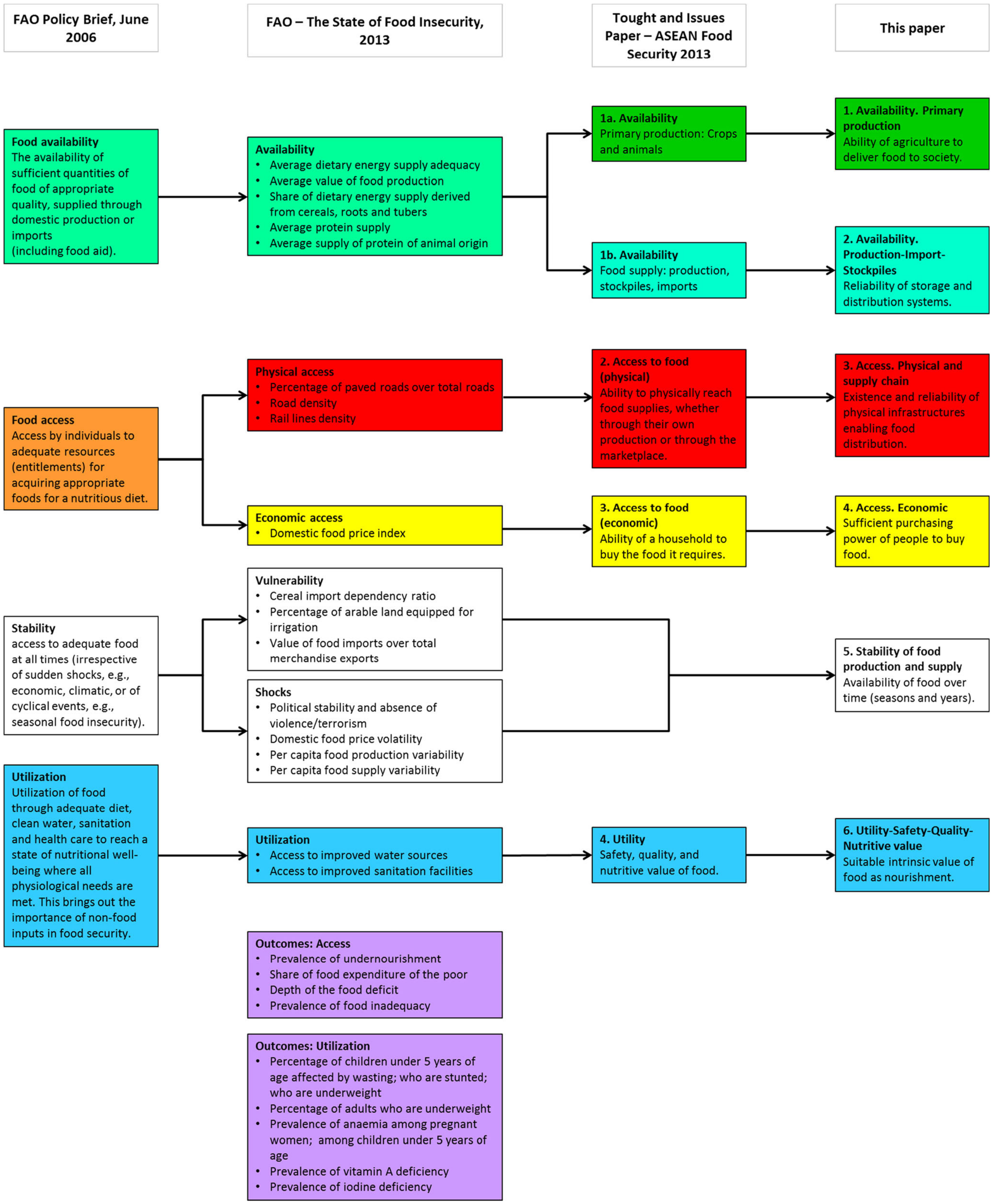

Fig. 1 Components of food security according to different sources, and as defined in this paper

stage, we develop a simple typology of production situations (i.e., of the agronomic, social, and economic contexts), which may help in the interpretation of the impacts of the plant diseases chosen as examples. In the third stage, these crop-pathogen examples are then examined through the filter of the components of food security, which they may, or may not, affect.

Potato late blight, Western Europe, 19th and twentieth century

Phytophthora infestans (Montagne) de Bary is the cause of a famine that killed or displaced a quarter of the Irish population in the nineteenth century. The potato blight of Ireland is documented in many articles and books (see e.g. Fraser 2003), where the events of the year 1845 (initial spread of the disease across Belgium, France, the Netherlands, and then the entire Western Europe), of 1846 (first strong impacts of the epidemics), and 1847 (further impacts and generalized famine), in particular, are documented (Bourke 1964). A key biological feature of this epidemic is that it resulted from the foundation in Europe of an immigrating pathogen species with an extremely small genetic diversity, possibly a single clonal lineage (Goodwin et al. 1994). The entire European potato crop was susceptible to the new pathogen. In Ireland, it destroyed the main staple of a population that was impoverished in the very harsh context of the Industrial Revolution, in a country where agriculture was in full transition as a result of the end of the Napoleonic wars. Potato producers were poor, farms and plots very small, infrastructures weak and technical support, nonexistent. Critically: potato was then the main subsistence crop in Ireland.

A second migration of *P. infestans* probably occurred in the late 1970s, when a new mating type of the pathogen was introduced in the European populations of the pathogen. This introduction completely changed the genetic structure of European pathogen populations, making the disease more difficult to manage through chemicals (Goodwin et al. 1996) and causing an overall increase in aggressiveness of the pathogen (Day and Shattock 1997). No disease epidemic with impacts of a magnitude nearly approaching that of the nineteenth century occurred, as the knowledge base had so much increased since then, along with the widespread use of chemical and prophylactic control.

Wheat rusts, North America, Europe, Africa, and Asia 20th and twenty-first century

The end of the twentieth century and the beginning of the 21st have seen unprecedented changes in the landscape of global wheat health. This is exemplified by the three rusts of wheat: stem, leaf, and stripe (yellow) rust, caused by *Puccinia graminis* f. sp. *tritici*, *P. triticina*, and *P. striiformis* f. sp. *tritici*, respectively.

The case of the cereal rusts in the USA is an exceptionally well-quantified example of disease impacts, where yield losses have been quantified on a yearly and state basis (Roelfs 1978). Variation of yield losses in one state of the USA (Fig. 2) indicates epidemics of stem and leaf (brown) rusts, the former very regular in the years 1918–1932, and the latter more erratic over the entire 1918–1976 period. Yield losses for Minnesota alone are in the range of the 10^4 tons yearly for each disease, a regular attrition of a statewide production, which is in the range of 10^6 tons yearly.

Stem (black) rust, caused by *Puccinia graminis* Pers. f. sp. *tritici* Eriks. & E. Henn., has historically been an important disease of wheat in Africa, the Middle East, South Asia, Australia and New Zealand, and in North and South America (Saari and Prescott 1985), as well Europe (Zadoks and Bouwman 1985). Pardey et al. (2013) recently produced a conservative estimate of global wheat yield losses to stem rust of 6.2 million tons yearly for the 1961–2009 period. Compared to leaf (brown) rust and stripe (yellow) rust of wheat, stem rust is sometimes considered the most damaging, because it affects not only leaf blades, but also leaf sheaths, stems, and heads (Eversmeyer and Kramer 2000). The emergence of new races of the pathogen in East Africa in 1998–2005, and their spread towards Central and South Asia, and towards North Africa therefore raised very serious concerns. However, an international effort, through the Global Rust Initiative, enabled the development of a strategy involving (1) adult plant resistance in primary risk (inoculum sources)

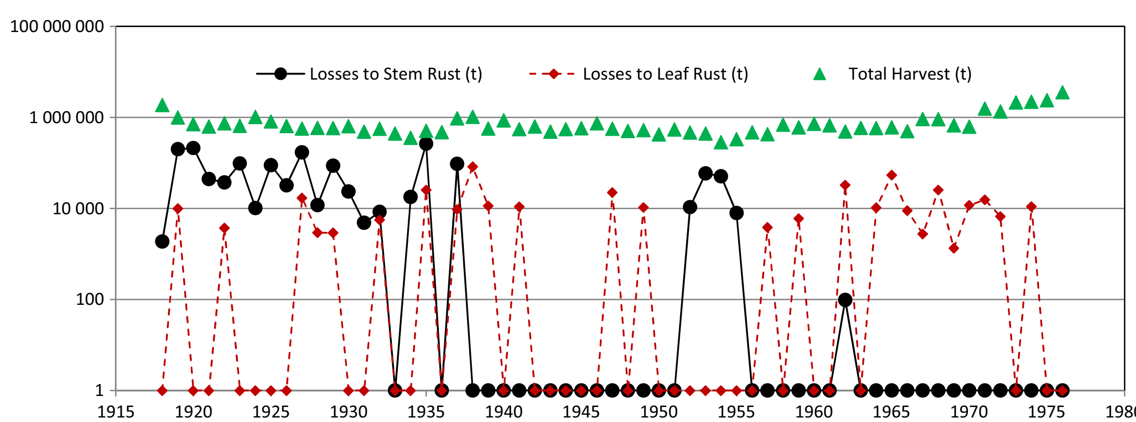

Fig. 2 Yield losses to leaf and stem rust in Minnesota, 1918–1976 (Roelfs 1978). Abscissa: time in years. Ordinates (Log_{10} scale): yield and yield losses, tons

areas, and (2) race-specific resistances in secondary risk areas (Singh et al. 2008).

Wheat rust threats are not limited to stem (black) rust. New stripe (yellow) rust strains that are more aggressive and that are adapted to higher temperatures have recently spread in North America and elsewhere in the world (Milus et al. 2009; Sørensen et al. 2014). Milus et al. (2009) report that annual wheat yield losses across all states east of the Rocky Mountains averaged 5 10^3 tons/year (range: 0 – 57 10^3 tons/year) for the period 1976–1999. But the average mean loss shifted to 883 10^3 tons/year (range: 93 10^3–2,125 10^3 tons/year), when the new isolates were established.

Fusarium head blight, North America, China, and Europe today

"Lush, green fields become blighted seemingly overnight". This description by McMullen et al. (1997) summarizes the impact of fusarium head blight (FHB) on the great plains of North America. FHB is an important disease in many wheat-producing areas, including Europe, China, the USA, Canada, and Brazil (Parry et al. 1995; Xu 2003; Savary 2014).

The disease has been associated with a large number of plant pathogens, but the literature from the USA and Canada mostly refers to *Fusarium graminearum* (teleomorph *Gibberella zeae*), while many different *Fusarium* species are generally considered in Europe (Parry et al. 1995; Xu 2003). In North America, recurrent epidemics have been reported for many years, but particularly severe epidemics have been taking place from the 1990s until today probably as a result of the expansion of wheat-maize rotation and of conservation tillage practices (Parry et al. 1995; McMullen et al. 1997, 2012; Dill-Macky and Jones 2000; Windels 2000; Xu 2003; Bateman et al. 2007). Following the typology of epidemics developed in Savary et al. (2011), FHB may be considered as a major chronic disease in many wheat production areas of the world, although acute episodes occur on a background of recurring epidemics. The 1993 epidemic which especially affected Minnesota, North and South Dakota, and Manitoba, led to the loss of 4.25 million tons of wheat, and over $ 1 billion loss in the USA alone (McMullen et al. 1997). FHB does cause important yield reductions, but the disease has become a primary concern because of the mycotoxins that may be produced in infected grains (Parry et al. 1995; McMullen et al. 1997; Xu 2003; Xu and Nicholson 2009; Bateman et al. 2007).

False smut of rice: Asia, today

False smut, once a sign of good rice harvest (Ou 1985; F. A. Elazegui, IRRI, personal communication) in Asia, has become one of the most important grain diseases of rice (e.g., Roy 1980; Taira 1982; Honkura 1989; Singh and Pophaly 2010). The pathogen (*Ustilaginoidea virens* Takahashi [teleomorph: *Villosiclava virens* (Nakata) Tanaka & Tanaka]) produces clusters of sporangia forming smut balls that are initially orange and then turn green to greenish black with age (Ou 1985). These smut balls replace spikelets and affect the formation of adjacent spikelets. Spores of pathogens may contaminate healthy seeds during harvesting and threshing. The rate of milled rice decreases as the number of infected grains increases (Ding et al. 1997). Increased disease intensity is associated with hybrid rice cultivation (Lu et al. 2009; Reddy et al. 2011). Reddy et al. (2011), in particular, analysed false smut intensities assessed in 129 districts belonging to 18 different states of India in 2005. For both the lowest (χ^2 = 4.768, $P < 0.05$) and the highest (χ^2 = 4.258, $P < 0.05$) disease estimates per district, their data indicate a significant linkage between widespread use (> 10% of rice acreage planted) vs. infrequent use of hybrids (< 10% of rice acreage) and occurrence of high (>5% panicles affected) vs. low disease incidence (<5% panicles). The pathogen produces two kinds of mycotoxins, namely ustiloxin (Koiso et al. 1992, 1998) and ustilaginoidin (Koyama and Natori 1988; Meng et al. 2015), which are toxic to animals.

Brown spot of rice: South Asia, twentieth century and today

Brown spot, caused by *Cochliobolus miyabeanus* (Ito and Kuribayashi) Drechs. ex Dastur. (Anamorph: *Bipolaris oryzae* (Breda de Haan) Shoemaker) occurs in all the rice-growing regions in the world (Ou 1985). The disease is responsible for regular epidemics all over Asia, especially when the crop encounters water and nutrient stresses, i.e., in poor production situations, where soils are marginal, fertilizer inputs limited, and water supply, irregular. Brown spot was termed "the poor farmers' rice disease" by Zadoks (1974). Extensive survey and crop-loss experimental work led to the estimate that *the average* rice yield losses to brown spot are in the range of 10% of the attainable yield across tropical Asia, making it one of the main rice yield-reducers (Savary et al. 2000). Despite the importance of this disease, research efforts on brown spot remain very limited, making it an orphan disease of rice (Barnwal et al. 2013).

Superimposed against this background of chronicity of the disease, acute brown spot epidemics have been reported. Brown spot has for instance been associated with two major rice disease epidemics in India, first in 1918–19, in the Krishna-Godavari delta, and second in 1942 in today's India and Bangladesh (Chakrabarti 2001). The latter epidemic was associated with the Great Bengal Famine discussed by Padmanabhan (1973) and Chakrabarti (2001). Although plant diseases and famines have very complex relationships (Zadoks 2008), one can safely consider that this plant disease had a very strong contribution to the weakening of an already fragile economic and social fabric, where infrastructures were gravely deficient.

Coffee rust in central America, today

Coffee rust, caused by *Hemileia vastatrix*, has been responsible for dramatic epidemics in various coffee-growing regions of the world, notably in Ceylon (today's Sri Lanka) in the nineteenth century, where it caused coffee cultivation to be abandoned. It had similar impacts in other countries of South- and South-East Asia (McCook and Vandermeer 2015). Since 2008, a series of epidemics have affected Mexico, Guatemala, Belize, El Salvador, Honduras, Costa Rica, Panama, the Dominican Republic, Colombia, Ecuador, and Peru (McCook and Vandermeer 2015). Coffee rust epidemics usually develop during and after the harvest period, when the multiplication of rust lesions reduces intercepted light, while massive spore production by rust lesions exhaust the reserves of coffee trees (Avelino et al. 2006). As a result, coffee rust epidemics usually have indirect effects, i.e., they affect crop performances in the following years. Recent epidemics in Central America were actually strong and early enough to have a measurable direct effect on coffee yield. Between 2011 and 2014, coffee production in Central America has been reduced by 17%, a loss equivalent to $616 million. However, because of global price decline, this further translated into a 50% fall of the coffee export value from Central America (McCook and Vandermeer 2015).

Avelino et al. (2015) list a whole array of partial factors to explain these epidemics in Central America, including: ageing coffee trees, wide use of susceptible cultivars, suboptimal crop management (due to an unfavourable overall economic context), increased rainfall levels, earlier rainy seasons, reduced temperature amplitude, and reduced global radiation.

Food system attributes that determine plant disease impacts

The above examples suggest that the impacts which plant disease epidemics may have on food systems depend on a series of interacting epidemiological, agricultural, and economic criteria. We propose to consider four such attributes: epidemiological type, nature of the affected crop, farm structure, and market structure.

Three patterns of plant disease epidemics

The epidemiological attribute pertains to the temporal frequency and spatial extent of crop losses caused by plant disease epidemics. One may consider three types of epidemic patterns and of associated losses (Savary et al. 2011):

1. chronic, for a disease that occurs on a regular, season after season, basis over large areas, causing regular attrition in system performances, including yield reductions;
2. acute, for a disease occurring irregularly, both temporally and spatially, and which may cause massive disruptions in system performances ("outbreak"); and
3. emerging, for a disease whose range is expanding to new areas.

A good example of a chronic epidemic is brown spot of rice in south Asia: the disease is omnipresent, every season, over very large areas, to the point of becoming almost unnoticed. Fusarium head blight of wheat, rice false smut, and coffee rust illustrate acute epidemics well, with irregular but considerable increases in disease intensity over variable, sometimes large areas. Potato late blight in Ireland in the mid-nineteenth century is a typical example of the third type, emerging epidemic. Epidemics of different types may be caused by similar, sometimes by the same, pathogens. For instance, leaf (brown) rust in the Indo-Gangetic Plains (Nagarajan and Joshi 1985), stripe (yellow) rust in Western Europe before 2000 (Zadoks and Bouwman 1985), in the great plains of North America today (Milus et al. 2009) and in North-Western Europe after 2000, may be considered as chronic, acute, and emerging epidemics, respectively. Shifts in epidemiological attributes occur because the temporal and spatial shapes of plant disease epidemics not only depend on the biological characteristics of the pathogen and of the host plant, but also on production situations, i.e. agricultural, social, environmental and economic contexts (Zadoks and Schein 1979; Savary et al. 2016).

Food crops and cash crops

The nature of the affected crop defines the nature of impacts. Damage to food crops may immediately cause a reduction of food provisioning (Component 1 in Fig. 1). By contrast, damage to cash crops may lead to reduced economic access to food (Component 4). These initial impacts may vary in intensity, depending on the strength and duration of the disease shock. They may then also translate into other impacts: epidemics on food crops may lead to a shortage in supply to storage systems or a reduction of exports (Component 2), or an erratic supply of food to markets (Component 5); while epidemics on cash crops may generate overall impoverishment leading to poor distribution and inefficient supply chains (Component 3). These sequelae may be seen as reflections of socio-economic contexts, and markets at different scales.

Farm structures

Farm structures may strongly affect the intensity of impacts. Pingali and Rosegrant (1995) discussed and analysed the general trend of farms evolving from subsistence, integrated, and diverse, to commercial and specialized. Even today, the vast majority of the global poor is rural (Chen and Ravallion 2007), and many depend on small, subsistence farms. These farms are very vulnerable to all three types of epidemics, immediately affecting Component 1, and rapidly affecting Components 2 and 5. Large, commercial farms, by contrast, are likely to be more vulnerable to acute or emerging epidemics if their capital structure is affected, with first impact on Components 2, potentially cascading to Components 3, 4, and 5.

Market structures

Market structures play an important role in the impacts, especially in terms of food availability (Component 2), stability (Component 5), and, indirectly, on economic access (Component 4). This applies of course for export crops such as coffee and impacts on Component 4 (Avelino et al. 2015), but is also true for food crops (Components 2 and 5). Between 2013 and 2016, the average annual global wheat production was 725 million metric tons, of which 22% were exported. By contrast, the global rice output in the same period was 494 million metric tons, with 9% export (FAO 2016). The contrasting cases of rice (the first, and yet the least traded, world food crop) and of wheat (the second, and widely traded, world food crop) have been widely discussed (e.g. Headey 2011).

Impacts of plant diseases on the components of food security

We can use the above examples to specify disease impacts on the six considered food security components (Table 1).

Potato late blight, Ireland, nineteenth century

Analyses by Bourke (1964) and Fraser (2003) provide a background to the impacts of late blight on five of the six food security components. The emergence of potato late blight in Ireland in the mid-nineteenth century had a rapid and brutal effect on food production (Component 1): while the effects had been incomplete (about 40% loss) in 1845, the potato crop of Ireland was altogether wiped out in 1846 (Bourke 1964) and the disease continued having massive effects in the following years (Fraser 2003). The very limited, local reserves were rapidly exhausted (Component 2). Some, but inefficient and too localized relief was attempted (Component 3), which did not compensate the shortage of food, and the extremely low purchasing power of a segment of the population (Component 4). The successive epidemics after 1845 gravely affected the availability of food over successive years, and during any given growing season (Component 5).

Wheat rusts, world's main wheat production areas, today

Considered collectively, the three wheat rusts represent the main yield-reducing factors in the world's key producing areas: the great plains of North America (Roelfs 1985); the plains of Western Europe (Zadoks and Bouwman 1985); the plains of Eastern Europe, Central Asia, and China; and the Indo-Gangetic plains (Saari and Prescott 1985).

First, the cereal rusts directly affect food production (Component 1), irrespective of the epidemiological pattern of epidemics – chronic, acute, or emerging. Second, acute or emerging epidemics can affect the stockpiles of exporting countries, the trade of grain between countries, and therefore imports and reserves in importing countries (Component 2). For instance, the occurrence of particularly severe (acute) leaf (brown) rust epidemics in the great plains of North America may affect wheat stockpiles; or massive stripe (yellow) rust (emerging) epidemics in the same producing area (e.g. in 2000–2005) can affect global trade and the status of reserves. As a result, major importers, such as several countries of North Africa and the Middle East, may be impacted. Infrastructures enabling physical access (Component 3) may be affected if wheat production is reduced in an area which depends on wheat for its revenues. Limited wheat availability in an area of traditional strong wheat consumption (e.g. the Indo-Gangetic Plains), on the other hand, may lead to increased local prices, and as a result, may strongly affect economic access (Component 4), or the availability of food over time (Component 5).

Fusarium head blight of wheat, Great Plains of North America

FHB impacts a wide array of food security components, which are documented by Windels (2000) from the economic and social viewpoint in the USA. The disease reduces yields and therefore directly reduces food production (Component 1). Mycotoxin contamination of the grain has no effect on yield, but on the uses of the grain: this represents a loss of grain for food and a substantial economic loss for growers. Economic losses can be amplified by a combination of inaccurate sampling and mycotoxin analyses with high error margins. Since FHB affects some of the world's most important breadbaskets and their storage infrastructures, it can also strongly affect Component 2. Recurring epidemics weaken the economic and social fabric, as well as the ability of wheat farms to survive, which further, but in a longer term, affect Component 1. Where wheat represents a source of income needed for food purchase, the disease may hamper the economic access to food (Component 4). Irregular epidemics, even where storage facilities are strong, can affect the stability of production (Component 5). The ability of a number of *Fusarium* species to produce mycotoxins has made FHB a

Table 1 Examples of impacts of plant disease on food security components

Components of Food Security	Potato Late Blight (Ireland, 19th century)	Wheat Rusts World's Main Wheat Production Areas, Today	Fusarium Head Blight, US Mid-West, Today	False Smut of Rice, Asia, Today	Brown Spot of Rice	Coffee Rust, Central America, today
1. Availability. Primary production	Very large	Large	Strongly impacted	Large	Large	Not affected
2. Availability. Import - Stockpiles	Large	Strongly impacted	Strongly impacted	Impacted	Strongly impacted	Impacted
3. Access. Physical and supply chain	Impacted	Impacted	Impacted	Not affected	Strongly impacted	Impacted
4. Access. Economical	Strongly impacted	Impacted	Impacted	Impacted	Strongly impacted	Large
5. Stability of food availability	Impacted	Impacted	Impacted	Impacted	Large	Not affected
6. Utility-Safety-Quality-Nutritive value	Not affected	Not affected	Very large	Large	Strongly impacted	Not affected

key factor that threatens the nutritional value of food (Component 6).

False smut of rice in Asia

Reported yield losses to false smut range from 1.0% to 13.5% (Nessa et al. 2015), as a result of unfilled and partially filled grains and lower grain weight (Component 1). Lu et al. (2009) report very large yield losses in several provinces of China, in Liaoning, Sichuan, and Hubei (with 633,000 ha affected and 1.37 million tons yield lost in this last province in 2005).

Component 2 is actually related to the disease cycle, in the sense that infected seeds may affect rice production during the subsequent cropping season, particularly in areas where farmers depend on locally produced seeds. The pathogen is considered to be of quarantine significance in some rice-growing countries (Mew et al. 1988). Quarantine and regulatory restrictions may hamper the flow of seeds to areas where these are needed. Yield reductions may be heavy enough to affect farmers' income and their access to food (Component 4). False smut is now part of this relatively small group of rice yield-reducers that may disrupt rice trade and prices, at least locally, thus contributing to a destabilisation of rice availability (Component 5). The toxins produced by the pathogen gravely affect the eating quality of contaminated rice (Component 6).

Brown spot of rice in South Asia, today

Amongst the disease examples considered, brown spot of rice probably affects the largest number of food security components. This is in part related to the versatile, chronic to acute, spatiotemporal nature of epidemics (Savary et al. 2011). Furthermore, the disease affects the physiology and the yield-building of rice crops through several injury mechanisms: a reduction of light interception, an accelerated rate of leaf senescence, a decrease in photosynthetic activity, and direct damage to the grain (Barnwal et al. 2013). Primary production is very seriously affected (Component 1): the disease is so frequent, omnipresent, that it is often – wrongly – taken for an abiotic stress, or is altogether not recognized. Reductions of yield performances, however, are very real (Barnwal et al. 2013), and have severe impacts on storage systems and stockpiles (Component 2). Actually, the Great Bengal Famine has, in part, been associated with poor storage systems, and the undermining effects of brown spot on stockpiles (Padmanabhan 1973). Brown spot epidemics affect poor farmers in poor countries, or in poor areas of emerging nations because of their chronicity: they make farmers poorer, and impoverish entire local or national economies; poor economies cannot maintain good infrastructures; as a result one may consider that brown spot epidemics affect infrastructures and the physical access to food (Component 3), e.g. roads,

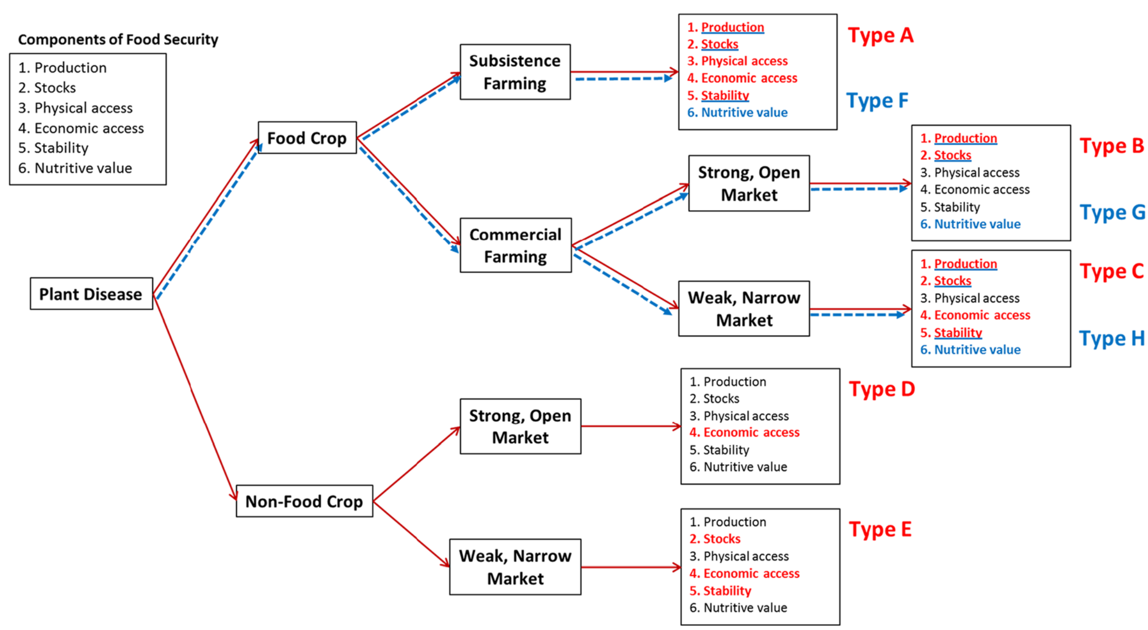

Fig. 3 Patterns of plant disease impacts on the components of food security. Six components of food security (Fig. 1) are considered (see box at top left). Crops and agricultural production are categorised as: Food or Non-Food; in Subsistence or Commercial Farming; and with Strong and Open, or Weak and Narrow supporting Market. The possible impacts of qualitative losses that specifically affect the nutritional value of food (including toxins) are shown in blue. Impacts are shown as colours in the successive boxes: plant disease in food crop of subsistence farming (A; with impacts on nutritive value: F); plant disease in food crops of commercial farming with strong and open market (B; with impacts on nutritive value: G); plant disease in food crops of commercial farming with weak and narrow market (C; with impacts on nutritive value: H); plant disease in non-food crops with strong and open market (D); plant disease in non-food crops with weak and narrow market (E). Impacts on food security components are illustrative only, see Discussion

railways, trains, and lorries – ironically, one of the other causes of the Great Bengal Famine (Padmanabhan 1973). Brown spot both reduces the rice production of poor farmers and their incomes, and therefore gravely affects economic access to food (Component 4). Massive brown spot epidemics are, fortunately, infrequent, and therefore the disease does not severely affect production stability (Component 5). Another feature of brown spot (Barnwal et al. 2013) is that it affects the grain and cooking quality of rice, and thus, brown spot does have a negative impact on Component 6.

Coffee rust in central America

The on-going coffee rust epidemic in Central America has multiple social and economic impacts. It primarily affects small-holders (with less than 7 ha farms) and migrant workers. The analysis by Avelino et al. (2015) indicates that over 2 10^6 persons are directly affected by the epidemic. A first impact of the disease is a reduction of economic access to food (Component 4) as a result of reduced incomes, reduced wages, and job destruction. Avelino et al. (2015) describe the recurring pattern of the ongoing epidemic, its weakening effect on production systems, and the impoverishment process it generates. Even if the impacts are not quantified, this affects communities and local infrastructures, leading to poorer access to food (Component 3). The frequent switches from food- to (failing) cash-crops such as coffee in the region ultimately lead to regional, national, and local food dependence, with potential impacts on the regularity of food availability (Component 5), and on the status of national food reserves (Component 2).

A framework to synthesize the impacts of plant diseases on the components of food security

The summarized effects of plant diseases on food security components of Table 1 indicates very diverse patterns of impacts, from mild to very severe, on all the considered components of food security. Our analysis suggests a framework to address plant disease impacts, with a series of criteria: the nature of the crop, the structure of farms, and market structures. Regarding the last criterion, two extremes might be considered: on the one hand, markets may be associated with very high transaction costs for farmers, as a reflection of poor physical access, insufficient information, poor infrastructures, and/or imperfect domestic markets (which we express by the phrase: "weak and narrow market"), and on the other hand, markets may be associated with minimal transaction costs (which we express with the phrase "strong and open markets"). Figure 3 proposes a framework for such crop-farm-market patterns.

The first criterion is the nature of the crop: plant diseases on food crops first affect food production (Component 1), possibly leading to impacts on other components, if the reduction of food production (yield losses) is large enough (upper half of Fig. 3, Types A, B, and C). On the other hand, diseases on non-food crops (lower half of Fig. 3, Types D and E) may first lead to impacts on the economic access to food (Component 4). Impacts may be restricted to this component only if the crop is supported by a strong and open market (Type D). If, however, the market of the diseased crop is weak and narrow (Type E), an entire local economy may be affected and other food security components may be affected, such as Component 2 (Reserves and stockpiles) and Component 5 (Stability of food availability).

The second criterion is the structure of farms for food crops (upper part of Fig. 3). In subsistence farming (Type A), all first five components of food security are exposed, even if Component 1 is first at stake. In commercial farming for food crops (Types B and C), plant disease leads first to reduction of production (Component 1), cascading in impacts on stockpiles (Component 2), and possibly on economic accessibility (Component 4) and on stability of supply (Component 5).

The third criterion is the market structure of food produce for commercial farming for food crops. Where market structures are weak (Type C), impacts on availability-production and stocks (Components 1 and 2) are likely to be stronger, hampering economic accessibility (Component 4) and in unstable supply (Component 5). Where market structures are strong and operate on large amounts traded (Type B), disease impacts may be easily absorbed. However, narrow markets where small quantities of food are traded, even when they are well functioning, are at risk of impacts on Components 1, 2, and possibly 5.

Plant disease epidemics that alter the nutritive value of food represent a class of their own in terms of impacts. These epidemics are represented in Fig. 3 by an additional set of arrows and symbols. Such epidemics in subsistence farming (Type F) may have catastrophic, and rapid consequences, with the fall of nutritive value of crops (or accumulation of toxins in food, Component 6), but also reduced production (Component 1), stocks (Component 2), and stability (Component 5). Plant disease epidemics causing a reduction of nutritional value can also have several grave impacts on commercial farms, if markets are weak and narrow (Type H), as the reduction of nutritive value (Component 6) is associated with reduced production, stocks, and stability (Components 1, 2, 5). If, however, markets are strong and open (Type G), such impacts may be mitigated, and restricted to production (Component 1) and stocks (Component 2).

The interpretive framework of Fig. 3 is indicative only, and is based on the crop-pathogen examples used here. Type A corresponds to small, food-oriented, subsistence farms. This is illustrated by the potato farms of Ireland in the nineteenth century, or by poor rainfed lowland rice farmers of South Asia today; the former were ruined by potato late blight, and the latter face rice brown spot. Type B corresponds to commercial farms in the New World, where wheat, the world's second food crop, is produced for a very large, strongly organized market, and where rust epidemics take place. Type C can be associated with commercial wheat farmers of the developing world, who are facing difficult market conditions, and where rust epidemics occur too. Type D may illustrate some of the coffee-growing areas of Central America where market conditions are favourable, while type E corresponds to coffee growers of Central America who are dealing with both coffee rust and a crisis on the coffee market.

Plant diseases leading to loss of food quality, and even the accumulation of toxins, represent another group of threats to food security components. Type G (Fig. 3) may correspond to the emerging situation created by false smut of rice in East and Tropical Asia. In the present analysis, we did not provide a specific example of toxin-producing plant disease in a context of subsistence farming (Fig. 3, Type F), or of commercial farming in a weak market context (Fig. 3, Type H). These situations are illustrated by the dramatic crop health state of maize-based subsistence farming in South Africa (due to the accumulation of fumonisins, ochratoxins, and aflatoxins; Wagacha and Muthomi 2008; Fig. 3, Type F), and commercial groundnut production in West Africa (due to aflatoxins, Fig. 3, Type H): in these contexts, populations are exposed to major health risks (Wild and Gong 2010), beyond the yield reductions, the reduction of stocks, and the fall of crop value.

Impacts on the different components of food security will depend also on the epidemiological patterns. Chronic epidemics may undermine local economies (and may be particularly harmful where subsistence farming dominates and trade is limited), leading to impacts on reserve sizes, physical infrastructures and increased poverty (Components 2, 3, and 4). The real danger of acute or emerging epidemics lies more in brutal shortages of food (Components 1 and 5) for the food crops, or, in the non-food crops, in raising poverty, weakening of farm and community revenues, leading to damaged infrastructures (Component 2) and poor economic access (Component 4). This additional layer of complexity created by epidemiological patterns is not included in the diagram of Fig. 3.

Discussion and conclusions

The nature of plant disease impacts

When discussing the consequences of any event in structures as complex as food systems, a first issue to ponder is the actual importance of this event – a typical question for the historian (Zadoks 2008). As indicated in the Introduction, quantitative data on the impacts of plant diseases are scarce, and one purpose of this article is actually to point out their usefulness, along with the need for a framework of analysis. Each of the examples given has been carefully chosen as a case where plant disease – in a given context, which we attempt to capture in part with the structure of Fig. 3 – may indeed be associated with an impact. Nevertheless, many of the examples we used could be subject for debate. Zadoks (2008) devotes an entire book to the reality of such questions – should a famine be considered the result of a plant disease epidemic, or the consequence of poor governments and disintegrating societies? A typical example is the Great Bengal famine, when plant disease did occur amidst very troubled times (Padmanabhan 1973; Tauger 2003).

"Causation is the central, most important, and most controversial, issue in the literature and theory of famines" (Tauger 2003). As a result, each of the examples chosen here is presumably open to questions as to the actual effects of plant disease on food security and its components. The role of brown spot in the Great Bengal Famine is perhaps iconic in such debates (Sen 1977; Tauger 2003). Even in this case, however, actual field data reported by Padmanabhan (1973) do indicate a strong yield reduction ***in direct relation with disease***, coinciding with the succession of events – a cyclone, a shift in climatic conditions, floods, and a disruption of infrastructure caused by war – and the occurrence of famine.

In the context of the present article, we wish to emphasize three points: (1) such debates should and will continue; it is necessary, as we tried here, to provide balanced evidence and contexts that would prevent the making of simplistic conclusions, (2) as we have seen, plant diseases are important not only because of the crises they potentially cause, but also because of the long-term strain they generate within production situations and on food systems, and this has been very poorly documented (Savary et al. 2006; Cheatham et al. 2009), and (3) the framework we propose here will hopefully contribute to useful assessments, and perhaps, quantifications.

Defining components for food security

The present analysis addresses the impact of plant diseases on food security and the decomposition of plant disease impacts on the components of food security. Food security has become a very active field of research in recent years. As a result, several efforts are currently attempting to produce definitions of food security, via its possible components, that would enable quantification, analysis, and interpretations. A new approach to food security was for instance recently proposed (Acharya et al. 2014) and subsequently elaborated (Gustafson et al. 2016), which measures outcomes at the overall food system level, based on seven metrics of "sustainable nutrition security" (SNS). This assessment method considers sustainability and nutrition, as well as the impacts of climate change, extreme events, and resource scarcity on the ability of food systems to meet accelerating demand. Up till now,

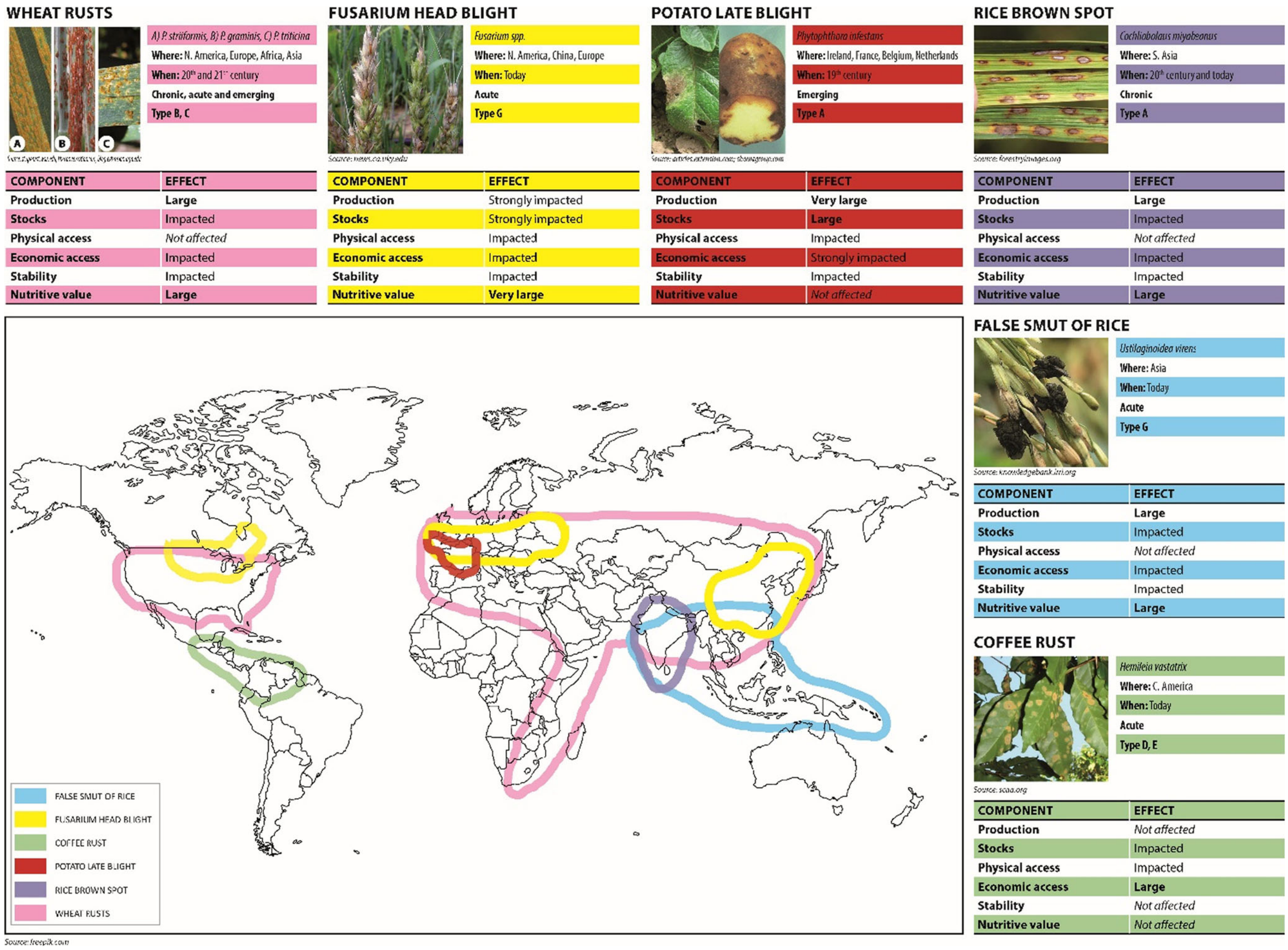

Fig. 4 Graphical summary of the plant disease examples used in this article. Geographic ranges only pertain to the examples discussed in the text and are only indicative

analyses of the components of food security (including this one) have focussed on factors that affect food security. The SNS approach aims at analysing the impacts of food security on social, economic, and food systems.

Considering global food intake from the angle of balanced diets (McKenzie and Williams 2015) may bring about different perspectives for food security components. For instance, increasing concerns about dry root rot of chickpea (*Cicer arietinum*) caused by *Rhizoctonia bataticola* (= *Macrophomina phaesolina*) in South Asia (Sharma and Pande 2013; Sharma et al. 2016) bring about concerns regarding the provisioning of plant proteins in countries where they are key components of diets (Jukanti et al. 2012). The SNS approach does incorporate balance in diets, and this component might be incorporated to improve the framework used in the present analysis.

Selecting crop-pathogen examples

Our selection of crop-pathogen systems enabled the addressing of impacts on food security in Fig. 1 and itemizing these impacts with respect to the six components of food security considered in this analysis. These examples of plant diseases are also well covered by the framework of Fig. 3. A synthesis of the findings of this article is provided in Fig. 4 as a graphical summary.

When considering the relevance of this framework, a question is whether the chosen examples are so few, and so particular, that they lead to circumstantial interpretations. Plant pathology textbooks provide a large number of illustrations of the importance of plant disease; unfortunately, the examples that are quantitatively well documented are few. Table 1 for instance involves two diseases of rice, but fails to mention rice blast, the most well-known, and presumably most studied (Zeigler et al. 1994) rice disease.

Rice blast, caused by the fungus *Magnaporthe oryzae* occurs in all rice-growing areas in the world (Ou 1985). Catastrophic rice blast epidemics are regularly reported, and have been documented as important historical events, especially in China and Japan (Ou 1985). Rice blast is a major disease of the first world food crop; its main effect is a very severe reduction, sometimes a complete loss, of yield. The disease therefore may lead to very large impact on Component 1 (Table 1). Yield losses may be large enough to threaten the buffering ability of storage and trade systems (Table 1, Component 2) of a modern-time district or province in Asia, and have been reported to cause extended shortages in historical times (Ou 1985). Because of the considerable economic importance of rice in Asia, such shortages may well impact local infrastructures (Component 3), local economies and food purchasing power (Component 4), and stability of food supply (Component 5). Because rice blast is not associated with mycotoxin production, or with a major reduction of grain quality, Component 6 is not to be considered in this case. As a result the profile of food security components affected by rice blast is very similar to that of potato late blight (Table 1). The rice blast example is therefore suggestive that our framework should account well for many other crop-pathogen examples.

Towards quantitative approaches

The number of components and interactions at play implies that a systems approach is required to address the functioning of food systems exposed to plant disease effects, be they in the form of progressive effects or brutal shocks. We believe that the above discussion sheds light on systems components that should be considered for inclusion in a mechanistic simulation of such effects:

- First, components of the food system should be apparent: (1) whether the crop system is food or non-food oriented; (2) the framework of trade of plant products – whether subsistence (with its own storage system, and presumably some excess which can be traded); and (3) the economic context of such trade – whether strong and open, or weak and narrow. The last attribute depends on components beyond the system analysed (e.g. the existence of world trade), but can include elements that are integral part of it (e.g. communication infrastructures, transport, and information), which, in turn may be affected by disease effects (e.g. Component 3).
- Second, the different components of food security should be incorporated.
- Third, the possible linkages between food security components should be outlined, to enable the cascading effects discussed here. Such links between components could be enabled by structural elements of the first point.
- Fourth, the strength and dynamics of disease effects should be included, to allow the modelling of chronic, acute, or emerging plant disease epidemics.

Such modelling work would enable a better understanding of the nature and consequence of disease effects on food security. This understanding would have application to both the management of present threats and the quantifying of the expected consequences of changes in the system, such as changes in economic or social structures that may mitigate impacts, and changes in crop health status, as new plant diseases affect a food system.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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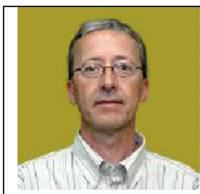
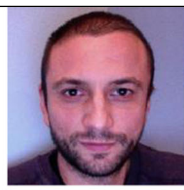
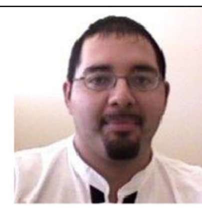
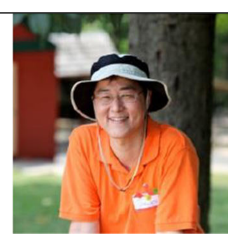
The Crop Health Group of AgMIP/PeDiMIP

The Pest and Disease Modelling Intercomparison and improvement Project (PeDiMIP) has been created within AgMIP (the Agricultural Model Intercomparison and Improvement Project) to advance insect and disease modelling for use in regional and global assessments of crop production, climate change and food security. Specifically, the Crop Health Group of PeDiMIP focuses on generic approaches to modelling the dynamics of injuries (i.e. disease and pest dynamics), and to model how the resulting injuries, individually or combined, translate into crop losses in diverse and shifting production situations. We intend to develop and share modelling structures, modelling programs, educational tools, and crop health data, in order to develop an international platform for crop health modelling. This work is part of an overarching effort to assess the impacts of global changes, especially climate change, on global food security.

 Serge Savary	 Simone Bregaglio	 Laetitia Willocquet	 David Gustafson	 Daniel Mason D'Croz
 Adam Sparks	 Nancy P. Castilla	 Annika Djurle	 Clémentine Allinne	 Mamta Sharma
 Vittorio Rossi	 Lilian Amorim	 Armando Bergamin Filho	 Jonathan Yuen	 Paul Esker
 Neil McRoberts	 Jacques Avelino	 Etienne Duveiller	 Jawoo Koo	 Karen Garrett