Crop losses due to diseases and their implications for global food production losses and food security

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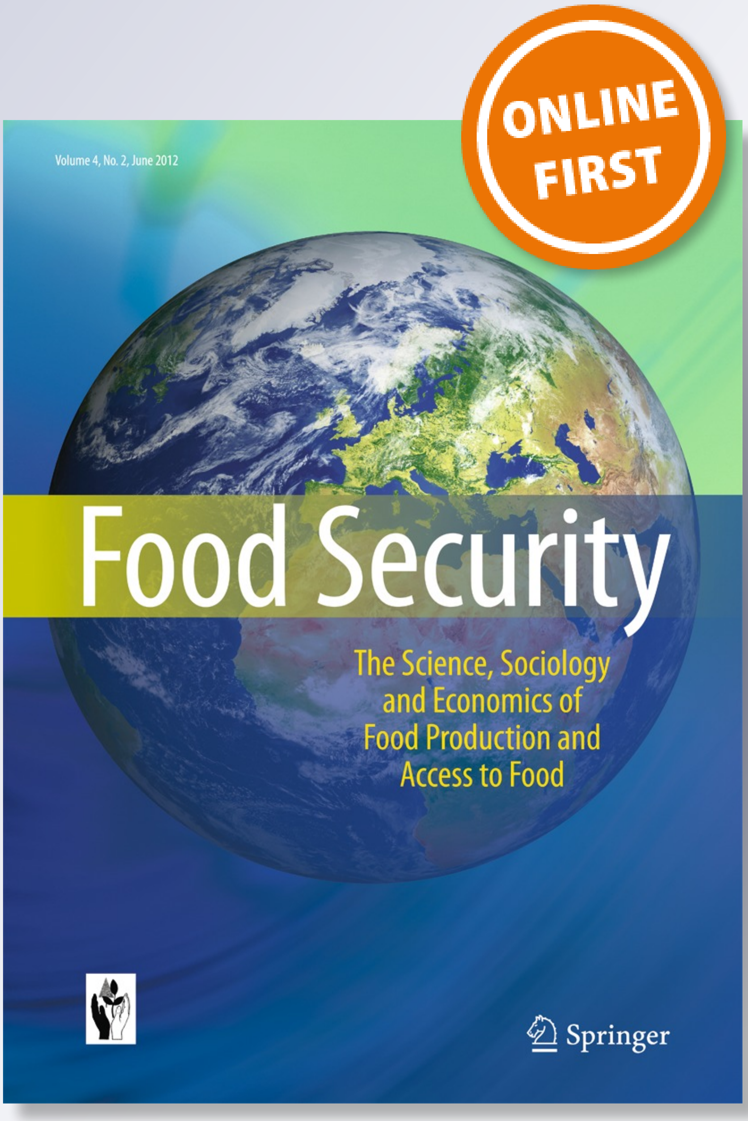

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EDITORIAL

Crop losses due to diseases and their implications for global food production losses and food security

Serge Savary · Andrea Ficke · Jean-Noël Aubertot · Clayton Hollier

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Introduction

The status of global food security, i.e., the balance between the growing food demand of the world population and global agricultural output, combined with discrepancies between supply and demand at the regional, national, and local scales (Smil 2000; UN Department of Economic and Social Affairs 2011; Ingram 2011), is alarming. This imbalance is not new (Dyson 1999) but has dramatically worsened during the recent decades, culminating recently in the 2008 food crisis. It is important to note that in mid-2011, food prices were back to their heights of the middle of the 2008 crisis (FAO 2011).

Plant protection in general and the protection of crops against plant diseases in particular, have an obvious role to play in meeting the growing demand for food quality and quantity (Strange and Scott 2005). Roughly, direct yield losses caused by pathogens, animals, and weeds, are altogether responsible for losses ranging between 20 and 40 % of global agricultural productivity (Teng and Krupa 1980; Teng 1987; Oerke et al. 1994; Oerke 2006). Crop losses due to pests and pathogens are direct, as well as indirect; they have a number of facets, some with short-, and others with long-term consequences (Zadoks 1967). The phrase "losses between 20 and 40 %" therefore inadequately reflects the true costs of crop losses to consumers, public health, societies, environments, economic fabrics and farmers.

The components of food security include food availability (production, import, reserves), physical and economic access to food, and food utilisation (e.g., nutritive value, safety), as has been recently reviewed by Ingram (2011). Although crop losses caused by plant disease directly affect the first of these components, they also affect others (e.g., the food utilisation component) directly or indirectly through the fabrics of trade, policies and societies (Zadoks 2008).

Most of the agricultural research conducted in the 20th century focused on increasing crop productivity as the world population and its food needs grew (Evans 1998; Smil 2000; Nellemann et al. 2009). Plant protection then primarily focused on protecting crops from yield losses due to biological and non-biological causes. The problem remains as challenging today as in the 20th century, with additional complexity generated by the reduced room for manoeuvre available environmentally, economically, and socially (FAO 2011; Brown 2011). This results from shrinking natural resources that are available to agriculture: these include water, agricultural land, arable soil, biodiversity, the availability of non-renewable energy, human labour, fertilizers (Smil 2000), and the deployment of some key inputs, such as high quality seeds and planting material (Evans 1998). In addition to yield losses caused by diseases, these new elements of complexity also include post harvest quality losses and the possible accumulation of toxins during and after the

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cropping season. While food security is a critical issue in the developing world, food safety has become a dominant concern in the developed world; however, the critical importance of food safety is now at last recognized in the developing world as well (e.g., Wild and Gong 2010).

In a pattern similar to the assumption of continued growing crop productivity (Alston et al. 2009), sustained and reliable assessment of crop losses has been taken for granted for decades, without novel, specific effort devoted to it. Decision-makers, policy-makers, scientists and farmers alike, have forgotten key concepts of crop loss assessment, leading to confusion. Confusion leads to fear, fear leads to wrong decisions, and wrong decisions lead to mis-management, both in terms of setting priorities (for research, especially), in development, and in actions at the field level (e.g., Savary 1994; Snapp and Heong 2003). The need to revive the field of crop loss assessment through renewed investigation and significant funding is acute. This would enable the use of new concepts and methods (e.g., McRoberts et al. 2011) for research prioritization, as well as identifying the most urgently needed plant protection efforts in times of economic crises. Crop loss assessment is a necessary first step towards the delivery of management tools that will benefit societies, environments, consumers and farmers most effectively. This review successively addresses a series of concepts pertaining to crop loss assessment, itemizes some methodological components for implementing these concepts and incorporates them in a systems perspective, which expands far beyond the conventional observation - experiment - modelling pathway. We then illustrate some of these principles with a few examples drawn from key world crops, their diseases, as well as other yield-reducing and harvest quality-reducing factors, including pathogen-produced toxins (Wild and Gong 2010). One main purpose of this review is to show that, in order to remain relevant, crop loss research, as a full branch of plant science, needs to consider the farm, political, and social levels. It therefore must link with other disciplinary fields that are often foreign to plant pathologists.

Reviews on crop losses caused by diseases commonly start with examples showing the dramatic and disastrous effects that plant disease epidemics have had historically. Zadoks (2008) conveys a more complex picture from History. Disastrous epidemics did occur. However, History also suggests that epidemics that were downplayed actually had long term and massive effects, while the effects of other plant disease epidemics, sometimes claimed to illustrate the importance of plant pathology, were confounded with other, quite different and often man-made, causes. Plant protection takes place in the complex fabric of societies and their agricultures (e.g., Ingram 2011). It is thus not surprising that epidemics, whether long or short, whether seemingly weak or massive, and whether localised or covering wide areas, would translate into quite different outcomes with different dimensions. History suggests that disease management, aimed at reducing crop losses, must operate within the fabric of human societies if it is to be efficient. It also suggests that, in order to understand, predict and reduce crop losses from plant diseases, plant pathologists have to learn from other sciences, which address this fabric.

General framework: problem definition and some methodological aspects

The framework we propose to develop includes three parts over several sections. In the first part, we wish to summarize some basic concepts pertaining to crop losses and their measurement. The second part deals with the multifaceted nature of crop losses, emphasizing hidden consequences, the nature of risks involved and avenues to address them. The third part introduces a geographic and crop-based structure, from which a few selected examples are drawn to illustrate the consequences of crop losses caused by diseases globally.

Injuries, crop loss, economic loss and uncertainty

Epidemics may lead to disease injuries, which may lead to crop loss (damage) which, in turn, may lead to economic loss (Fig. 1; Zadoks and Schein 1979; Zadoks 1985). These relationships are neither linear (Large 1966; James 1974; Madden 1983; Teng 1987; Campbell and Madden 1990; Madden et al. 2000; Savary et al. 2006a; Madden et al. 2007) nor are they automatic: epidemics do not always lead to measurable injuries, neither do injuries necessarily lead to measurable crop losses, nor do crop losses necessarily lead to measurable economic losses (Zadoks 1985; Rabbinge et al. 1989). In particular, one may refer to damage (or crop loss) functions when speaking of relationship between injury and crop losses, and to loss (or economic loss) functions when referring to the link between crop losses and economic loss (Zadoks 1985; Teng 1987). While damage functions are primarily dependent on damage mechanisms caused by diseases (and more generally harmful agents), (economic) loss functions (Zadoks 1985) are primarily dependent (Savary et al. 2006a) on production situations, including the attainable crop yield, the objectives of agricultural production, market variation and, more generally, the socio-economic context where production is taking place (Rabbinge 1982). The non-linearity of injury-damage (yield loss) relationships was for instance examined in detail by Madden et al. (2000) in the case of systemic (e.g., viral) diseases, with the compounding complexity elements of heterogeneous injury distribution in a crop stand and variable timing of epidemic onset. It is the very non-linearity of these relationships that renders decision-making in plant protection so difficult, because producers are faced with a "grey area" where uncertainty lies (Zadoks 1989).

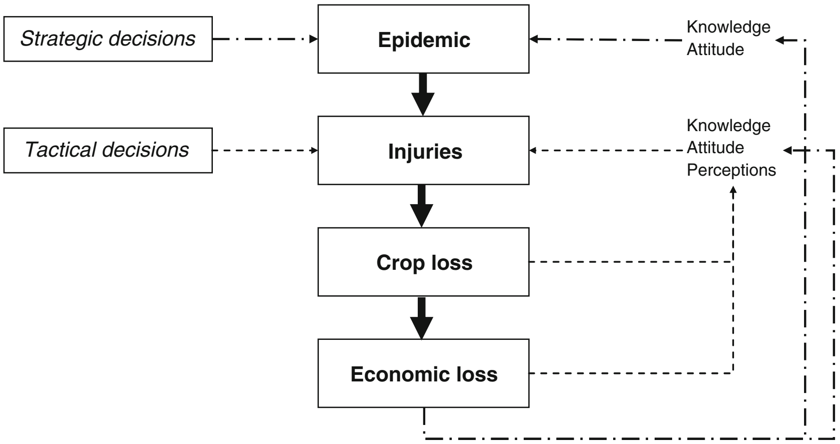

Fig. 1 A simplified diagram of the relationships between epidemics, injuries, crop losses and economic losses, and their linkages with strategic decisions and knowledge, attitudes, and perceptions

General principles, derived from injury-damage and crop loss-economic loss relationships however exist. The very purpose of sustainable disease management (and of plant protection in general) lies in reducing the size of this grey area using these principles.

Types of plant protection decisions

Strategic decisions (Fig. 1) are made before crop establishment (Zadoks 1985). Such decisions include short-term ones (e.g., the choice of a resistant cultivar against a disease) but also decisions that do not directly pertain to disease management and yet have numerous crop health consequences (e.g., choices of the type of crop establishment, crop rotation, or cropping system; Palti 1981). Strategic decisions also include whether or not to engage in a breeding program to introduce, enhance or improve resistance to disease, including the judicious deployment of plants with different resistances over time and space at local, national, or international scales. This last example represents a long-term strategic decision with consequences that may be seen, at best, 10 years later in annual crops (e.g., Savary et al. 2006a; Alston et al. 2009). Because of the R & D costs they entail, such decisions must be borne from hard evidence, which only careful assessment of crop loss analyses can provide.

Tactical decisions (Fig. 1) are made in the course of a given cropping season. Because they reflect prior decisions made upstream in a crop production system, tactical decisions entail many fewer degrees of freedom than strategic ones. A typical tactical decision at the field scale in plant protections is to spray or not to spray with a biocide. EPIPRE (Zadoks 1989), a decision system for multiple disease and pest management in winter wheat for Western Europe, partitioned such a decision into three options: spray, do not spray, or wait and see, generating one additional, useful, yet implied, degree of freedom, which farmers could use. Many other tactical decisions dealing with crop management, (e.g., fertilizer topdressing or irrigation) also have major consequences on crop health (Palti 1981).

Yield levels and the FAO definition of yield loss

The concepts of potential (theoretical), attainable (uninjured) and actual yields provide yardsticks to measure yield gaps and assess potential progress (Zadoks 1967; 1985; Rabbinge et al. 1989; Chiarappa 1971; 1981). The potential yield (Yp) of a crop is determined by the genetic make-up of cultivated plants, current temperature regimes, and radiation; Yp is achieved without any limitation of nutrients and water at any development stage, and without any injury caused by pathogens, animals, or weeds. The attainable yield (Ya) depends on the former factors, overlaid by an array of yield-limiting factors that are inherent in a given production situation: e.g. shortage of water and nutrients at some development stages, as well as excesses of water and mineral compounds, which may cause toxicities. The actual yield (Y) is the yield actually harvested: it encompasses the yield-defining factors, the yield-limiting factors, and incorporates the yield-reducing effects of injuries caused by harmful organisms.

Such a categorization implies simplifications. Some diseases strongly depend on the levels of some yield-limiting factors (or their alleviation). For instance, brown spot of rice, caused by the fungus *Cochliobolus myabeanus*, is dependent on the occurrence of drought (Chakrabarti 2001), or yield losses caused by Septoria diseases of wheat depend on cropping practices, especially fertilizer inputs (Leath et al. 1993). The underlying mechanisms of such relationships are complex (Zadoks and Schein 1979; Rabbinge et al. 1989) and involve, for instance, the predisposition of plants to infection (Schoeneweiss 1975), reflecting their physiological status (and thus, yield-limiting factors), or the indirect effects of yield-limiting factors on pathogen cycles (e.g., via microclimatic conditions). Yet, if used with due understanding of their underlying hypotheses, the typology of potential, attainable, and actual yields has provided a solid framework for an array of scientific advances and applications (e.g., Parlevliet 1981; Rabbinge et al. 1989; Rossing 1991a; b; Savary and Zadoks 1992; Teng and Savary 1992; Teng et al. 1993). The FAO definition of yield loss is the difference between the attainable and actual yield levels: Ya-Y (Chiarappa 1981). A fraction of this gap may be filled using available methods, up to the point of reaching an economic optimum, the 'economic' yield level (Ye), lying between Y and Ya. Ye represents the target of optimized disease (pest) management, from a yield point of view. The remainder of the gap, Ya-Ye corresponds to plant protection efforts that would today be uneconomical. From a crop yield perspective, Ya-Ye represents the progress that remains to be made in improving pest control (Chiarappa 1981). The definition of what should be an 'economic' yield, however, is a critical question that lies beyond the scope of this article, but represents an area of important multidisciplinary research with social and environmental dimensions (e.g., UNEP 2007, Chap. 9).

Damage mechanisms

Numerous studies have addressed the physiology of the diseased plant and canopy, (e.g., Livne and Daly 1966; Van der Wal 1975; Magyarosy et al. 1976; Mitchell 1979; Ayres 1981; Mendgen 1981; Rabbinge et al. 1985; Rossing 1991a; Wu and Hanlin 1992; Silva et al. 1998; Bassanezi et al. 2001a; b; de Jesus Junior et al. 2001; Lopes and Berger 2001), enabling the definition of a series of damage mechanisms (Rabbinge and Vereyken 1980; Rabbinge and Rijsdijk 1981; Boote et al. 1983): (1) stand reducers; (2) photosynthetic rate reducers; (3) leaf senescence accelerators; (4) light stealers; (5) assimilate sappers; (6) tissue consumers; and (7) turgor reducers. This array of damage mechanisms may be seen as universal and applicable to any harmful organism as shown by a series of studies (e.g., Gomes Carneiro et al. 2000; Johnson et al. 1986; Johnson et al. 1987; Savary and Zadoks 1992). Collectively, these mechanisms amount to a reduction of radiation interception or to a reduction of radiation use efficiency by growing crop canopies (Waggoner and Berger 1987; Johnson 1987). As a result these mechanisms represent a basis for crop loss simulation modelling concepts (e.g., Teng and Gaunt 1980; Loomis and Adams 1983; Pace and Mackenzie 1987; Rouse 1988) and studies (e.g., Teng et al. 1977; Johnson and Teng 1990; Rossing 1991a; b; Johnson 1992; Pinnschmidt et al. 1995; Willocquet et al. 2000; 2002; 2004).

These models elucidate a number of factors, including the ranking of harmful organisms in their yield-reducing effects over a range of production situations, the effects of new crop characteristics on vulnerability to damage, and the linkage of multiple pest models to injury profile predictors (based, e.g., on cropping practices), The elucidation of these factors allow the design of crop management systems that are less vulnerable to pests. Simulation models, being based on experimental data quantifying processes at a given scale (e.g., damage mechanisms at the plant level), enable projections into scenarios at higher levels of a hierarchy (e.g., yield loss at the crop stand scale), where a range of factors are modified. Simulation models therefore are unique tools allowing the use of experimental data to explore possible future scenarios.

One should note that the above series of damage mechanism are intended to address yield, not crop, losses. Another group of damage mechanisms should thus be added to the seven described previously in this section, which would more fully allow addressing crop losses i.e. (8) Food quality reducers (e.g., mycotoxin producers, such as *Aspergillus* spp. or *Fusarium* spp).

Dimensions of crop losses, hidden and indirect losses and costs, and public health

The above sections strongly emphasize the yield component of crop losses. Crop losses should be considered within a structured typology (Zadoks 1967; Zadoks and Schein 1979):

- Direct losses

  (1) Primary losses: (a) yield, (b) quality, (c) cost of control, (d) extra cost of harvesting, (e) extra cost of grading, (f) costs of replanting, (g) loss of income by less profitable replacement crop;
  (2) Secondary losses: (a) contamination of sowing and planting material, (b) soil-borne diseases, (c) weakening by premature defoliation of trees / perennials, (d) cost of control
- Indirect losses

  (a) farm, (b) rural community, (c) exporters, (d) trade: wholesale; retail, (e) consumers, (f) government, (g) environment.

We are not aware of any report having addressed the entire set of facets of crop losses for a given disease in a given crop, let alone in a multiple pest-crop system. Such studies, with an emphasis on the multidimensional consequences of crop losses, are necessary today, as natural resources available to agriculture are shrinking, and because of the feedback of environment, societies, and economics on individual farm operations. Such studies would enable a true prioritization for plant protection, and would pave the way to integrated plant protection programs where advances in crop loss research would better serve the diversity of stakeholders.

The above list of crop loss dimensions does not directly include the public health aspects associated with plant protection and plant diseases. The former is the classic costs of pesticide use, which is only one component of tactical decisions (Pimentel et al. 1992): $ 9 billion were spent in 1992 in the USA, including chemical costs and human health impacts. The latter is the largely unknown cost of mycotoxins (Munkvold 2003; Wild and Gong 2010).

Massive efforts are underway to address the problem of fusarium head blight in wheat in Northern America and Western Europe (e.g., Paul et al. 2005a; b; 2010), but aflatoxins and fumonisins (Gelderblom et al. 1988) are contaminating a large fraction of the world's food, including maize, cereals, groundnuts, and tree nuts (Wild and Gong 2010). Aflatoxins are hepatocarcinogenic in humans, particularly in conjunction with chronic infection by hepatitis B virus. Fumonisins are associated with liver and kidney tumours in rodents, with studies implying a possible link with increased oesophageal cancer and neural tube defects in humans (Wild and Gong 2010). Mycotoxin contamination has become one of the most pressing and challenging problems facing plant pathologists today.

Risk and a categorization of crop loss problems

A typology of epidemics was recently proposed (Savary et al. 2011a), with: (1) chronic epidemics corresponding to generally mild epidemics that regularly occur over large areas; (2) acute epidemics occurring infrequently, sometimes at very high level of intensity over small, or comparatively restricted areas; and (3) emerging epidemics occurring under exceptional conditions, affecting potentially very large areas, with sometimes very high intensities. This typology allows for transition, i.e., for a disease shifting from one category to another, or belonging to two categories. Similarly, one could consider: (1) epidemics causing chronic crop losses, that occur regularly over large areas where they cause comparatively low crop losses (Ec); (2) epidemics causing acute crop losses, that occur infrequently, over small, or comparatively restricted areas, sometimes causing very high crop losses (Ea); and (3) emerging epidemics (Ee), affecting potentially very large areas, potentially causing heavy crop losses.

One definition of risk may be borrowed from Rowe (1980): $R = P * M$, where P is risk probability, and M is risk magnitude. In plant pathology, P may be translated into the probability of an epidemic occurring, and M, into the crop loss consequences of such an epidemic. For instance, infrequent epidemics with minor consequences, frequent epidemics with minor consequences, infrequent epidemics with large consequences, and frequent epidemics with large consequences would be associated with progressively increasing risks. Using the above definition, the risks associated with the three categories of epidemics would thus be:

- Ec: R = high P * low-moderate M;
- Ea: R = low P * moderate-high M; and
- Ee: R = very low P * moderate-high M.

As a result, the R-values associated with chronic, acute, and emerging epidemics would be: low to moderate, low to high, and very low to moderate, respectively.

The above requires development. Briefly, P would first need an operational definition (i.e., a quantitative threshold) enabling the distinguishing of epidemics from non-epidemics (Yuen and Hughes 2002). Second, M would need further specification too. Limiting M to yield loss might be a first step. There, however, would be a need to incorporate the multiple dimensionalities of M in order to truly address crop losses, and not yield losses only. In a recent review (Savary et al. 2011c), a case was made to stress the environmental, agro-ecological, and socio-economic attrition caused by chronic epidemics, which is often down-played, as these diseases are perceived as 'minor', i.e., as 'business as usual'. The public health dimension has to be considered, too. For instance aspergillus wilt is a minor disease of groundnut in West Africa, causing very low yield losses, while the disease is endemic (high P). Limiting M to yield loss would thus translate into a low R. However, the accumulation of aflatoxins in the diet causes acute intoxication and is associated with grave complications (Wild and Gong 2010). Incorporating the public health dimension of crop loss in M would change the risk value from low-moderate to high.

Research on plant protection as part of a systems approach

A wide array of elements other than accurate knowledge of crop losses is at play in decision-making for crop health management (Rossing et al. 1994a; b; c; Hughes et al. 1999). One is the search of an economic balance between the cost of disease management options and the benefit of their implementation within a context of uncertainty (where, in particular, the notions of "epidemic" and "non-epidemic" are operationalized). Critical progress has been made on the topic (Breukers et al. 2007; McRoberts et al. 2011), which largely makes use of Bayesian approaches (e.g., Yuen et al. 1996; Yuen and Hughes 2002), and is now expanding to Q-methodology used in social sciences (McRoberts et al. 2011). The human component is directly linked with the latter point but much is still needed to analyze the pathway: knowledge ➔ attitude ➔ perception ➔ decision (Savary 1994). Note that the paths of relationships in Fig. 1 differ whether one considers tactical or strategic decisions. Perception is not included in the drivers of strategic decisions, whereas it is for the tactical ones. This is because one may usefully distinguish Attitudes (i.e., the conceptual framework under which a decision is made) from Perceptions (in which Attitudes, fed by Knowledge, are overlaid with the constant flow of new information and needs, be they related to plant protection or not). While, therefore, Attitudes are relatively stable over time, because they build upon Knowledge (and accumulated experience, especially of the producers), Perceptions are much more volatile, since they are directly influenced by real-time observation and information (Savary 1994; Heong and Escalada 1997). A focal point for plant protection research, and a reason why crop loss magnitude, *M,* may not always be a key driver of a decision, is that farmers are dealing with many issues other than a particular disease, a particular crop, and even a given cropping season (e.g., Zadoks and Schein 1979). This, partly, explains why farmers may make seemingly counter-intuitive tactical decisions (Savary 1994), or why the transition from one disease management strategy to a new, better one may not succeed (McRoberts et al. 2011).

Quantitative and qualitative losses in relation to agricultural objectives and intensification

Table 1 presents a simplified overview of the disease (plant protection) risks considering different levels of intensification, different production objectives (high/low yield productivity or high/low harvest quality), and different types of production environments. Only few, very broad, and admittedly over-simplified, categories for agricultural intensification, production objectives, and environments are considered. Yet this table suggests that plant disease (plant protection) risks broadly increase with (1) agricultural intensification, and (2) switch in objectives, from productivity to quality. Importantly, this seems to equally apply to both temperate and tropical environments.

The framework of Table 1 is expanded in Table 2 where a few crop examples are given. Again, the very broad categories chosen lead to likely overlaps, or partial misclassifications of the listed examples. Yet the array of examples suggests that the framework of Table 1 is a workable one.

The examples we provide below do not suggest that differences exist between the likelihood of diseases (pests) being more frequent, causing severe epidemics (outbreaks) under temperate or tropical environments. Using the definition of risk used here, these tables would thus suggest that:

(1) the gradient in risk suggested by Tables 1 and 2 is not due to differences in epidemiological vulnerability, but to increasing magnitudes of epidemiological consequences, expressed by the crop losses caused by diseases (and, generally, pests); and

(2) while disease management efforts are mostly devoted to minimize the likelihood of epidemics occurring, *P*, much remains to be done to quantify and reduce crop loss, and especially harvest quality losses and toxin accumulation, *M*.

The examples we provide below highlight these two points. These examples have been chosen because they emphasize different aspects, from different angles, with different approaches and outcomes. These outcomes are based largely on the definition of risk we chose to use. We did so while recognizing that this definition has limitations, and needs further investigation. This point will be discussed in the last part of the review.

Crop losses in wheat in the USA

The wide range of facets of crop losses, as a *problématique*, encompassing biological, ecological, economical, and sociological considerations (Hollier 2011), expanding far beyond the attainable-actual yield gap (Teng and James 2002), connected to the mismatch between global food production and human population (e.g., FAO 2011), and affecting social networks in a hierarchy of scales (farm, rural communities, produce companies, exporters, governments), is particularly well illustrated by wheat production in the United States. Wheat in the US was harvested from 18.6 million hectares in 2011 yielding just over 35.4 million tons of an overall value of more than US$15 billion (NASS 2011). Large variation in wheat production in the US occurs, reflecting the effects of biological, ecological, technological and socio-economic factors (Hanson et al. 1982; Cook and Veseth 1992). Current research to improve wheat yields includes old and newer techniques such as conventional

Table 1 Relationships between intensity of production and crop loss risk

Agricultural intensification	Main production objective			
	Productivity		Quality	
	Temperate	Tropical	Temperate	Tropical
Extensive	Low	Low	Low	Moderate
	Variably well documented	Poorly documented	Variably well documented	Poorly documented
Semi-intensive	Moderate	Moderate	High	Very high
	Well documented	Poorly documented	Generally well documented	Variably well documented
Intensive and very intensive	High	High	Very high	Very high
	Generally well documented.	Variably well documented	Well documented	Poorly documented

From Zadoks and Schein 1979, modified

Table 2 Relationships between intensity of production and crop loss risk: examples

Agricultural intensification	Main production objective			
	Productivity		Quality	
	Temperate	Tropical	Temperate	Tropical
Extensive	• Wildrice: Minnesota • Redwood: western US • Softwoods: Scandinavia, Russia	• Tropical hardwood: Asia, Africa, S. America • Cacao: some West Africa areas • Copra, coconut fibers: Polynesia	• Cork collection: Portugal, Algeria • Wild blueberries: Northeast US • Cranberries: US	• Various tropical fruits
Semi-intensive	• Wheat: US • Cider apple orchards: UK • Some vineyards: Europe • Pine plantations: northern Europe, S.E. Asia, USA	• Wheat: S. Asia • Dry cereals: W. and Central Asia • Plantains: Africa • Cassava: Africa • Oil palms: W. Africa, S.E. Asia • Rubber tree: W. Africa	• Wheat: Western Europe, Russia, Ukraine, USA, S. America • Potato: E. Europe	• Cacao: West Africa • Coffee: South and Central America, Africa, S.E. Asia • Basmati rice: India, Pakistan
Intensive	• Cereals: N.W. Europe • Potato: China, W. Europe, US • Maize, Soybean: US, S. America • Citrus: Israel, Florida, California	• Rubber tree: S.E. Asia • Bananas: Central America	• Barley, Oats: W. Europe • Grand vin vineyards: France, California, Australia • Potato: N.W. Europe	• Tea: India, China, Japan, Indonesia • Greenhouse flowers: Central America
Very intensive	• Dwarf orchards: W. Europe	• Rice: S. and S.E. Asia	• Vegetables: Europe, USA, Canada • Flower production: Central America, S.E. Asia	• Vegetables: Asia, C. and S. America, Africa • Greenhouse flowers: Southern Europe, US, The Netherlands

See Table 1 for risk classification

From Zadoks and Schein 1979, modified

breeding, biotechnology, interspecific and intergeneric hybridization, and basic studies of the physiology of the host-pathogen/pest interactions (Curtis et al. 2002). We concentrate here only on wheat diseases in the US.

Over 100 diseases of biological or non-biological causes affect wheat in the US. Some diseases are of local, yet sometimes acute, importance, whereas others have nationwide impact (Bockus et al. 2010). However, only a few wheat diseases have been addressed with respect to the crop losses they may cause. This is in particular the case of the three wheat rusts (leaf, stem, and stripe), and Fusarium head blight, which have received the most attention (Calpouzos et al. 1976; Murray et al. 1994; Johnson et al. 1998).

Determining crop losses in wheat due to disease in the US has taken many forms (Calpouzos et al. 1976; Johnson et al. 1998). These range from the “best guess” expert opinions to more scientific approaches based on yield comparisons performed over years through formal crop loss assessment experimentation. Expert opinions are carefully considered, as they are based on years of experience of professionals in the field. For example, based on interviews with crop loss estimators from wheat states, one commonly used approach is a survey technique, in which the estimator obtains a “feel” for the level of disease in the area or state. The level of disease is then compared to crop losses the wheat crop experienced in previous years. Such estimates are sometimes criticized because of their lack of scientific basis. However, when compared to “ground proof” data, expert opinion-derived estimates have commonly been found to be reasonably accurate. Another approach involving surveys in commercial fields is to compare wheat disease injuries from commercial fields with reactions on wheat variety collections grown in close proximity by University scientists. At harvest, disease reactions and harvested yields are compared to the same type of data observed in commercial fields. This approach is considered more accurate.

A third type of crop loss assessment takes into consideration the growth stage of wheat at the time of initial disease occurrence as a measurement of risk and then a measurement of disease severity during the early stages of grain development. For instance, Calpouzos et al. (1976) determined that the yield loss risk caused by stem rust was influenced by disease severity and the timing of disease onset relative to crop development. They determined that when stem rust onset occurred earlier than heading, there was a 99 % risk of yield loss, which dropped to 75 % if onset of the epidemic occurred at heading/flowering, and to only 12 % if it occurred at early grain development. Using another approach, known as the single-point or critical stage approach (Romig and Calpouzos 1970), yield loss estimates were based on stem rust assessment at the ¾ berry stage (Feeke's growth stage 10.54; DeWolf et al. 2011). Vanderplank (1963) however suggested that yield loss of small grains should consider the entire crop development for polycyclic diseases, being either proportional to the area under the disease progress curve or proportional to disease severity at a critical development stage (Doling and Doodson 1968). The critical stage approach was more accurate for measuring wheat stem rust loss (Romig and Calpouzos 1970).

Sharma-Poudyal and Chen (2011) showed that the number of days with rainfall in the US Pacific Northwest is correlated with yield loss due to stripe rust of wheat. They further showed that winter temperature variables were more correlated to yield loss than temperature during other seasons. Thus, accumulated negative degree days summed with daily (summer) thermic time were correlated to winter wheat yield loss. By contrast, Fusarium head blight losses can be calculated using an economic model as the difference in producer revenue due to the disease in affected districts. Production losses are estimated by comparing actual yields to regression forecasts. Regression models are used to quantify the impact of Fusarium head blight-related supply reductions (Johnson et al. 1998).

Yield losses due to wheat rusts alone are estimated at US $5 billion per year, whereas yield losses due to Fusarium head blight have been estimated at US $3 billion since the early 1990s (Schumann and D'Arcy 2009). These figures only consider the financial losses due to yield reductions. Additional losses caused by diseases are incurred in other aspects of the wheat crop environment, as part of a system consisting of the farm, rural community, grain buyer, shipper, exporter, and society as a whole. Wheat is not only a staple food crop in many parts of the world; it also is a major commodity on the international market (FAO 2008). Examples of impact follow.

In parts of the US wheat hay is used for animal consumption. In the farm sector, when rusted wheat plants are harvested for forage or silage, quality is compromised due to extensive desiccation and wilting of injured leaves. Forage losses and nutritive value reductions are to be expected when severely infected crop stands are harvested for forage (Marsalis and Goldberg 2011).

Crop loss effects on the producer and the community can be devastating. The number of farms is dwindling in the USA (EPA 2011; USDA 2011). Many producers borrow money in order to ensure their annual crop production. When the yields are lower than expected, loans may not be paid in full, and farms can be lost to the lending agency. Livelihoods are lost, and many farm families are forced to leave communities with which they have been associated for much of their lives. This contributes to an erosion of know-how in these communities. Further, credit ratings for farmers are reduced, and it is difficult to start over even in another community. Such an erosion of the agricultural fabric from crop losses is documented in more detail in Zadoks and Schein (1979), and is part of the list of indirect losses caused by disease listed above.

Heavy yield loss to diseases implies reduced market volume for grain buyers. They also translate into reduced activity for transport companies. Overall, an entire sector of the economy may be affected. Further, trade with other nations is compromised due to a reduction of product. Also, the US grain carry-over stocks are reduced. US grain exports to the rest of the world during 2010–11 was over 21 million tons, which is approximately 60 % of the US annual production (NASS 2011). With an estimated US$5 billion loss annually to grain rust diseases, the US wheat producers experience approximately 20 % economic loss annually.

Other components of crop loss include the constant funding inputs necessary for research by industry and universities to find, or renew, host-plant resistances to reduce losses from rust (Marasasa et al. 2003; Dixon et al. 2006; Solh et al. 2011), Fusarium head blight, and other diseases. Additionally, management inputs, especially fungicides which only protect (attainable) yields and do not enhance them, add tremendously to the overall cost of production. The consequences of crop losses in wheat in the US therefore cascade over a number of components of agricultural systems, and society at large. Crop loss in a key crop such as wheat in the USA — the largest wheat exporter worldwide (FAO 2011) — ultimately affect the need to feed a food-deprived world and maintain a globally safe and secure food supply.

Quality losses in cereals in Europe's Northern countries

In Northernmost Europe (Norway, Finland, and Sweden), cereal crops are grown at higher latitudes than anywhere else in the world (Peltonen-Sainio et al. 2009), with cool maritime climates and short growing seasons. However, predicted climate change scenarios of global temperature increase (Pachauri and Reisinger 2004) could significantly increase the food production potential in these areas (Peltonen-Sainio et al. 2009; Olesen and Bindi 2002).

Cereal diseases in the Nordic countries and their management

The major pests in Norwegian cereals, besides weeds, are fungal diseases, such as Fusarium head blight on wheat, oat, and barley (consisting of a diverse complex of mycotoxin producing and non-mycotoxin producing Fusarium species), leaf blotch diseases on wheat (*Stagonospora nodorum*, *Septoria tritici*, *Drechslera tritici-repentis*), barley (*D. teres, Rynchosporium secalis, Cochliobolous sativus, Ramularia collo-cygni*), and oat (*D. avenae*, *Stagonospora avenae*) and powdery mildew on all three crops (*Blumeria graminis*; Brodal et al. 2009; Ficke et al. 2011). Fungicide trials over 2 years (2008 and 2009) in barley showed an average yield response of 9 % to the most effective fungicide treatment, with *D. teres* and *Ramularia collo-cygni* being the main pathogens found in the trials (Abrahamsen et al. 2011). Powdery mildews are considered of lower importance in barley due to wide employment of *mlo*-resistance genes in the Norwegian barley germplasm. The average yield increase due to the most effective pesticide treatment in different spring wheat trials over 5 years (2006–2010), varied between 7 % and 15 % (Abrahamsen et al. 2011) depending on the varieties. *S. nodorum* was the dominating pathogen in these field trials (Abrahamsen et al. 2011). Leaf blotch diseases continue to be the main focus in Norwegian breeding efforts because of their yield-reducing effects, the difficulty in phenotyping resistance(s), and because of the lack of appropriate molecular markers for resistance to this disease complex. Fusarium head blight (FHB) in oats and wheat has also become a major research and breeding focus in Norway due to its increased occurrence and to the risk of its contaminating feed and food products with highly toxic mycotoxins H2/HT2 and/or Deoxynivalenol (DON) (Bergsjø et al. 1993; Langseth et al. 1999; Brodal et al. 2011). In 2008, 80 % of the winter wheat, 65 % of the spring wheat and 50 % of the barley area were sprayed with fungicides in Norway. Oats were not protected with fungicides until 2009, when the presence of FHB demanded chemical disease management options. Frequent rains in autumn can delay cereal harvests, leading to reduced grain quality due to sprouting and increased mycotoxin contamination. On September, 8th, 2011, 80 % of the Norwegian wheat crop was still standing in the fields due to wet weather. Grain quality was thus reduced from food to fodder grade with consequential price reductions for the farmer. The freely available decision support system VIPS (Varsling Innen Plante Skadegjørere, ‘Warning against plant pests and diseases’; Brodal et al. 2007) was designed to predict high risk of disease and pests in Norwegian cereals, fruits, and vegetables. This system also provides advice to extension personnel and farmers on measures and timing for disease and pest management to increase the cost efficiency and sustainability of cereal production (Brodal et al. 2007). Even though governmental research institutes have focused on yield increase and disease reduction for many years, sound and reliable data on overall Norwegian yield losses in cereals due to diseases are few and fluctuate considerably among years, locations, and varieties, limiting crop loss data to very rough estimates of yield loss, without considering indirect effects of diseases.

Leaf blotch diseases (LBD) on winter wheat are also considered the most important diseases in Swedish cereals. Other diseases such as powdery mildew, brown rust (*Puccinia triticina*) and yellow rust (*P. striiformis*) contribute to yield losses as well (Wiik et al. 1995). In fungicide trials, Wiik (2009) reported increased winter wheat yields from 6 to 12 $t.ha^{-1}$ between 1983 and 2005. Control of LBD accounted for the largest fraction of yield increase, followed by powdery mildew, brown rust, and yellow rust (Wiik 2009). The average yield increase in oats due to fungicide treatment in 2010 reached 0.26 $t.ha^{-1}$, based on actual yields ranging from 4.39 $t.ha^{-1}$ to 8.82 $t.ha^{-1}$ (Roland 2011). Recent reports from the Swedish grain industry indicate an increase in mycotoxin contamination in oats in 2011, which would further increase the indirect crop losses due to FHB.

A field survey in 2009 identified the most important diseases in Finland to be fungal leaf spot diseases (*D. teres, C. sativus* and *R. secalis*) on barley, leaf blotch diseases in spring wheat, and oat leaf spot (*D. chaetomioides*) and other leaf blotch diseases (*S. avenae* and *C. sativus*) on oat (Jalli 2011). Powdery mildew and yellow rust were considered minor diseases. However, *Fusarium langsethiae* on barley and oats and *R. collo-cygni* on barley were only recently identified, in 2004 and 2001, respectively, and are considered to be emerging pathogens also in the rest of Europe (Walters et al. 2008; Jalli 2011). The average yield increase from fungicide use in four-year field trials was 11 % in barley and 13 % in spring wheat (Laine et al. 2009). Currently, 73 % of Finnish farmers treat cereal fields with fungicides (Mäenpää 2010).

Crop losses in cereals in the Nordic countries

The relationship between fungal diseases and crop losses are generally based on yield losses in $t.ha^{-1}$, comparing grain yield in fungicide treated, nearly disease-free, field plots with grain yield from non-fungicide treated field plots, and thus with variable levels of disease injuries (Bhatal et al. 2003). While these estimates might be useful in determining the quantitative yield loss due to diseases, they are mostly irrelevant for gaining insight into the qualitative crop losses caused by plant diseases. Fusarium head blight is broadly considered to be less yield reducing than leaf blotch diseases in all the Nordic countries. However, the economic impact of the former disease on the cereal industry might be many times the magnitude of the latter disease, due to mycotoxin contamination of food products, fodder and feed.

In the 2005 and 2006 field seasons, the mycotoxin (mainly T2/HT2 and DON) contents in some Norwegian oat samples exceeded the recommended threshold for DON in oats and wheat for human consumption of 1,750 μg.kg^{-1} and 1,250 μg.kg^{-1}, respectively, as well as the recommended threshold for animal feed in Norway (8,000 μg.kg^{-1}; Norgesfôr 2010). De-hulling of oats reduced the mycotoxin concentration, but also added processing costs. In 2009 and 2010, the mycotoxin concentration in many oat samples again exceeded recommended thresholds for human and animal consumption, leading to extensive testing of harvested oat samples by the Norwegian agricultural purchasing and marketing Co-op 'Norsk Fellekjøp' in 2010 and 2011. By 2010, Fellekjøp had 55,000 tonnes of mycotoxin-contaminated oats from the previous year blended with mycotoxin-free grains from the running year, in order to reach an overall concentration below the acceptable threshold, and so allow the grains to be processed as animal feed, (Vermes 2010). The administrative director of Norske Felleskjøp claimed the costs for the grain producers to mix the highly contaminated grains with healthy grains would be 22×10^6 NOK (2.75×10^6 Euros), compared to 100–110×10^6 NOK (12.5–13.75×10^6 Euros), if the contaminated grain had been burned (Vermes 2010). Increased costs for testing, sorting, de-hulling and mixing of the oat samples led Fellekjøp to demand a penalty price reduction for grain lots exceeding a certain mycotoxin threshold and a reduction in oat grain quantity delivered. Consequently, the area cropped with oats in Norway had to be reduced by one-third (Mellemstrand 2010). Meanwhile, animal farmers, especially pig farmers, claimed 0.5–1×10^6 losses NOK per year (0.0625–0.125×10^6 Euros per year) and per farm, due to feeding their animals with mycotoxin-contaminated products and experiencing associated reduction in animal health (Aadnesen 2011).

Grain imports into Norway are usually controlled by taxes and amounts of imported carbohydrates are determined based on the actual need and demand each year. While oats for human consumption were almost entirely grown in Norway until 2008, reaching a maximum of 16,000 tonnes in 2007, oat imports increased exponentially in 2009 and 2010, while Norwegian grown oats for human consumption dropped back to 6,000 tonnes in 2010 (Solbakken 2010). After adjusting their prognosis for oat yield and mycotoxin contamination for 2011, the Statens Landbruksforvaltning in Norway accepted an import quota of 30,000 t of carbohydrates for feed and fodder to meet the demands of the animal industry, accepting the added import taxes to their product prices (206–207 NOK or 25.75–25.86 Euro extra per ton of feed oats in 2010; Pettersborg 2010). In September 2011, Norway had to import an additional 260,000 t of human-food quality wheat for its own home market, due to the low quality of wheat harvested that year (Torhild Nilsen 2011).

The cereal health situation in the Nordic countries provides a fresh illustration of the importance of the qualitative and quantitative losses that plant diseases are causing. The overall indirect economic costs for individual farmers, the grain industry, and society in general, are difficult to estimate, but they do relate back, even if not entirely, to fungal pathogens and need to be considered to complete the complex picture of current and future crop losses and the role plant diseases play in meeting the growing demand for food and fibre world wide.

Crop losses to diseases in rice in tropical Asia

The causes, contexts, and importance of crop losses in rice have been discussed in several articles and reviews (Savary et al. 2006a; Savary et al. 2000a; b). Rice is of strategic importance in Asia, where roughly 60 % of the world population lives (United Nations, Department of Economic and Social Affairs 2011), and where it represents the first source of caloric intake. Rice is also an important staple food in many parts of the world, including Central and South America, Africa, and some European countries.

A combination of three complementary approaches was used to assess yield losses at the regional (Tropical Asia) scale in lowland (irrigated and rain-fed) rice. The first approach involves surveys conducted with a standardized protocol in several hundred farmers' fields in China, India, the Philippines, Thailand, and Vietnam. This led to (1) characterizing a limited set of injury profiles (IP), (2) characterizing a limited set of production situations (PS, i.e., the agronomic and environmental contexts of rice production, including, e.g., fertilizer use, water supply, fraction of arable land under rice), (3) linking IP and PS and showing that injury profiles are strongly associated with production situations (Savary et al. 2000a). This also led to measuring the levels of individual injuries, and the actual yield harvested in each field (grand mean: 4.12 t.ha^{-1}). The second approach involved a series of linked experiments, where the attainable yield, Ya, was varied through different crop establishment dates and fertilizer inputs, and where a range of pest injuries were artificially generated in micro-fields. This led to the development of a statistical yield loss model using principal component regression, which enabled the derivation of damage (crop loss) functions at variable attainable yields for the main injuries found in the survey (Savary et al. 2000b). The resulting model thus allows generation of yield loss estimates given a specified attainable yield (reflecting a given production situation) either for a given level of a particular injury, or for a given combination of injuries (IP). The third approach was to develop a simple, production-situation-specific, mechanistic simulation model, RICEPEST. The model was a derivation of the structure developed by Johnson for potato (Johnson and Teng 1990; Johnson 1992) with additional elements from the universal crop growth model SUCROS (Van Keulen et al. 1982). The model was developed and tested in successive stages, the last evaluation phase involving simultaneous experiments in India, China, and the Philippines (Willocquet et al. 2002). RICEPEST allows generation of yield loss estimates at specified attainable yields for given injury profiles. The model also enables one to project what the yield gains generated from plant protection could be in these contexts (Willocquet et al. 2004).

Table 3 represents a synthesis of the above approaches. Large differences are observed in absolute (i.e., in t.ha^{-1}) yield loss value, reaching 2.3 t.ha^{-1}, or over 40 % of the harvested yield. The strongest yield reducer among diseases are sheath blight (SHB), brown spot (BS), and sheath rot (SHR), whereas bacterial blight (BLB), leaf blast (LB), and neck blast (NB) are responsible for much lower yield losses. Overall, insect injuries (brown plant hoppers, BPH; defoliators, DEF, dead hearts caused by stem borers, DH; and white heads caused by stem borers, WH) are responsible for much lower yield losses. Weeds are by far the strongest yield-reducers, causing 0.7 to 1.2 t.ha^{-1}, or 10 to 20 % yield losses.

Yield gains from management may vary widely, in part because of the ranges of management efficiencies, in part because of the differences in harmful effects, and in part because of differences in the inherent efficiency of management of individual yield reducers. Overall, however, one should expect an approximate 15 % increase in yield, or a 1.2 t.ha^{-1} flat increase, if these available management tools were implemented.

The combination of the above survey, experimental, and modeling approaches have shown that 120 to 200×10^6 t of grain yield are lost yearly to pests over the 87×10^6 ha of lowland rice in Asia. Yet, only 25 million tons of rice is traded each year globally, i.e., only 4 % of the world rice

Table 3 Chronic yield losses to harmful organisms in rice in tropical Asia, yield gains from current management, and efficiency of crop health management

	Yield loss		Yield gain		Management efficiency
	absolute (t.ha^{-1})	%	absolute (t.ha^{-1})	%	
IP(1)	1.4–2.3	25–43	1.2–5.7	16–69	0.4–0.7
BLB	0–0.03	0–0.6	0–0.9	0–17	0.9–1
SHB	0.3–0.7	5–10	0–2.4	0–29	0–0.8
BS	0–0.5	0–10	0	0	0
LB	0–0.1	0–1.7	0–3.5	0–65	0.9–1
NB	0–0.1	0–2.1	0–2.1	0–40	0.9–1
SHR	0.1–0.4	1.3–7.3	0	0	0
BPH	0–0.01	0–0.3	0.1–0.3	0.8–5.3	0.9–1
DEF	0.01–0.05	0.2–0.9	0–0.1	0.1–0.9	0.3–0.6
DH	0.02–0.05	0.3–1.0	0.02–0.12	0.3–2.3	0.5–0.8
WH	0.1–0.3	1.9–5.8	0.1–0.7	1.9–13.2	0.5–0.7
WEED	0.7–1.2	12–22	0.5–3.1	9–51	0.4–0.8
snails		trace (2)			
rats		trace (2)			
birds		trace (2)			

(1) IP: combined injury profile; BLB: bacterial blight; SHB: sheath blight; BS: brown spot; LB: leaf blast; NB: neck blast; SHR: sheath rot; BPH: brown plant hoppers; DEF: defoliating insects; DH: dead hearts caused by stem borers; WH: white heads caused by stem borers; WEED: weed infestation

(2) trace: less than 1 % relative yield loss in the PS×IP combination where the mode of corresponding injury is the highest

IP: injury profile: combination of injuries at their median levels across a survey in several hundreds of farmers' fields in China, India, the Philippines, Thailand, and Vietnam. Please refer to text for other symbols

In each column, the first figure corresponds to the minimum value for a given IP, and the second figure, to the highest value for a given IP

From Savary et al. 2000a; b; Willocquet et al. 2004; Savary et al. 2006a production (FAO 2011). These numbers provide a measure of the constraint exerted by pests on rice productivity and trade in Asia — where the largest importing country actually only needs about 1–2 million tons per annum. These numbers may also be compared with those for maize (100×10^6 t traded, i.e., 12 % of world production), and wheat (145×10^6 t traded, i.e., 21 % of world production). As a result, crop losses affecting rice, one of the three most important staple crops for the world population, are of global significance. Because the global rice market is very thin, minor changes in availability have large impacts on prices (Willocquet et al. 2011).

Simulation modeling also allows shifting from yield loss to yield gains, and enables simulation of the implementation of crop health management tools. Management efficiencies, i.e., the gains, relative to current yield levels, that could be accrued from better crop health management can thus be computed. Table 3 therefore also illustrates where priorities for research in plant protection in lowland rice lie in Tropical Asia, where management has been efficient and should be sustained (see the figures for bacterial blight and the two injuries caused by blast), and the tremendous gains that could be achieved, were available management tools implemented.

As the consequences of global change unfold (Savary et al. 2011a), the spectrum of rice pests, and especially rice diseases, is changing with respect to their relative importance. Diseases which used to be considered secondary, such as false smut (teleomorph: *Claviceps oryzae-sativae*, anamorph: *Ustilaginoidea virens*), sheath rot (*Sarocladium oryzae*), along with a number of viral diseases, are gaining importance in South and South-East Asia. These not only raise concerns on food security for a major food crop worldwide, but on global food safety as well.

Yield losses in wheat in France

Wheat represents the main field crop in France, with nearly 4.8 million hectares grown in 2006 (FAO 2011). France is also one of the largest pesticide consumers worldwide (Aubertot et al. 2006), despite growing concerns associated with the negative externalities associated with conventional means of intensifying agriculture (including, e.g. intensive use of pesticides, of fertilizers, of growth regulators, and classical tillage) (Médiène et al. 2011). The following section provides an overview of approaches aiming at providing crop loss data in wheat in France and its use.

Monitoring of injuries

Diseases (and pests in general) in wheat are regularly monitored in France, with the aim of providing near to real-time information on crop health risks (e.g., Aubertot et al. 2006). One important element of wheat production in France is the large diversity of production situations (agronomic, socio-economic, and environmental), leading to widely variable patterns of multiple injuries (Savary et al. 2006b; Médiène et al. 2011).

Experiments

Experiments have been set up to establish injury-damage relationships on wheat (e.g., Schoeny et al. 2001) for some major wheat diseases in experimental stations. These results do not, however, provide information on actual losses in commercial fields, where crop management (including plant protection) differ, and where a number of diseases (and pests) occur. At the crop - multiple disease (pest) system level, Soudais et al. (2010) used several experiments where yield losses of wheat caused by various injury profiles associated with an array of production situations in Europe were measured. These experiments involved the characterization of agronomic, environmental, and economic performances of contrasting cropping systems. In order to rank the various wheat pests in terms of the yield losses they cause, each experimental plot had a treated and an untreated area against any occurring pest, enabling the measurement of both the actual and the attainable yield. Such experimental results enabled the quantifying of yield losses, and the relationships between production situations, injury profiles, and yield losses. Additional field work is necessary:

(1) to outscale experimental yield loss results to a range of production situations,
(2) to outscale these results to variable arrays of injury combinations, and
(3) to rank wheat pests according to the crop losses they cause in varying production situations.

Simulation modelling

Simulation modelling enables the exploitation of (1) field experimental data, (2) biological understanding of damage functions, (3) economic reasoning, and (4) knowledge in crop health management tools, towards a number of objectives, including:

(1) quantifying the benefits of current and yet-to-be-deployed plant protection tools - including, e.g., host plant resistance, and agronomic practices,
(2) development of maps of the distribution of yield losses in France using Geographic Information Systems.

WHEATPEST (Willocquet et al. 2008; Soudais et al. 2010) is a simulation model aimed at modelling yield losses caused on wheat by injury profiles in varying production situations. The model's structure is directly transposed from

RICEPEST (Willocquet et al. 2002, 2004) and addresses a range of key pests of wheat in Western Europe. As in RICEPEST, WHEATPEST enables the modelling of (1) yield losses to individual pests, (2) yield losses to a combination of pests, i.e., an injury profile, and (3) yield gains accrued by pest management options, whether existing, or to be developed. The last point highlights the outscaling power of simulation modelling based on mechanistic processes, i.e., experimental knowledge of damage mechanisms. The model structure is simple enough to enable a number of applications.

First, measurements of injuries by the different pest components of injury profiles in commercial fields at the national scale can be used as input variables of WHEATPEST, along with other variables describing varying production situations. This would lead to the first objective mentioned above. Maps representing actual or attainable (i.e., uninjured) yields and yield losses at the national scale could be generated, leading to the second of the above objectives. These combined results could enable research prioritisation at the national scale and the design of less vulnerable cropping systems.

Expert panels

Expert panels have played an important role in guiding and synthesising research, as exemplified by expert panel-based data reported by the European network ENDURE on wheat (Jørgensen et al. 2008). Results from such panel consultancy include ranges of estimated yield losses by selected diseases at the national scale: Septoria leaf blotch (0.3–5.0 t.ha^{-1}), brown rust (0–4.0 t.ha^{-1}), yellow rust (0–6.0 t.ha^{-1}), eyespot (0–2.5 t.ha^{-1}), Fusarium head blight (0–2.0 t.ha^{-1}), powdery mildew (0–1.5 t.ha^{-1}), tan spot (0–2.0 t.ha^{-1}), take-all (0–2.0 t.ha^{-1}), Rhizoctonia sharp eyespot (0–0.5 t.ha^{-1}), and *Stagonospora nodorum* leaf blotch (0–0.5 t.ha^{-1}). The second figure within each parenthesis of this list represents extremes that very seldom occur, and which never occur simultaneously. For instance, assuming an attainable yield of $Ya=8$ t.ha^{-1} (800 g.m^{-2}), and using the formula of Padwick (1956) as a simple way to avoid double accounting, the relative yield losses (RYL) associated with these extreme values would be:

$$RYL = 1 - \prod_{i=1}^{i=n} \left(1 - \frac{YL_i}{Ya}\right)$$

where $\prod_{i=1}^{i=n}$ denotes the product of the ratio of n individual yield losses to specific pests, YL_i, resulting in $RYL=0.9777$. Such extreme values, if combined, would thus result in 97.77 % yield losses, which is extremely unlikely, especially when one considers that only a few key wheat diseases, and no other pests (weeds and animals) are taken into account. Despite such shortcomings, the above ranges provide a preliminary ranking against which future results from research may be compared.

Expert knowledge further allows producing preliminary, average-scenario, maps of yield losses attributable to a set of wheat diseases (Jørgensen et al. 2008). Such maps, broadly, indicate a gradient of decreasing yield losses from 2.5 t.ha^{-1} to 1 t.ha^{-1} along a North-West to South-East transect. This transect largely reflects the different climatic zones of France, which in turn determine both weather patterns during cropping seasons and crop establishment dates. Again, it will be interesting to see how this expert-based output compares with formal approaches incorporating, e.g., variety types (and the pest resistances they may carry) and the widely diverse crop management practices used in the country.

Wheat yield losses in France: current knowledge and future needs

Far too little is known about yield losses in wheat in France, despite the fact that crop management decisions should be grounded in information on yield losses as a prime component among several other factors. While a number of national and international networks addressing crop protection exist, there is a lack of specific efforts dedicated to the integration of (1) quantification of injuries caused by pests (plant pathogens, animals, weeds), (2) characterization of production situations, and (3) measurement of actual yields in commercial fields. Despite past efforts, a number of questions remain on yield losses due to diseases and other pests of wheat in France. These questions especially pertain to:

- the interaction amongst pests in their yield-reducing effects;
- the effects of production situations (along with production objectives) on injury profiles;
- the true level of interactions between attainable yields and yield losses; and
- shifts in pest importance as a result of changes in crop management.

These questions are challenging and inter-connected. Addressing them obviously calls for a systems approach.

Conclusion

The above sections highlight why plant protection is part of the management of complex systems (Teng and Savary 1992), where a holistic view involving a combination of angles and approaches is required. These include ecology, epidemiology, biology, agronomy, public health medicine, psychology, economics, and the tools of their trade: statistical models, simulation models, Bayesian statistical and information theory approaches, economic modelling, as well as psychometric analysis. Crop loss research thus lies at the crossroads of diverse disciplinary areas. As a result, while a long standing and critical field of investigation of its own, crop loss research does not have a clear academic home. One may consider that the topic is entering a complete transition, and this may be one cause of the seemingly slow progress the field has seen over the past decade.

The definition of risk we used in this review, $R = P \times M$, implicitly assumes that P and M are independent events. This is often not the case. On the one hand, epidemics may occur, which may not reach levels high enough to cause crop losses. On the other hand, important crop losses may occur even when P is small. This occurs in particular when one considers harvest quality, long-term attrition of the performances of a system, or rapid accumulation of toxins at negligible disease levels. A threshold needs to be defined for risk magnitude, which is not independent of the level of epidemics or their dynamics. Thus, a probabilistic view of R emerges, where the crop loss risk incurred by epidemics is made conditional to the probability distributions of P (the likelihood of an epidemic occurring above a pre-set threshold), or of M (the likelihood of crop loss occurring above a given threshold). Thus, one could for instance write: $R = P \times \mathrm{p}(M \mid P)$, where $\mathrm{p}(M \mid P)$ is the probability of the value of M, conditional to the prior knowledge of P.

The use of Bayesian statistics has indeed been recently applied, e.g. Yuen et al. (1996) and Yuen and Hughes (2002) to improve decisions in disease management, although the approach has concentrated on tactical decisions and has seldom addressed strategic ones (e.g. Esker et al. 2006). The more complex cases of injury profiles, which can be expressed as health syndromes (Savary, et al. 2011b), where each disease occupies an ecological niche within a syndrome of diseases, and more generally, of organisms harmful to the crop and its harvest (McRoberts et al. 2003), largely remains a field for future analyses with very useful applications. Farmers are usually not interested in a single disease (or pest) during the course of a cropping season. Rather they are more interested in the overall combination of risks their production system is exposed to.

This review suggests three main conclusions:

1- There is a wide, and expanding, array of methods to measure, analyse, predict, and minimise crop losses, as exemplified by e.g., the combination of simulation models with GIS. Much of the body of new methods belongs to the field of Ecology and applied Mathematics; however, a wide range of them is also to be borrowed from other disciplinary areas, especially the Social Sciences and Public Health Medicine. Combined together, these methodologies should attract young scientists with diverse backgrounds providing a critical opportunity for this field of investigation to develop.

2- However, new methodology will never supersede actual data. We still know too little of the physiology of the diseased plant, especially when non-biological, yield-limiting factors occur. We know much too little of what is happening in farmers' fields with respect to diseases and pests, and to crop management. Importantly, specifically designed crop loss experiments are needed to quantify risks, or to parameterise and test models.

3- The consequences of harmful effects go far deeper than just direct reduction in yields. Consequences include critical indirect effects along economic fabrics and food chains. Plant diseases, in particular, are often not the main yield reducers, but their impacts on harvest quality (food processing) and safety (toxins) are very serious in many crops and environments worldwide. These indirect effects, of diseases especially, are so poorly documented that one may assume that they are grossly underestimated, as several recent studies suggest.

These conclusions should represent an incentive to address the challenge, the scientific value, and the practical applications of disease assessments, their timing and quantification, as well as their relationships and their predictive value for crop losses. This review should also lead to a reconsideration of oversimplified crop loss estimates, account for the multidimensional costs of crop losses, and start to evaluate the indirect cost of reduced product quality to add to the disease-yield loss relationship. These considerations are necessary for the prioritization of research in an extremely tight race between food production and growing food demand, at a time when environmental resources are shrinking, funding is becoming scarce, public extension services are vanishing, and public expectations are increasing.

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