Crop loss analysis and global food supply: focusing now on required harvests

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Review

Crop loss analysis and global food supply: focusing now on required harvests

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Abstract

Historically, the path of crop loss assessment research has known three phases: exploratory, development and implementation. These phases took place at different periods of agricultural research, with a common thread to improve our knowledge of the impact of diseases on crop yield quantity and quality. In this review, we provide a discussion on these phases. In particular, we emphasize the seminal research that has laid a foundation for a new phase to develop. We do this through an examination of the measurement of injury and crop losses, the current statistical models used to define thresholds and damage functions, and what is currently known regarding qualitative losses. Crop loss research enters a fourth phase of crop loss assessment, the multi-criteria assessment phase. In the latter portion of the review, we provide a brief discussion on the efforts, the concepts, and the necessary multidisciplinary dialogue, that the multi-criteria assessment phase requires in order for crop loss assessment to truly change the ways diseases are managed and how management itself is truly seen among the disciplinary fields that contribute to sustainable agricultural development.

Keywords: Required yield, Multidisciplinary research, Production situation, Injury/disease profile, Integrated pest management

Review Methodology: This review was developed through a review of the literature using several different search tools, including CAB Abstracts, Web of Science and Google Scholar. Keywords for searches included: 'crop loss assessment', 'crop loss assessment and plant (botanical) diseases', 'crop loss assessment methods'. In addition, we have collected over many years an extensive literature related to this subject that was used to reference with our keyword searches.

Introduction

The repeated calls for accurate crop loss assessments (e.g. [1–5]) without a true international, concerted response in terms of large-scale programmes aiming at developing and updating global databases begs the question of why and whether such a concerted assessment can be achieved. The answer to the second part of this question is not moot: numerous reviews have shown that methods actually do exist, can be shared and taught. It is the first part of the question – why has such effort not been attempted – that requires considerations that go far beyond the usual concerns of plant pathology. This review attempts to reach out of traditional plant pathology not only with questions, but to connect with disciplinary fields and paradigms that underscore the importance of crop losses as markers of systems' performances.

Crop protection and crop losses are part of a continuum of processes within agricultural production. By and large, crop loss research addresses series of connected entities, which can be referred as holons. These include individual plant–pathogen systems (and their many, layered, components), epidemics, crop loss and many consequences that crop losses (or their prevention) may have. Holons [6, 7] are self-contained, open, individual systems, which interact with other holons at the same level of integration, and/or with holons higher-up, or lower-down, in the hierarchy of integration levels to which they belong. Ecological examples of holons would, for instance, consist of individuals, species, communities, ecosystems, biomes and biospheres. Crop health research also addresses holons pertaining to the quality and quantity of harvested products, the multidimensional costs to achieve such production levels (and of the costs associated with untaken harvests), and the consequences of such costs along the food and fibre production/supply chain. Human individuals and groups constitute a third group of holons that includes individual farmers, advisors, extension services and researchers, policy-makers and decision-makers.

These three chains of holons are in a constant, dynamic, interaction at various scales [8] and we need to better understand how the mechanics of crop losses arise from these interactions. Understanding is required because pre-harvest crop loss to diseases are, roughly, about 10% of the technical maximum (attainable) yield — crop losses to harmful organisms, in general, range from 20 to 40% [4, 5, 9] – and such losses may lead to important, and sometimes dramatic consequences [10].

Owing to the importance of pre- and post-harvest losses, crop loss research needs to remain as a major branch of crop health research. In the second part of this review, we shall emphasize the need for bridging disciplinary areas to address crop losses. As a starting point, one has to ponder that crop loss information, the hard data on which the science can be based, is mostly patchy, in many cases not complete enough for serious policy development, thus preventing any problem structuring [8] to take place, and yet crop losses and their consequences are the very reason why plant diseases pose a threat to global food security [11].

A Synthesis of Crop Loss Assessment Approaches

A brief historical perspective

Crop loss assessment has been the theme of many texts and syntheses. Much of this information is nowadays considered as part of a collective knowledge of the plant protection community. Yet, discrepancies in views and methods still exist, leading Strange and Scott [11] in a recent, often-quoted review, to state: 'The measurement of disease continues to be an area fraught with difficulty' and 'there is usually no simple relationship between measures of symptoms and the failure to reach achievable yields.' This review, firstly, stresses the existence of a body of methods to quantify and model crop losses (i.e. both the qualitative and quantitative reductions in crop production caused by harmful agents). The subject indeed is difficult, but the complexity that underpins this subject should act as an attractor, rather than deterrent, to scientists. Secondly, we shall stress, following many authors, that the assessment of crop losses (and not yield losses alone) is central to any objective approach to crop health management. Thirdly, the quantification, analysis and modelling of crop losses to diseases (and to crop harmful agents in general) requires a collective effort from the scientific community to develop standards and methods enabling research and its applications to proceed into the future. While many textbooks on botanical epidemiology exist, few textbooks specifically deal with crop loss assessment, modelling, and its applications to disease and crop health management (e.g. [4]). This is, in part, related to the importance of the cross-disciplinary nature of crop losses. Our review will attempt to show how and why crop losses, as one phenomenon occurring in multi-layered, spatially and temporally multi-scaled, man-made ecological systems, scientifically deserve, and technically require, multidisciplinary approaches. Such approaches can have massive impacts on societies, environments and human well-being.

This synthesis is based on key texts, including Zadoks and Schein [12], Teng [4], Rabbinge *et al.* [13] and Campbell and Madden [14]. Zadoks [15] distinguished three historical phases in crop loss assessment, modelling and analyses: (i) an exploratory phase, starting in the nineteenth century, (ii) a development phase from the middle of the First World War through the mid-twentieth century and (iii) an implementation phase, initiated by the beginning of the 1970s [2, 3]. Owing to widely shared concerns about the sustainability of ecosystems, the ability of the biosphere to provide food to a growing population (e.g. [16]), the increased multidisciplinary nature of (agro)ecological research, and the emergence of methodological concepts and means to address complex systems (e.g. [8]), we believe that crop loss research has now entered a new phase, where increased emphasis is given to the environmental, social and economic dimensions of crop losses. We shall call this new phase, 'the multi-criteria assessment phase'.

The first three phases were connected to one another, and the 'development' and 'implementation' phases are still unfolding. Indeed, much novel research and applications still remain to be developed in these areas, and can fuel new thinking, enabling the new, 'multi-criteria assessment' phase to develop. This new phase has much to do with networking ideas across different disciplines, from social sciences – including sociology, anthropology, the behavioural sciences and economic sciences at different scales – to ecology, as well as with the development of new approaches to model, analyse and make use of crop loss information. The aim is to move towards sustainable crop health management [4, 17, 18]. Indeed, earlier thinkers in the field (e.g. [4, 12]) also had such developments in mind at the time when the field of crop loss research was being established.

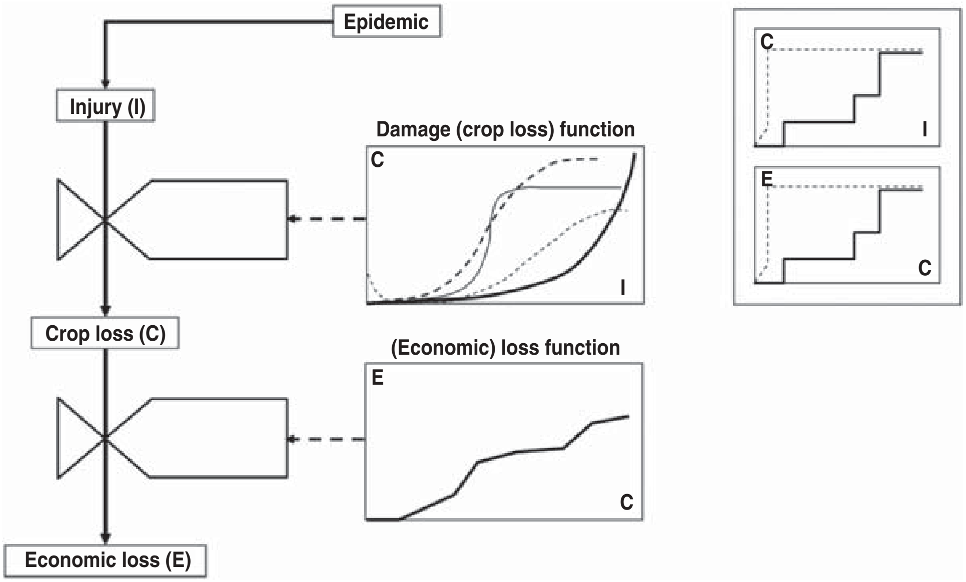

Figure 1. Diagrammatic relationships between injury, damage (crop loss) and (economic) loss. The diagram indicates the linkages between crop loss and injury, and between crop loss and economic loss (as state variables of a system) through specific rates. The main diagram applies to both quantitative and qualitative losses, i.e. crop loss. Several possible shapes of the damage function are indicated. The economic loss function is theoretical and reflects market variations. The particular case of a high quality-associated crop is illustrated by smaller damage and loss functions in the insert, with identical, and abrupt changes of crop loss and economic loss when injury and crop loss increase, respectively. Adapted from Savary [20]

Injury, crop loss and economic loss

The proximate reason why plant diseases matter is their economic impact. Diseases cause injuries to growing cultivated plants, which may cause crop losses; crop losses in turn may cause economic losses. The double relationship, [injury – crop loss] and [crop loss – economic loss], are neither automatic nor linear, however. On the contrary, these relationships are complex, being governed by damage functions (injury – crop loss) and economic loss functions (crop loss – economic loss). Complex, non-linear, and variable damage and economic loss functions [13, 15, 19, 20] represent the very basis of integrated disease management, and more broadly of integrated pest management, originally called 'integrated control' by its first designers [21].

These relationships between injury, crop loss (damage) and (economic) loss are sketched in Figure 1, with a cascade of links, starting from the occurrence of epidemics. Figure 1 also suggests that damage functions vary, depending not only on the nature of the pathosystems but also, and more importantly, on production situations [22]. The concept of production situation, that is, the bio-physical and socio-economic context where agricultural production takes place [22], thus provides a central link between the bio-physical and socio-economic 'worlds' [23]. Differences in, or shifts of, production situations are primary causes of changes of damage functions, because attainable (un-injured) harvests are reflections of production situations. Changing production situations are also a main cause for variability in loss functions, because harvest values depend on production situations as well.

The very notion of what crop loss really means and key differences in concepts ('epidemic', 'injury', 'crop loss' and 'economic loss') are sometimes lost. This leads to fear, delayed (and later-on hasty) or automatic decisions regarding crop protection. This is illustrated by the pesticide misuse and abuse in both the developing (e.g. [24]) and the developed [25] countries. Despite the history of research and extensive publications on crop losses, efforts to spread understanding of key concepts of crop loss are even more critical today when discussions related to sustainability, climate change and increased trade are high on the priority list of policy makers.

Measuring injury

The measurement of injuries caused by plant pathogens has been the focus of several seminal texts [1–4, 12, 19, 26, 27]. The proper measurement of injury is central to addressing crop loss in a suitable methodological framework. Butt and Royle [28] developed a globally accepted glossary of terms used in botanical epidemiology enabling operational definitions, i.e. measurement methods [12] to be developed. Such a glossary is attempted in Table 1, with crop loss as a focus, which strongly suggests that much remains to do with respect to the development of operational definitions bridging plant pathologists (plant protection specialists), social scientists and ecologists.

Table 1 Types of terms grouped according to levels in crop loss information and types of information

Crop loss information level	Descriptive term denoting process	Qualitative term denoting state, property or options	Methodological term denoting operational definition
Injury	• Stand reducer • Photosynthetic rate reducer • Leaf senescence accelerator • Light stealer • Assimilate sapper • Tissue consumer • Turgor reducer • Toxin • Product appearance	• Lesion • Crop development stage • Crop physiological stage	• Radiation interception • Radiation use efficiency • Yield components • Yield assessment • Quality assessment
Crop loss (damage)	• Potential yield • Attainable yield • Actual yield • Economic yield • Primitive yield • Desirable yield • Desirable crop performance	• Production situation • Yield loss • Quality loss • Toxin • Crop management • Management options • Strategic decision, short or long term • Tactical decision	• Yield loss measurement • Quality loss assessment • Toxin concentration • Product grading • Yield gain • Crop performance gain • Expectation • Regret
Economic loss	• Loss of harvestable crop • Loss of crop value • Hampered harvest • Partly injured harvest • Crop stand lost • Shift to another crop • Costs to farming communities • Costs to wholesale dealers • Costs to consumers • Costs to governments	• Market preference • Consumer's preference • Production chain • Extra cost of harvesting • Extra cost of grading • Extra cost of replanting • Opportunity cost	
Environmental costs	• Pesticide contamination: air, water, soil • Collateral impact: pollinators • Collateral impact: natural enemies • Collateral impact: loss of biodiversity on farmland • Collateral impact: loss of non-cultivated land biodiversity • Landscape beauty, tourism	• Pesticide: costs of human hazards • Cost of water, soil, decontamination • Cost of decreased pollination • Cost of suppressed natural control • Cost of lost ecosystem services	
Other costs	• Agricultural equipment contamination • Soil contamination • Seed contamination • Weakening of perennial crop	• Food security • Food safety • System's sustainability • System's resilience • Community stability • Social unrest • Market share • Product reputation • Culture • Beauty	

The measurement of injuries may aim to determine: (i) the effect of host plant resistance; (ii) the effect of chemical protection or other crop management practices; (iii) the dynamics of plant diseases; or (iv) the level of injury which may lead to crop loss. These objectives are quite different and thus require different methods. This is because, for example, lesions of similar epidemiological relevance may not have the same consequences on the diseased plant physiology. Classical examples include (1) potato late blight lesions on the stems or on the leaf blades, (2) rice blast lesions on leaves, on leaf collars, on panicle rachis, or on panicle necks (H.O. Pinnschmidt, personal communication [12]), or (3) apple scab lesions on the foliage (reduction of radiation interception and early senescence), on the very young fruits (fruit abortion) and on fruits approaching harvest (unmarketable fruits, depending on the market and consumer's preferences; L. Parisi, personal communication). Surprisingly, these four objectives are commonly confused, leading to conceptual, statistical or interpretation difficulties. For instance, Yuen and Forbes [29] remind us that "the susceptibility and resistance of plants to pathogens are closely related, but quantification of either relies on different assumptions". Several texts (e.g. [2, 3, 26, 27, 30–32]) further document this issue.

As a summary [5]: (1) crop loss studies emphasize injury assessment; (2) epidemiological measurements often are irrelevant to crop loss assessment; (3) a given pathogen may cause different injuries; and (4) conversely, widely different pathogens (and widely different harmful agents) may cause identical injuries [33, 34].

Measuring crop losses

The methodologies for crop loss assessment have been the subject of several reviews, including Chiarappa [2, 3] and Teng [4], which we cannot fully cover here. A number of methods have been described and compared with generate the required crop loss data [35], from microfield experiments, to the nature of treatments that may be considered, to data collection, including the specifics of data entry, encoding and processing [36]. An important issue that Bowen and Teng [36] underscore is the 'real risk of collecting too much data, such that the data base becomes so unwieldy and difficult to use'. Another critical point pertains to the way crop losses (and very often, crop yield losses) are expressed, and therefore measured. Pace and MacKenzie [37] emphasized that expressing yield losses as '% yield loss', as is very often done, may have little meaning unless additional information is provided, since this leads us to ask, 'x % of what?'. Pace and MacKenzie [37] recommend the use of absolute measures to report yield losses, such as metric tonne per hectare. This remark echoes the linked concepts of attainable yield (and, more generally, attainable crop performance) and production situations, which are discussed later in the review.

Contrary to classical epidemiological field experiments, or to experiments aimed at testing control methods (e.g. varieties and chemicals), the purpose of crop loss experiments is not to compare treatments (e.g. protected versus unprotected [35]). This difference underscores the need for crop-loss-specific approaches for data collection and processing. The typical purpose of a crop-loss experiment is to produce a range of injury levels, enabling the analysis of the crop's response with respect to variable levels of injuries. The response is measured at a specified level of agricultural technology, as part of a characterized production situation [13]. This is congruent with, and leads to, the development of damage functions [38], which, in turn constitute the basis of any reasoning for plant protection, including the threshold theory [19].

The definition of crop loss

The FAO developed a definition for crop loss in 1967 [15]. This definition provided the basis for a number of reference texts, including: Chiarappa [2, 3], Zadoks and Schein [12] and Teng [4]. The definition pertains to yield levels, and thus to yield losses and not to qualitative losses. It nevertheless can be used to include the qualitative component of crop loss.

- The primitive yield, Y_i, is that of landraces selected for stable, not maximized, yield. Primitive yields are harvested under variable, sometimes unfavourable soil and climate condition. This yield level does not involve direct plant protection measures (the choice of landraces is an indirect one).
- The theoretical (or potential) yield, Y_p, is the yield that would be achieved if all the physiological requirements of the growing crop were met at each of its development stages. Harvest of the potential yield implies a full protection against yield-reducing factors, which often requires a continuous preventive chemical 'umbrella'. The potential yield corresponds to the performance of a given crop genotype provided with a given level of radiation, and is achieved when no yield-limiting or yield-reducing factors occur [13].
- The attainable yield, Y_a, is achieved when crops are grown under optimal conditions using fully the available modern technology, such as, for example, in experimental plots [2]. Y_a refers to the yield of un-injured crops, under prevailing yield-limiting factors (water and nutrients [13]). Thus, Y_a is a marker of a given production situation [5].
- The economic yield, Y_e, corresponds to the yield level achieved using affordable management practices (which vary with locale, crop, production objectives, etc.). The economic yield therefore is usually lower, and sometimes approaches the attainable yield. Y_e, therefore depends directly on the considered production situation.
- The actual yield, Y, is the yield level achieved by farmers. It usually is much higher than the primitive yield, and lower than the economic yield, implying that crop management is often sub-economical.
- The FAO definition of yield loss is the difference between the attainable yield and the actual yield: $Y_a – Y$.

These definitions invite two remarks. First, the definition of 'economic yield' very much has to do with (1) what is deemed 'economical' or not, in either the short or long term, and (2) will therefore depend on the production objectives of a given crop in a given production situation. Quality performances incorporate qualitative losses, and thus, crop losses in their full dimensions. Second, the FAO definition emphasizes absolute measurements for yield losses, not relative ones (e.g. percentage). The percentages (i.e. an intensive variable [8]) that are commonly

Table 2 A series of functional relationships for injury – yield loss relationships

Type of functional relationships	Example equation	Remarks	Reference
Single point models	$Y=0.57 \times X$	Y: yield loss in % X: % of blasted nodes 30 days after heading	Katsube and Koshimizu [40]
	$L=2.5(M)^{1/2}$	L: mean reduction of grain yield (%) attributable to powdery mildew in spring barley M: powdery mildew at GS=10.5 (Feekes scale)	Large [1]
Multiple point models	$L=1.867X_1+0.446X_2+1.440X_3+0.628X_4+0.193X_5+0.180X_6+0.343X_7+0.829X_8$	L: tuber yield loss in % X_i: weekly potato late blight severity (%) increment	James *et al*. [27]
	$L=5.38+5.26X_2+0.33X_5+0.50X_7$	L: wheat yield loss in % X_i: wheat leaf rust severity (%) at boot, early Berry and early dough growth stages	Burleigh *et al*. [41]
Area under disease process curve (AUDPC)	$L=0.43(\text{AUDPC})-14.95$	L: cowpea yield loss in % AUDPC: area under Cercospora severity progress curve	Schneider *et al*. [42]

used to report yield losses are in most cases relative to the attainable yield, and therefore depend on the production situation under consideration. Generalizing reported percentages of loss from one production situation to another is difficult [5], and may lead to biased estimates. As described by Waibel [39], farmers' perspectives of loss have a historical component and tend to emphasize worst-case scenarios, which may even be overestimated by policy-makers or advisors.

Statistical models to represent the relationships between injury and crop loss

An overview of a large body of research on this topic [4, 5, 12, 14] is provided in Table 2, with three main initial approaches to address the yield loss – injury relationship (i.e. damage functions) for single-disease pathosystems. The pattern of hypothesized relationship can be very simple (single-point models) to more complex. Single-point models assume that the yield-loss-injury relationship can be captured in a simple equation. Multiple point models imply that it is the dynamics of injury in relation with that of the host crop that matter most. One of the examples of Table 2 refers to injury levels at specified development stages. Area under disease progress curve (AUDPC) models infer that an integral representation of injury over a cropping season matters most.

Table 2 requires three remarks. Firstly, the equations indicate that the amount of injury inflicted by diseases (or harmful agents) can be represented directly by a measure of disease intensity, which may not always be the case. Secondly, these equations involve yield reductions in percent, bringing about the question raised earlier: these percentages are referring to some level of reference yield, which will vary from one location to another, i.e. from one production situation [22] to another. In other words, these equations are not generic, and thus cannot be transferred from one production situation to another one. These equations therefore aim at describing and predicting – not at providing explanations. Thirdly, all the equations shown (and many of the examples which will follow) concentrate on yield, and not crop, losses: qualitative losses, despite their importance, are newcomers in the field of crop loss assessment and modelling.

As indicated earlier, the notion of production situation not only is essential to the description and analysis of crop losses but also is essential to understand the causes and address the multidimensional implications of crop losses. Given production situations determine both the biotechnical and socio-economical context of agriculture, production situations define the room for manoeuvre, i.e. the options for management of crop health in a complex system.

The approaches to describing the relationships between injuries caused by plant pathogens (I) and crop losses (L) have not been, by any means, limited to the types exemplified in Table 2. Damage functions, generally, are not linear, as indicated by the equation derived by Large [1]. Non-linear relationships are particularly well illustrated by the model derived by Madden and co-workers [43, 44]:

$$L=1-\exp[-\{(X-d)/b\}s]$$

where L is the yield loss expressed as a proportion, X is the disease (injury) at one point of time (crop development stage), and d, b and s are parameters to be estimated. The parameter, d, in particular, represents the threshold below which no yield loss takes place.

Emphasis has also been placed on the relationships between crop losses and crop development stage(s) using the response surface concept [4]. Classical studies of this type include Calpouzos [45] and Teng and Gaunt [46]. In particular, the response surface model developed by Teng and Gaunt [46], which involves crop development stages, leads to multidimensional damage functions, represents a critical step in better understanding crop losses.

A holistic approach to better understanding epidemics has long been advocated [47]. As a corollary, the second part of this review expands the boundaries of the system where crop loss occur, have impact, and may be managed [12, 48] within and beyond ecological limits, with a range of new angles and approaches.

Multivariate methodologies provide one approach to further linking the epidemics and losses with the broad ecological system. One may first consider the (common) case where two, or a few, harmful agents are responsible for crop losses. This is exemplified in studies such as those of the sudden death disease caused by *Verticillium dahliae* and *Pratylenchus penetrans* in potato [49], where discriminant analysis was used, as well as in studies conducted by Bowen *et al.* [50] on the yield-reducing effects of foliar diseases in wheat. One of the best-documented examples of such studies is grounded on very carefully designed field experiments dealing with potato diseases and pests by Johnson [51, 52]. Although the study on sudden death in potato indicates that the two pathogens interact to cause an injury, the work on potato by Johnson on other diseases and pests indicated that there were less than additive effects of individual injuries on yield losses. This example has a generic value and illustrates an array of methods.

Pinstrup-Andersen *et al.* [53] introduced the concept of injury profile and paved the way towards multivariate crop loss analysis. However, the almost geologic notion of 'profile' contradicts the concept of injuries competing in their yield-reducing effect, i.e. that crop losses cannot be incurred twice by two distinct injuries as the early equation developed by Padwick [54] indicates:

$$\mathrm{RYL} = 1 - (1 - \mathrm{RYL}_1) \times \ldots \times (1 - \mathrm{RYL}_n)$$

where RYL is the relative yield loss expressed as a proportion and RYL_i are the relative yield losses due to a series of injuries.

The philosophy of addressing a range of yield reducers (e.g. [55]), rather than single diseases at a time has been exemplified in relatively limited series of cases [5], including the work conducted on wheat in Australia by Stynes [56], on maize in Central America by Walls *et al.* [57], and in tropical Asia by Savary *et al.* [58]. These analyses do not always lead to yield loss estimates (the principal component regression approach, however, does enable such estimates [57]). They do inform us, however, of the close relationships between changing production situations and shifting crop health syndromes (changes in the dynamics of a group of diseases or crop-limiting factors in an area), which has direct impact on the threshold theory we discuss below.

Production situations, and their reflections as attainable yield and crop performance, have major consequences on the levels of crop loss incurred in a system. This was for instance shown in an analysis of the groundnut-rust-*Cercospora* leaf spots pathosystem in Côte d'Ivoire [59]. Correspondence analysis performed on a series of concatenated, unreplicated yield loss experiments show that one may see the effect of the crop health syndrome in two phases (Figure 2): (1) a first phase, where attainable yields, while increasing, drive an increase in actual yields that are marginally affected (the paths of the Y_a and Y vectors are nearly collinear) by any injury caused by rust or any of the two *Cercospora* diseases (the two yield vectors are nearly orthogonal to the disease vector), and (2) a second phase, where attainable yields exceed 1 tonne/ha, where diseases disrupt the driving effect of increasing attainable yield on actual yield (the vector of increasing attainable yields is collinear, but opposite, to disease occurrence). A threshold in attainable yield thus becomes apparent, below which diseases have marginal effects, and above which any increase in targeted attainable yield will require increasing plant protection if actual yields are to progress. This threshold sets, for instance, a target for breeders to increase host plant resistance in these production situations where fungicide use is not an option.

Modelling the mechanistic relationships between injury and crop loss

The methods summarized so far refer to empirical disease – crop loss relationships. Savary *et al.* [5] referred to these relationships as 'type 2 knowledge'. Although this type of knowledge enables us to describe, analyse and quantify crop losses, it does not necessarily allow understanding of them. By understanding, we refer to the ability to provide measures of a phenomenon based on its underpinning mechanisms. This can be generated by deriving the behaviour of the phenomenon considered at one level of integration (hierarchy level) through the use of quantitatively documented process that underpin the phenomenon at the next, lower, level of integration [13]. Mechanistic simulation models have been developed in crop loss research, among other fields, to exactly fill two needs: one is to generate quantitative syntheses of processes occurring at a given level of integration and quantify their outcome; the other is to consider alternative future scenarios, where the processes occurring at the lower level of integration still occur, but in a different, new, framework of parameters and driving variables. The consequences of such scenarios can thus be assessed. Mechanistic simulation models thus provide 'type 3 and 4' knowledge [5], in two areas. They first have a heuristic

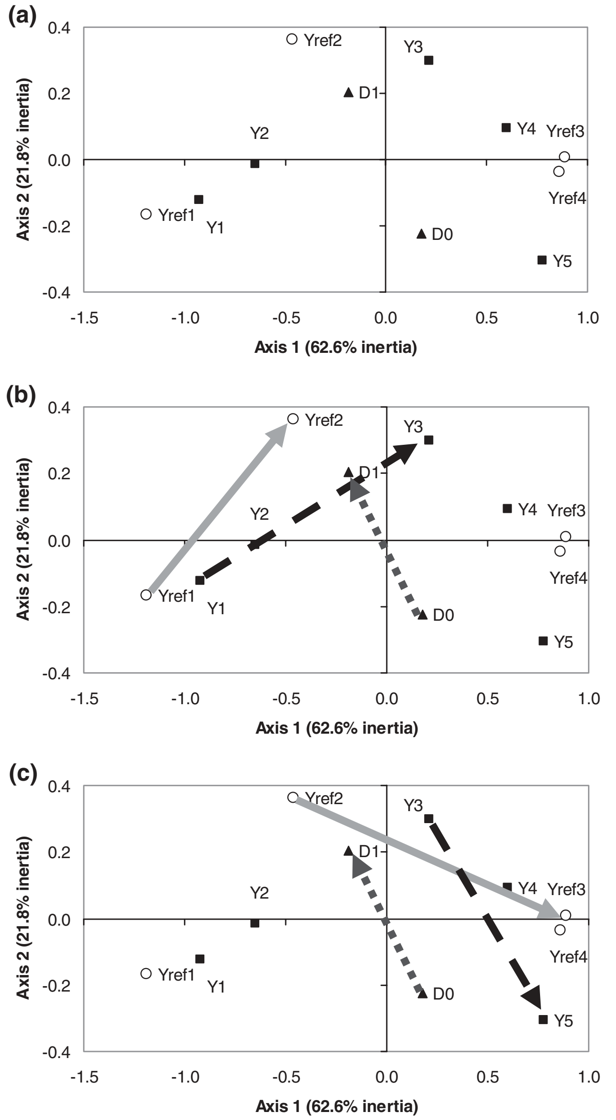

Figure 2. A correspondence analysis of relationships between attainable yield, actual yield and multiple injuries (rust, cercosporas) in groundnut. The first panel (a) shows the overall relationships among categorized levels of variables: *D* (diseases – present or absent), *Y* (actual yield), and Yref (reference yield, i.e. yield of protected plots equivalent to attainable yield). Panels (b) and (c) provide interpretations of the correspondence analysis. Adapted from Savary and Zadoks [59]

value, enabling scientists to identify knowledge gaps, i.e. insufficient information that hampers understanding the processes addressed at the upper level of integration (crop loss). They also provide us with extrapolation tools based on scenarios. Mechanistic simulation models have been reviewed by, e.g. Loomis and Adams [60], Teng [61], Gaunt [62] and Savary *et al.* [5]. Only some of the features are highlighted here.

- There is a continuum of approaches between formal field experiments and mechanistic simulation modelling and this is exemplified by the work by Johnson [63, 64] and co-workers.
- Surveys in farmers' fields at various scales and mechanistic simulation modelling are connected, because results from surveys enable one to (1) provide a framework to modelling and (2) construct developing scenarios that modelling can address [65].
- Mechanistic simulation modelling enables researchers to quantify yield gains accrued from better management of crop health affected by a number of interacting harmful agents, or of a specific disease [65].
- Mechanistic simulation modelling offers one among several interdisciplinary bridges, where plant protection, ecology and natural resource management, and the social sciences can meet [8, 66].

The threshold theory

The relationship between injuries caused by plant diseases (or any harmful organism) and crop loss has been termed 'the damage function' [19, 38]. The shape of damage functions depend on the nature of the harmful organism considered (and therefore on the type of damage mechanisms associated with a given harmful organism), and on the simultaneous occurrence of other harmful organisms affecting the same crop [13, 19, 38]. Another source of variability of damage functions is the attainable yield where a range of injuries may occur [13, 19, 38]. In the case of rice, for example, the slope of the damage function increases, is independent, or decreases with an increasing level of attainable yield, when a crop stand is affected by sheath blight (caused by *Rhizoctonia solani*), weeds or tungro (caused by two viral species), respectively [67].

Qualitative losses caused by diseases

Much of the methodology described so far in this review only addresses yield losses, and not qualitative losses. The impacts of injuries on the appearance and taste of harvestable produces are very large and poorly documented. Wilkinson *et al.* [18] and Chandler *et al.* [68] both cite a loss estimate of 20%, but that number is based on data used in an article by Pimentel [69], revealing a pressing need for the available figures to be updated. In addition, the difficulty in documenting the impact of qualitative losses is that it is related to the particular, and highly variable, shapes of the damage functions (Figure 2), which depend on markets. Market forces are particularly strong for high-quality produce, fresh produce and export commodities. Thus, qualitative crop losses particularly, but not only, affect agricultural production in the developed world.

Apart from their effects on the appearance and taste, post-harvest related losses have a tremendous public health component in both the developing and developed world. One aspect is the cost of pesticides, which is only one component of tactical decisions ($9 billion were spent in 1992 in the USA, including chemical costs and human health impacts [70]). Another is the largely unknown and probably massive, cost of mycotoxins [71, 72]. Currently, considerable efforts are addressing the *Fusarium* head blight in wheat in northern America and western Europe (e.g. [73–75]), but aflatoxins and fumonisins [76] are contaminating a large fraction of the world's food, including maize, cereals, groundnuts and tree nuts [72]. Mycotoxin contamination has become an emergency for plant pathologists today and an area that needs increased efforts to better understand their overall impact.

What is Missing in Crop Loss Assessment?

There are still several areas of where research needs to progress in order to move into the 'multi-criteria phase' (Table 1). Recent publications have shown the need to broaden our methods in order to tackle agriculturally related problems from new angles. Hughes *et al.* [77] especially emphasized the challenges in understanding economic yield losses, indicating that crop loss truly cannot be measured accurately until action is too late. In order to deliver a multi-criteria phase, the scientific community needs to address crop loss on several fronts. A prerequisite is continued resources – regular funding – to assess crop loss annually to understand how diseases affect crop production, while it is simultaneously impacted by climate change and globalization.

As previously stated, core areas of need include: (1) the dearth of research to clearly quantify post-harvest losses; (2) the lack of concern about qualitative losses, and the insufficient data to (a) document and (b) analyze – with an array of methods, that would engage disciplinary fields such as economics and public health – their manifold consequences [18, 68, 69], including in the supply chain [78]; and [3] the persistent, chronic, lack of data on yield losses themselves, which are of interest to economists, breeders, sociologists, to name few disciplinary areas plant pathologists need to work more with.

To illustrate the second point above, Cembali *et al.* [79], for example, when describing the benefits of a prevention for damage to fruit, discussed a combination of components ranging from those factors that directly affect marketability to those factors that would be considered more subtle but nonetheless affect marketability (e.g. consumer preference). In some respects, these ideas hearken back to many of the discussions related to adoption or acceptance of integrated pest management principles [80].

Our knowledge gap in what is actually happening in farmers' fields remains extremely large, and actually, is increasing [23]. This is a critical issue at times when cropping practices, and the associated crop health, are shifting rapidly. Waibel [39] emphasized this point when stating that farm management decisions required pest-specific information at the level that it would be applied – i.e. farm management level. While this poses a very challenging situation, since it is difficult to easily provide prescriptive information on a farm by farm basis, it does also provide an opportunity for improving our ability to integrate risk from the grower's perspective, or other end-user for that matter. Furthermore though, while the tools exist for assessing crop loss, a review of the recent literature suggests that there needs to be a new influx of research related to crop loss assessment. For example, Oerke and Dehne [81], citing earlier work [82] indicated that the estimates of loss were based on an examination of the published literature. We propose that in the area of decision-making, a combination of factors needs to be integrated. As several researchers have shown, growers, as well as policy makers, have a tendency to focus on the history of epidemics and the worst-case scenarios when making crop management decisions. Recognizing that these are not the only groups making farm management decisions (others include farm managers, contractors, academic and extension personnel, industry and government personnel, to name but a few [83]), crop loss data need to provide a solid economic framework for end-users to benefit appropriately.

Decision Theoretic Approaches to Study Yield and Yield Loss: Components in a Systems Analysis of Yield Production

Currently, there exists a common benchmark of a 2:1 financial advantage required before a decision-support tool is used in place of the existing cropping practices [84]. The many decision tools available have been confronted in many instances by a lack of adoption by farmers. This may be in part because growers are generally risk-averse and aim to reduce variation from field to field or year to year [83]. Yuen and Hughes [85] indicated that when there is minimal information available to end-users, most forecasting systems will provide useful information. However, as illustrated with reference to EPIPRE [86, 87] after a short period of time, the use of the information system decreased because producers had gained in expertise (i.e. essentially learned from the system), to the point where they did not need the decision tool any longer. In this case, the decreased use of EPIPRE, after an initial period of adoption, was therefore a measure of its success. McRoberts *et al.* [88] used an information-theoretic basis to develop a set of guidelines that decision tool developers, funding agencies and policy makers could use to do structure pre-development discussions in order to increase the chances of useful tools being developed.

The concept of 'uncertainty' should be seen as both a challenge and an opportunity for improving the knowledge and delivery of new information related to crop loss assessment. This idea is not new. However, it has not truly been incorporated into the majority of decision systems. Uncertainty is a component of risk (along with the potential impact of a disease, for example). It is important to emphasize this point since, as stated in McRoberts *et al.* [80], the idea of risk may differ between the developer of a decision tool and the decision maker. Gold [89] indicated that researchers should not shy away from uncertainty in the evaluation of probabilities and utilities, and instead attempt to embrace it and incorporate it into analyses of crop performance and potential impacts of management decisions.

As crop loss analysis moves from consideration of biological interactions between crops and yield-reducing agents to consideration of the implications of crop loss and human actions that can be taken to prevent it, it moves from the domain of biology to that of economics. Economic analyses may take several forms [83]: positive economics deals strictly with cause and effect relationships that can be inferred from empirical data; normative economics concerns how decision-making should be directed towards achieving particular objectives that are considered 'best' according to an *a priori* value judgement [90]. Both positive and normative approaches may, additionally, either be deterministic or incorporate uncertainty in a number of ways. One of the most common ways to incorporate uncertainty is to replace single-cost, pay-off or utility values with probability-weighted expected values.

Incorporating probabilities into the calculation of yields and yield losses raises the issue of whether the calculations are to be based on empirical probabilities or subjective ones. McRoberts *et al.* [80] discuss arguments in favour of using subjective probabilities in expected value calculations. Gold's [91] pragmatic view that since decisions are made by decision-makers who are subjective, it is simply more realistic for formal analysis to work with subjective probabilities seems as compelling as any.

One concept from economics/social science which appears to have particular usefulness in developing a new approach to how we analyse yield and crop losses is expected regret. We expand on the idea in the next section but the basic idea is straightforward. Regrets are costs that are measured relative to the least cost which could have been incurred (with hindsight) had perfect information been available when choices were made. Expected regrets are calculated similarly to other expected value when outcomes are in some sense stochastic. See McRoberts *et al.* [80] for more details related to this concept. The basic, and new, notion this article forwards is that expected regret can be used to link plant protection with social science and economics. In particular, this approach aims to understand the primary factors that an individual or a group of individuals uses to construct perceptions of risk as a combination of the uncertainty and dread, which is a measure of the perception of the size of negative impact (potential).

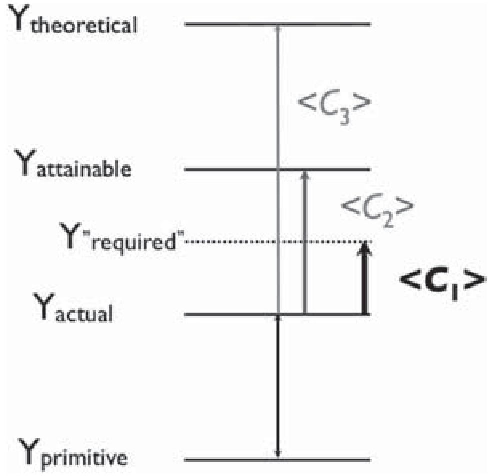

Figure 3. Modified framework for rethinking the different elements of crop loss. In particular, an additional element is proposed term the 'required yield', which exists between attainable and actual yield. Crop loss would incorporate the term (C1) in relating loss with decision theory. The term C2 would represent the regret related with not being able to close the crop loss gap using currently available management tactics. See text for more information regarding the interrelationships between individual levels

Bridging the Policy-Science Disconnection in Global Food Security: It is Time for a Paradigm Shift for the Science of Yield Loss Studies

Earlier in this review, we summarized and defined the core levels that have been used to describe crop loss, based on the terminology originally developed for yield and the different levels of loss. Our own discussions related to crop loss have centred on the idea of what is a practical reduction in losses caused by diseases. As such, we propose a modified hierarchy (Figure 3) that incorporates the concept of required yield. This idea bears itself from the extensive literature related to future population levels as well as the expected needs to meet those demands. Achieving attainable yields is not only technically unrealistic in most grower settings, but not desirable in most cases, because of the overwhelming economical and environmental (we do not refer here only to pesticide over-use, but also to spatio-temporal genetic uniformity of crops, over-fertilization, among others) costs that such an aim would entail. As shown by Savary *et al.* [5, 58, 67] for very different crops, production situations and pest profiles can be very diverse in many production situations. This implies that, in such situations, a single approach to reducing those losses (a single 'silver bullet') does not exist. The required yield is a concept that fits well in a multi-criteria system, as well as being adaptable for working in a decision theory framework. In Figure 3, we define three levels, C1, C2, C3, to indicate the difference between the theoretical yield and actual yield (C3), the difference between the attainable yield and the actual yield (C2) and the difference between the required yield and the actual yield (C1). Each of these differences can be thought of as a regret. For example, C3 can be thought of as the regret associated with having to grow crops under the constraints of the real world so that theoretical yields are not available. Clearly, in the context of crop loss, as in so many areas of life, some regrets are more important than others. Of the three identified in the hierarchy we propose, the most important regret is C1; the regret experienced when actual yields are lower than required yields. The difference, C2–C1, is reflective of the regret that occurs with the decision-making process for mitigating diseases. Realistically though, the diversity of crop practices around the world makes it challenging to fully capture C2 and C3. The first priority for both science and policy should be to achieve the state C1=0 by making sure actual yields are at least as great as required yields. We suspect that this is, indeed, the focus that most policy formulation in this area has had for some time. We are not so sure the same can be said of the science associated with yield loss. However, by giving less emphasis to the somewhat esoteric regrets that occur when we fail to achieve theoretical or even attainable yields and placing more emphasis on eliminating the regret of not achieving the required yield, we believe that crop and yield loss assessment, as a discipline, may be rejuvenated by a new sense of practical worth.

Reducing the regret of insufficient or unstable global food production has far-reaching implications for other policy areas in a world where an increasing human population will continue to cause increasing demand for food. Reducing the regret associated with not meeting required food supply is likely to demand multiple compromises in other dimensions of our relationship with the environment. Thankfully, the tools exist to analyse these trade-off relationships in a scientific way [8] so that the information needed for good policy making can be provided to decision makers.

Summary

The goal of this review was to describe the conceptual framework related to crop loss assessment as well as the many tools in existence for conducting research related to crop loss assessment. In the latter sections of the review, emphasis was placed on our gaps in knowledge as well as on how we need to develop more integrative approaches for further improving both the understanding of crop loss as well as the methods to mitigate these losses. Lastly, we proposed a conceptual framework for restructuring the concept of crop loss, which connects with a decision-theory framework, and therefore a range of diverse disciplines to address the multiple dimensions of crop losses. In spite of the vast knowledge that has developed over time, our knowledge lags in terms of the impact of many crop pests under current production practices. One of the major challenges is to also reshape the question in a manner that is more clearly understandable by key stakeholders. Opportunities exist, but they require long-term commitments in order to better differentiate the losses inflicted on crops.

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