A Synthesis of Methods to Assess Crop Losses Caused by Plant Diseases

A report of the Global Plant Health Assessment Project
to the Crop Loss Assessment Subject Matter Committee
and to the Executive Committee of the ISPP

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Intended readership

This Synthesis is intended for Professors who are teaching, as well as Scientists, Students and Practitioners who are using methods to assess crop losses from field work.

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Overview of this report

Much is written today on the losses caused by plant pathogens. Plant diseases are a cause for massive losses in quantity and quality of harvests; new technologies are increasingly reported in the literature, which might assist in quantifying these losses; and the literature indicates a drift in concepts and in semantic, while suggesting that methods are readily available. This report addresses briefly these points, emphasising the assessment methods that could globally be shared by the scientific community.

The report rapidly synthesises the reasons why crop loss information is useful, and who uses it. It especially emphasises the fact that, as a topic, crop loss assessment constitutes a bridge between plant pathology and a number of science fields, as well as an interface with decision-making and policy design: as such, plant pathology has much to deliver to society through accurate, reliable, crop loss data. In order to achieve this, reliable methods are needed to assess crop losses caused by plant diseases. These methods also need to be shareable globally amongst plant pathologists and across disciplinary fields. It also seem that crop loss assessment is commonly seen as an impossible task, which involves a large yet unknown number of elements. This perception acts as a deterrent toward efforts to gather information which is acutely needed. This report attempts to dispel this perception, first in insisting that methods exist, and second in showing that pathways toward success can be designed.

A last section of the report points at a few areas where research on crop loss is an exciting scientific endeavour. These areas concern the quantification of mycotoxins in harvests; the combination of disease injuries in injury profiles which affect crop performances in complex ways; the dynamics of pathogens within that of, and as part of, plant microbiomes – phytobiomes; the interaction of plant pathogens, and the phytobiome, with abiotic, plant physiological, stresses; and the development and use of an open-access, free, crop loss data base curated by plant pathologists. Overlapping these themes is the critically important, and so scientifically valid, question of the future of plant health — its consequences on crop performances of the future – in a world where climate, societies, and agricultural systems, are changing rapidly.

Although this report cites a number of references, this text is not meant to be a review, and the references are intended only for the reader's convenience and encourage further investigation.

How to read this report

Readers may differ in their possible interest in this report. If questions concern:

- the meaning and purposes of crop loss assessment, please see Section 2;
- the definition of crop losses (caused by pathogens as well as other organisms), please see Sections 3 and 4;
- the strategy required for crop loss investigations, please see Sections 5 and 6;
- practical details, and an introduction to available resources, on crop loss assessment, please see Section 6;
- possible workflows to generate crop loss data, please see Sections 7 and 8;
- elements on technical advances on the subject is addressed briefly in Section 9;
- some of the interesting, challenging, scientific questions that still await further investigation, some directions are offered at the end Section 9 (sub-section 9.4).

Note on the numbering of Tables, Figures, and Boxes: these are made relative to the given section of the report they belong to. The same applies to reference lists, provided at the end of each section.

1. Why this report: a background on research for crop loss assessment

There are internationally agreed-upon methods to assess crop losses caused by plant diseases (and pests), as well as there are internationally agreed-upon methods to assess the intensity of diseases. Yet publications and reports worldwide use an array of different concepts, terminology, and methods to document and report crop losses caused by plant diseases.

As a result, these internationally agreed-upon methods seem increasingly overlooked. One fundamental reason for this is the lack of communication among the scientific community – among plant pathologists, between plant pathologists and scientists involved in other agriculture-related fields, and between scientists and policy-makers as well as the wider public. The disarray in the body of methods may be seen as a main reason for a weakening in the understanding of concepts, resulting in a drift in the meaning of scientific words – the two, communication and semantic drift being closely linked. Cohesive, collectively approved, scientific terminology is necessary. The meaning of scientific words must not however be fossilised, but on the contrary needs to be regularly re-examined, not on the basis of new technology, but because new scientific concepts emerge. Concepts and the terms to refer to them, and therefore, methods, must evolve and progress. In science, methods play a pivotal role in this dynamic.

Methods are central to science. They translate concepts into procedures to acquire information; they guide observations. Methods express, in terms of operational definitions, the conceptual definition that scientists develop and agree upon. (For additional information on the notions of conceptual definition and operational definition in plant pathology, the reader is advised to Zadoks, 1972, and Palti and Kranz, 1980).

The purpose of this report is first to provide an overview of the methods mobilised to assess crop losses to plant diseases. In so doing, the report revisits concepts and words that refer to crop losses and their assessment. Another purpose is to outline the scientific questions associated with the assessment of crop losses caused by plant diseases, since these questions drive the development of methods. A third purpose is to highlight the role of crop loss assessment, as one facet of plant pathology, in linking plant pathology with other fields of science. These links are many. One may, in no particular order of importance, mention: plant physiology (the pathogen-plant relations, or the abiotic stresses-pathogens-plant interactions); the social sciences (including economy and the behavioural sciences associated with decision-making); or ecology (such as the functioning of a crop stand as an ecosystem involving two, and sometimes an array of, interacting organisms, along with elements of the chemical and physical environment, each with varying levels of human manipulation and control).

This report thus focuses on methods for observation, measurements, and data acquisition. This report does not address the many approaches to analyse crop loss information: this is deferred to other specialised texts, even though perspectives on the topic are offered. Crop loss information also is a major output of phytopathological research, with applications for the simple citizen and the farmer, and for national or global policy-maker. This aspect is only summarised here.

Terminology matters because the use of words connects to concepts, and therefore is linked with methods. This report makes use of three main sources in this respect: Butt and Royle (1980) for a comprehensive landscape of terms in plant disease epidemiology and their (crop loss) consequences, and Van der Plank (1975) for the consequences of the mis-use of terms in plant pathology. The interested reader is referred to these foundational texts.

References

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Zadoks, J.C. (1972) Methodology of epidemiological research. Annual Review of Phytopathology 10:253-276.

2. Meaning and purposes of crop loss assessment

The purpose of this report is to outline a framework for the quantification of losses caused by plant pathogens in agriculture. While most of the material assembled here concerns plant diseases caused by plant pathogens, the basic concepts and many of the approaches are also applicable to other organisms that reduce crop performances, including insects, mites, nematodes, slugs, as well as weeds and parasitic plants. What is reported is meant to be a set of general yet practical and concrete guidelines to acquire data on disease levels in plants (which is to be seen as an objective measure of the state of plant health, inasmuch as infectious diseases are considered), and on the crop losses caused by plant diseases.

The goals of this report are to meet two important needs:

- **an overview of methods and procedures for the collection of data that can be trusted by users and scientific peers**; and
- **establishing procedures that facilitate data sharing among scientists, thus enabling comparisons and further analyses.**

These goals are challenging, because considering agriculture at a global scale implies addressing a diversity of pathosystems and of agricultural contexts. This seems to preclude advocating the notion of "best practice" on a systematic basis. However, the report emphasises on widely applicable concepts, and outlines general methods that can find wide application for the conduct of field work aimed at generating disease and crop loss data.

This is made possible from the work of many scientists whose efforts have led to a body of knowledge, from which the concepts and methods reported here are derived. Therefore, this material is meant to offer a concrete course of action for field practitioners whose aim is to generate data on disease and the losses they cause, using principles that enable the acquisition of reliable and shareable information, bearing in mind the specific context where field work is conducted, as well as the limitations of resources which may be available. The material is presented so as to provide overviews of both the course of thinking and the course of action. These are meant to be applicable in any type of agriculture, irrespective of agricultural objectives, anywhere in the world. These courses of thinking and actions are represented by "workflows".

2.1 The meaning of crop losses due to plant pathogens

A *production situation* is the context where agricultural production takes place (Rabbinge and De Wit, 1989). This context encompasses the environmental (biological and physical), social, economic, cultural, and technological elements which determine, limit, and reduce crop performances. One of the many attributes of a production situation is the actual yield, that is to say, the crop yield which actually is harvested. As an attribute, crop yield pertains to agriculture only; other plant-based systems would not, or not well, be described using it. Crop yield is a quantitative attribute of plant-based production situations, and so are the losses in yield. The dimension of crop yield is biomass (dimension: [M]). Very frequently, the harvested crop biomass is made relative to the cultivated area (dimension: $[L^2]$), so that a frequent dimension of yield is $[M.L^{-2}]$. Accepted international crop yield units are $kg.ha^{-1}$, or $t.ha^{-1}$. Aside "crop yield", ways of expressing crop performance could be used. One could use different dimensions, such as for instance, the amount of biomass harvested per amount of labour time invested (the dimension of yield would be: $[M.T^{-1}]$, [T] denoting the dimension of time), of energy spent (the dimension of yield would be: $[M.M^{-1}.L^{-2}.T^2]$, and so: $[T^2L^{-2}]$), or again, the financial value (dimension: [$]) of the harvest, and the dimension of yield would be: $[\$.L^{-2}]$. These dimensions are seldom used, however, despite their meaning from the energetic, social, or financial standpoints.

A *crop loss*, on the other hand, is any reduction, in quantity or in quality, which is caused by plant pathogens, or by any organism that interferes with the build-up of crop yield and of harvest quality (Chiarappa, 1971). That reduction, in turn, is measured with reference to *attainable* crop performances,

that is to say, with reference to what would be achieved in absence of disease. This reference, as far as the quantitative crop yield is concerned, is termed attainable yield, Ya (Rabbinge and de Wit, 1989).

The attainable yield (Ya) may be considered as one acceptable reflection of a given production situation. A single figure, Ya, arguably does not make justice to the multidimensional nature of what a production situation is. We note that most agricultural research over the past century has dealt with crop yield, used as a key marker of a system's performance, irrespective of ever-changing research paradigms: conventional, subsistence, sustainable, organic, "sustainably intensified", or "agroecological" agricultures, for example. We also note that (1) the very meaning of crop loss depends on the production situation considered, and (2) that the amount of loss caused by a given disease is likely to vary, positively or negatively, with a change in production situation.

Agriculture, however, is much more than production; and production itself is far from being fully accounted for by crop yield: many other characteristics of what is being harvested matter, sometimes considerably, which refer to the quality of harvests. The quality of harvests is paramount for the industry (for example the sugar content of sugar beet, or the length of fibres in cotton), for the ulterior usage of harvests (such as the protein contents of wheat grains, intended for bread, or for pasta, for example), for the use of harvests as animal feed (which must meet the physiological needs of animals), and for human food.

The *Codex Alimentarius* (the "food code"), which probably derives from some of the oldest laws that human societies developed across the world, and which is published by the Food and Agriculture Organization (FAO) and World Health Organization (WHO) of the United Nations, defines rules relative to human food, food production, food labelling, and food safety. Harvests intended to human food must be satisfactorily nourishing, and they must never be toxic. The occurrence of (myco)toxins in harvests is a major challenge that plant pathologists face – and unlike crop yield loss, it is a quality loss.

Seldom addressed is the inherent, immaterial, value of a cultivated crop stand, or of an orchard planted to a given variety, of what these plants produce and what they mean. A lost harvest – the loss of a cultivar or cultivated type can have considerable spiritual, cultural, or societal consequences. The fact that agriculture probably started in household gardens comes to mind. There, in very small spaces, very few plants were tended, to become widespread crops with immense use. This report unfortunately does not address this point further.

2.2. Different purposes of crop loss assessment

Table 2.2 offers an overview of the purposes of crop loss assessment. These are many, including: (1) priorities for disease management at the country, regional, or global scales, (2) priorities for plant breeding, (3) priorities for chemical or biological control against plant pathogens, (4) overall priorities in strategies for disease management, and (5) research priorities for disease management, especially under shifts in climate and environment, and/or changes in structure and goals of agricultural systems.

These purposes for the use of crop loss information are illustrative only, being based on what has been, is, or could be in existence. As purposes expand in richness and connected dimensions, the role of crop loss assessment becomes less apparent, being linked with other elements to achieve them.

References

Chiarappa, L. (1971) Crop Loss Assessment Methods. Commonwealth Agricultural Bureaux, Oxfordshire, U.K.

Rabbinge, R., and de Wit, C. T. (1989) Systems, models and simulation. Pages 3-15 in: Simulation and Systems Management in Crop Protection. R. Rabbinge, S. A. Ward, and H. H. van Laar, eds. Pudoc, Wageningen, the Netherlands. Free access at: https://edepot.wur.nl/169067

Table 2.2. Purposes of crop loss assessment

Purpose	Main methods	Expected results	Remarks - Requirements (1)
1. Priorities for disease management actions at the country or regional scales	• Surveys in farmers' fields. • Field-experimental research. • Experts' opinions. • Molecular tools and platforms.	Overall ranking of diseases in terms of losses in quality and quantity (includes mycotoxin contamination). Types of data (1) from surveys: quantitative or qualitative; (2) from field experiments: usually quantitative, and (3) from experts: qualitative.	• Large endeavour, multiple contributors and structures, heavy co-ordination. Can be very costly. • Surveys: requires strong co-ordination across scales (provinces, countries); agreed-upon procedures; very large financial support; broad institutional (international) acceptance. • Experimental research: co-ordinated network of experiments with identical designs. • Experts' opinions: lighter effort. Requires careful selection and balance among stakeholders. Entails inter-disciplinary effort.
2. Research priorities for disease management actions at the country scale	• Surveys in farmers' fields. • Field-experimental research. • Experts' opinions. • Molecular tools and platforms.	As above, at the country scale.	• Surveys: imply national institutional support and oversight; co-ordination across scales (districts, provinces); agreed-upon procedures; sufficient financial support. • Experimental research: as 1. • Experts' opinions: as 1. Should involve farmers (producers) and up- and down-stream operators.
3. Research priorities on disease management at the regional or global scales	• Surveys in farmers' fields. • Field-experimental research. • Modelling studies. • Molecular tools and platforms.	Ranking of diseases according to importance, research duration, research goals, and research costs.	• Surveys: as 1. • Experimental research: as 1. Must be linked with the modelling work. • Modelling studies: implies a set of agreed-upon modelling instruments/structures; model evaluation protocols; co-ordination among modellers.
4. Plant breeding priorities for host plant resistance to plant pathogens	• Field-experimental research. • Germplasm exchange (International). • Molecular tools and platforms. • Modelling studies.	Ranking of diseases according to importance, genetic resources, anticipated breeding difficulties, measurement challenges, research goals and objectives.	• Long-term endeavour, multiple iterations, regular re-evaluation, heavy infrastructure. Very costly. • Field-experimental research: agreed-upon protocols (field designs, measurements) and statistical methods. • (International) germplasm exchange agreements; implies institutional authority and ethical oversight. Agreed-upon, networked, and shared breeding activities. • Molecular tools and platforms: sufficient infrastructure required (dedicated laboratories; in- and ex-situ conservation: seed banks). • Modelling studies: as 3.
5. Chemical and biological control priorities against plant pathogens	• Surveys in farmers' fields. • Field-experimental research. • Modelling studies. • Experts' opinions.	Identification of best products (efficacy, efficiency, economic effectiveness, shelf-life, environmental impacts) for priority diseases in specified domains.	• Surveys: as 1 or 2 depending on geographical scale. Enables defining (geographical, ecological, social, economic, and technical domains) • Field-experimental research: as 1 or 4. • Modelling studies: as 3 (includes biologicals and new products). • Experts' opinions: as 3.
6. Overall priorities in strategies for disease management	• Surveys in farmers' fields. • Field-experimental research. • Modelling studies. • Experts' opinions.	Identification of best strategies – combinations of control instruments (efficacy, sustainability) for priority diseases in specified domains.	• Surveys: as 5 • Field-experimental research: as 1 or 4. • Modelling studies: increasingly required with the increase in number of components considered (crop management, landscape, host plant resistances, chemicals, biologicals). • Experts' opinions: as 3.
7. Future research priorities for disease management under shifts in climate and environment	• Surveys in farmers' fields. • Field-experimental research. • Controlled environment experiments. • Modelling studies.	Identification of best strategies (efficacy, sustainability) for anticipated disease profiles in specified domains.	• Ambitious endeavour; heavy infrastructure. Can be very costly. • Surveys: as 1. Results may provide ground for "*space-for-time*" hypotheses. • Field-experimental research: Specific settings and equipment required. May be multi-locational. • Infrastructure for controlled environment experiments. • Scenarios for shifts in climate and environment. • Modelling studies: Interdisciplinary. Need to combine abiotic and biological (crop, pathogens, interactions) processes.
8. Future research priorities for disease management under shifts in agriculture	• Surveys in farmers' fields. • Field-experimental research. • Modelling studies. • Policy evaluations.	Outline of agricultural domains (landscape, crop distribution, genetic diversity, farming system, farm size) adapted to new environmental, social, and economic contexts.	• Ambitious endeavour; heavy infrastructure. Very costly. • Surveys: as 1, 2, and 7 ("space for time") • Field-experimental research: as 1 and 4, amplified: landscapes, seasons. • Scenarios for shifts in agricultural systems (climate, environment, social, economic, and technological). • Modelling studies: as 7. Requires consideration of cropping systems. • Policy evaluations: foresight analyses; overall systems performances.

(1) Training of scientific field and laboratory personnel not listed.

3. Levels and dimensions of crop losses

3.1. Typologies of losses

The negative impacts of pathogens (and any other organism) on crop performances can be considered in many different ways depending on the scale (individual, farm, society, the environment) and the horizon of time considered. Following Zadoks and Schein (1979), a typology of crop losses is summarised in **Table 3.1**, and is described below.

3.2. Potential and actual losses

A first distinction is based on whether no action is being taken, as opposed to some level of control is being implemented. In the first case, potential losses occur, whereas actual losses occur in the second. Note that "*control*" here refers to any means, genetic (host plant resistance), chemical (pesticide), biological (bio-control agents), agricultural (crop rotation and establishment and crop management (Palti, 2012), that may be used to suppress disease and reduce losses. The term *control* therefore is used to refer to the result of decisions that are tactical, with short-term expected effects, as well as strategic decisions, taken to achieve long-term objectives. Strategic control actions, as a result, are linked with numerous other agricultural choices that are not related to disease management.

3.3. Direct and indirect losses

A second dichotomy is based on whether losses are directly attributable to plant pathogens or any other organism that reduce crop performances, or whether losses are indirect consequences (beyond the crop scale) of direct losses. Some of these indirect losses, but not all, can readily be expressed in financial terms. Examples of indirect losses are (a) at the farm scale where losses may reduce the overall farming activities and threaten their sustainability, ecologically or financially; (b) at the rural community scale which may be negatively affected by an overall decline; (c) among exporters who may fail fulfilling contracts and lose credibility; (d) in the commercial world where wholesale as well as retail dealers may suffer losses; (e) for consumers, who may face higher prices of agricultural products, or loss of product quality; (f) for governments with a cascade of effects linked to international trade and taxes; and (g) for the environment. In the latter case, crop losses necessarily impact natural resources, since crop loss amounts also to a waste of land, of energy, of water, of nutrients, and if applicable, unnecessary agricultural effluents (chemical fertilisers or pesticides) that have been used for no result.

3.4. Primary and secondary losses

Among the direct losses caused by plant pathogens or any other organisms that reduce crop performances, a distinction can be made between primary and secondary losses. Primary losses refer to losses that are directly affecting the current growing season of a given crop (annual or perennial); these are (1) losses in yield, (2) losses in quality of harvests (this includes reduction of technological characteristics, such as sugar contents in sugar beet, downgrading due to appearance of the harvested product, or the accumulation of mycotoxins), (3) additional expenses in harvesting caused by disease, (4) costs generated by additional expenses required by within-season disease control, (5) costs accrued by the need for grading of harvest products (e.g., damaged or undamaged, normal or undersized, fruits or tubers), (6) costs caused by the need for crop-re-establishment, and (7) economic losses caused by disease imposing the necessity of growing another, less profitable crop (e.g., soil-borne pathogens with very long survival duration ability).

Secondary losses refer to losses incurred in future crops. Secondary losses include (1) the contamination of agricultural tools and machines, (2) the long-term establishment of a soil-borne pathogen, (3) the weakening of plants by disease (this especially applies to perennial crops), and (4) the costs of control (including in this case the costs associated with long-term, strategic decisions for disease management).

Again, many of these losses are, or can, be expressed in monetary terms. However, losses can be both economic or non-financial, or only non-financial and immaterial. For instance (primary loss type 7 of **Table 3.1**), not being able to grow a traditional Japonica glutinous rice variety that is consumed in Southern China on the occasion of weddings because of regular neck and panicle blast epidemics, and have to grow a high yielding Indica variety instead, is a non-financial cultural cost.

3.5. Other contrasting types of losses

Losses in human food crops (in quantity or quality) are of specific relevance in the meaning of agriculture for food security. One may distinguish the acute losses caused by brutal plant disease epidemics over food crops, and the chronic losses caused by resident pathogens. The former may draw immediate attention, raise alarm, and trigger response. The latter instead are caused by regular, low- to moderate-level epidemics that occur every or most growing seasons. Such chronic epidemics are thus a common sight to farmers, they remain essentially undetected as a cause of loss to farmers and administrators alike, and yet can be responsible for a systematic attrition of the performances of agricultural systems, including food supply. This case especially applies in developing countries, especially where agricultural support infrastructure is weak.

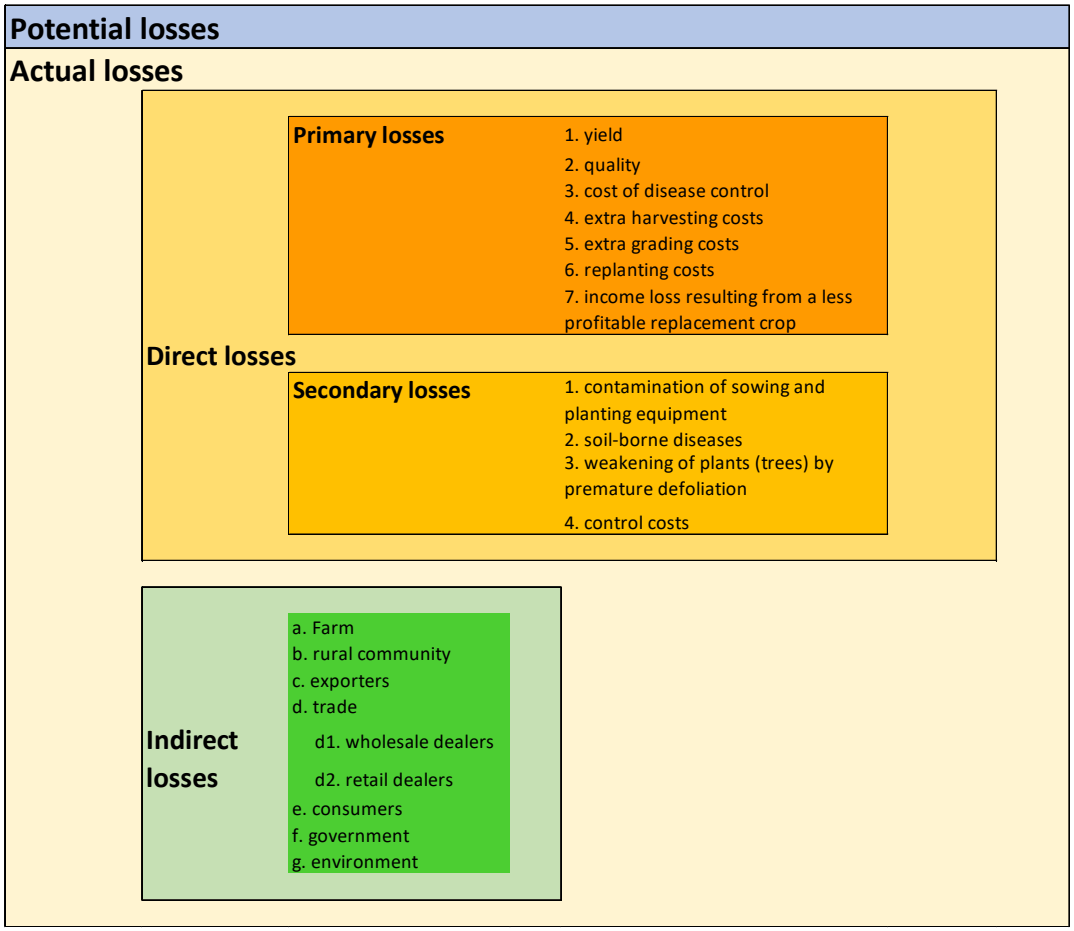
Another contrast is that of quantity vs. quality. Losses to plant pathogens (and other organisms) may affect harvests intended for the industry (with attributes related to, e.g., fibre, cellulose, starch, or sugar content), for animal feed (with their nutrients), for various human uses (stimulants, such as coffee or tea), and human food (with their nutritional value). Quality losses often are at least as important as quantity losses.

References

Palti, J. (2012) Cultural practices and infectious crop diseases. Berlin: Springer Science & Business Media.

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Table 3.1. A typology of losses caused by plant pathogens in agriculture



Sources: J.C. Zadoks, 1967. Pages 149-158 in: FAO papers presented at the Symposium on Crop Losses, FAO, Rome; J.C. Zadoks and R.D. Schein, 1979. Page 240. Epidemiology and plant Disease Management. New York: Oxford University Press.

Potential losses occur in total absence of control: these too may be direct or indirect losses, and (if direct) primary or secondary;

Actual losses occur in actual production situations;

Direct losses are directly caused by disease;

Indirect losses are caused by the consequences of disease (indirect losses, also, affect multiple scales of societies and the environment);

Primary losses are in the short-term, affecting the outcomes of a given growing season;

Secondary losses are in the long-term, affecting agricultural performances over successive seasons.

4. Quantitative yield losses

Quantitative yield losses, that is, the losses in harvested biomass caused by plant pathogens, occupy a special place in the methodology of crop loss assessment. This is because (i) such losses have a long-known and accepted metric (mass), (ii) such type of loss has been the subject of a very large number of studies, (iii) such types of losses are among the most common, and therefore (iv) methods to address quantitative yield loss are both well-established and serve as a template (to be modified) for other types of losses.

4.1. Definitions for quantitative yield losses

Theoretical production ecology defines a series of agricultural yield levels:

- The *theoretical yield*, which is achieved under optimum conditions (temperature, water, and nutrients) at every stage of the development of a crop, and which is determined only by a set of *yield defining factors* (including plant genotype and radiation at a given latitude).
- The *attainable yield*, which is achieved when a set of *yield-limiting factors* occur, i.e., when a crop stand is exposed to limited supply of water and/or of nutrients.
- The *actual yield*, which is achieved under actual farmer's field conditions, and where a combination of *yield-limiting factors* and of *yield reducing* factors are at play. Yield reducing factors include physical factors (e.g., frosts, heat waves, floods) and an array of biological factors including plant pathogens and other yield-reducing organisms.

Two other yield levels are used in the agricultural literature. One is the "economic yield" (**Fig. 4.1**), which corresponds to the economic balance between investment to the crop (i.e., seed, land preparation, crop establishment, up to harvest) and the economic value of the harvested crop. The other is the "primitive yield", which seldom is used now, and corresponds to harvests achieved in total absence of plant protection. The resulting different yield levels are displayed in **Fig. 4.1**, a classic diagram of the crop loss literature (Zadoks and Schein, 1979; Chiarappa, 1981).

Each yield level is associated in **Fig. 4.1** with simplified annotation on *production situations*. Some elaboration on two of the production situations indicated in **Fig. 4.1** is necessary. The production situation labelled "technical maximum" corresponds to a specific context, where the growing crop, while limited in its (yield) performance by physical factors, is not affected by yield reducing factors. The attainable yield associated with this production situation therefore is the yardstick of yield loss measurement, because it represents the level of yield that would be harvested if disease were entirely absent during a growing season. Pathogens and any other yield-reducing factors excluded, the attainable yield is thus a marker of a given production situation. The production situation labelled "sub-optimal (current) situation" refers to the same production situation, where pathogens and any other yield-reducing factors are taken into account, which may reduce crop yield within the limits of the efficiency of control that may be implemented.

The formal definition of yield loss is the difference between the attainable yield (Ya) and the actual yield (Y): YL = Ya – Y (Zadoks and Schein, 1979; Chiarappa, 1981). Other levels of yield losses are indicated on **Fig. 4.1**:

- the theoretical loss is the difference between the theoretical yield and the actual yield;
- the gap between the "economic yield" and the actual yield is termed "economic loss" (this represents the yield losses that would be avoided if economically effective control were applied);
- the gap between the attainable yield and the "economic yield" is termed "potential loss" (this difference represents the yield loss that cannot be prevented using current management instruments under the current economic context); and
- the gap between the theoretical and attainable yields is termed "unavoidable loss" (implying that, irrespective of the level of control, yield losses unavoidably occur because no control can be fully effective).

The formal definition of yield losses thus includes two additive components: one (the "economic loss") is the level of yield losses that can actually be avoided, in a given production situation, and at costs that are just equal to the benefit accrued by the level of control used; and the other (the potential loss) is the level of yield losses that could be avoided, but at inacceptable costs of control. This definition therefore enables to measure what scientific progress in disease management could generate in increasing the level of disease control at acceptable costs, and thus, in reducing potential losses. One component thus represents the progress in disease management that has been achieved, and the other, the progress which is still necessary, in a given production situation.

4.2. On defoliation

Early experiments involving the mechanical removal of foliage, for example in sorghum (Pauli and Stickler, 1961) has been an early approach to address the effect of harmful organisms in crops, as exemplified in **Fig. 4.2**. Data indicate that defoliation has a less-than-proportional effect on biomass accumulation (for instance, a 66% defoliation at boot stage only reduces biomass by 44%). Furthermore, successively decreasing levels of defoliation have decreasingly effects on biomass accumulation.

Plant pathogens affect the physiology of a growing crop stand in many different ways. **Fig. 4.2** indicates that it takes considerable amounts of mechanical defoliation to suppress the dynamics of crop biomass accumulation and achieve crop yield reduction. Yet, many foliage diseases cause heavy yield losses, drawing the efforts of considerable research, and generating scores of publications until today. It has been known for a very long time that reduction of leaf area alone is very far from explaining yield losses: the effects of foliage diseases involve much more than just leaf area reduction or defoliation. The processes through which yield reduction occurs as a result of plant disease effects are dynamic, multiple, and diverse; and these processes are profoundly affected by the changing physiology of the host crop as it develops. The overall process of crop yield reduction caused by plant pathogens therefore must be recognised as complex. The dynamics of crop yield reduction has been better understood through major advances.

The mechanical defoliation approach to understand yield losses caused by plant diseases is not valid, for a number of reasons: (1) plant diseases, even if affecting crop foliage only (many do not), do not cause injury at a single point of time only, (2) the eco-physiological effect of plant diseases entails much more than foliage removal. Yet, it is true that the results of **Fig. 4.2** are indicative of the consequence of Beer's law applied to the interception of radiation by a canopy, which indeed is used to model the effect of foliage disease on crop yield. (The Beer-Lambert law, commonly referred to as Beer's law, describes the attenuation in intensity of a radiation beam passing through a homogenous medium with which it interacts. In the case of a crop stand, this medium is the crop canopy.)

4.3. Damage mechanisms

Plant pathogens, and generally organisms acting as crop yield reducers, impair crop physiological processes through a limited number of pathways leading to yield losses. These pathways are referred to as damage mechanisms. Seven such pathways are generally considered (Rabbinge and Rijsdijk, 1981; Boote et al., 1983); an eighth is added here (Savary and Willocquet, 2020). These damage mechanisms are described below and in **Table 4.3**:

1. "light stealing", results from the multiplication of lesions on a crop foliage, leading to a reduction of the radiation intercepted by the photosynthetically active area.
2. "leaf senescence acceleration" results from the production of toxins by pathogens and of the alteration of the host physiology.
3. "tissue consumption" results from the degradation of host tissues, as e.g., common moulds.
4. "stand reduction" results from death of individual plants in a crop stand, as e.g. in damping-off fungi.

5. “photosynthetic rate reduction” results from the alteration or destruction of the photosynthesis apparatus (molecules or organelles), as, e.g., caused by toxins produced by some fungi, or from the overall performances of photosynthesis, resulting from a disruption in water supply to the photosynthesis apparatus.
6. “turgor reduction” is caused by any agent that disrupts transport in the xylem or phloem.
7. “assimilate sapping” refers to the uptake of carbohydrates immediately after their photosynthesis and prior to their partition to plant organs.
8. The additional eighth damage mechanism, “harvest destruction” refers to the destruction of harvestable tissues of, especially, cereals. The rice blast, in its neck and panicle form, exemplifies that damage mechanism.

4.4. Disease injury as a concept

Rice leaf blast causes lesions on different aerial plant tissues. Lesions of the same area, with similar sporulating areas for instance, are produced on leaf blades, on the collar of leaves (at varying heights in plants), at the base of panicles (necks), or at the base of panicle branches (panicle blast). These lesions may be seen as equivalent from the epidemiological standpoint, contributing similarly to disease progress (except for their positioning in a canopy and the availability of spores for dispersal). However, these lesions are very different from the standpoint of crop yield.

Disease assessment serves a number of different purposes, and thus may follow different procedures and methods. The disease information that is relevant to understand and analyse yield loss must be conceptually congruent with the processes leading to the loss of crop yield. A disease information that is relevant to understand and analyse yield losses is the disease injury. Disease *injury* is defined as “any visible and measurable symptoms caused by a harmful organism” (Zadoks, 1985) occurring on a growing crop stand; injury can be quantitatively measured. In the case of rice blast for example, leaf blast injury can be measured as the fraction of leaf area showing leaf blast symptoms, whereas collar, neck, and panicle blast injuries can be measured as fractions of leaf collars, necks, and panicle branches showing symptoms, respectively.

The injury concept, which is designed to only address quantitative yield losses, may be extended to quality losses. This may prove difficult, however. An important example of quality loss caused by plant disease is that of the accumulation of mycotoxins. Considering fusarium head blight of wheat, the amount of disease observed on wheat heads should be thought of as a straightforward, simple measurement of injury. Research (Madden and Paul, 2020), however, shows that the relation: (intensity of fusarium head blight) x (deoxynivalenol concentration in wheat grain) is not straightforward. Addressing such relationships is a priority area for research.

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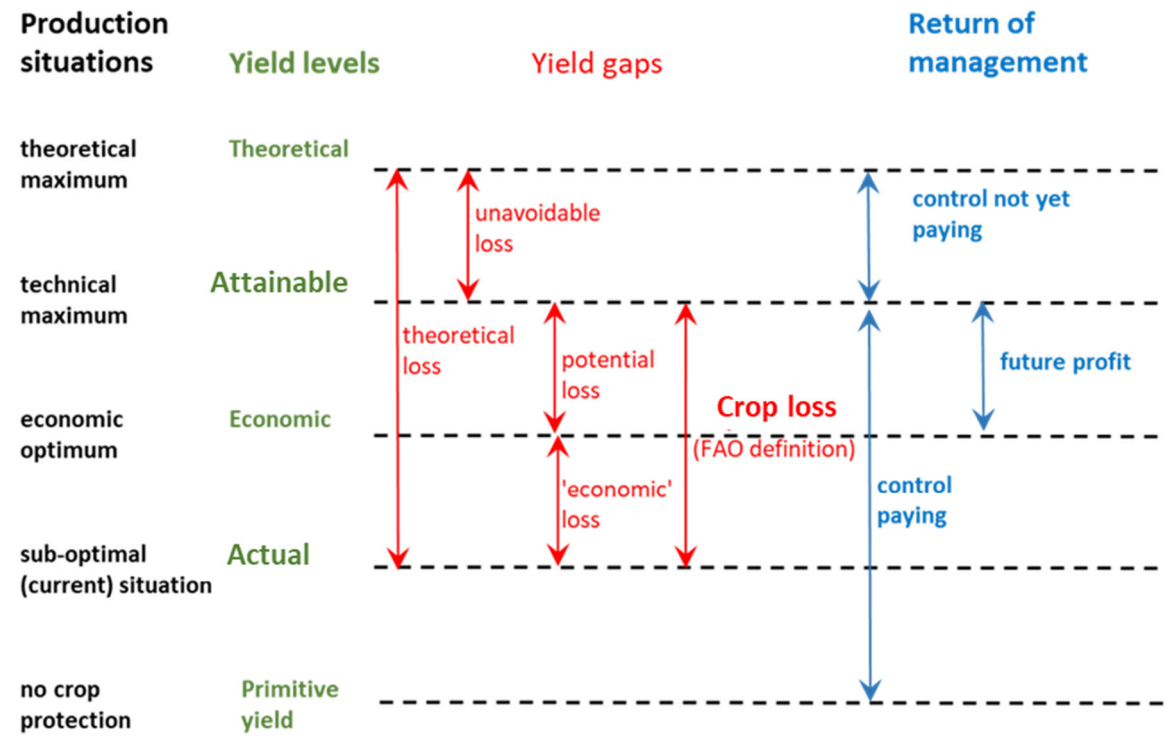
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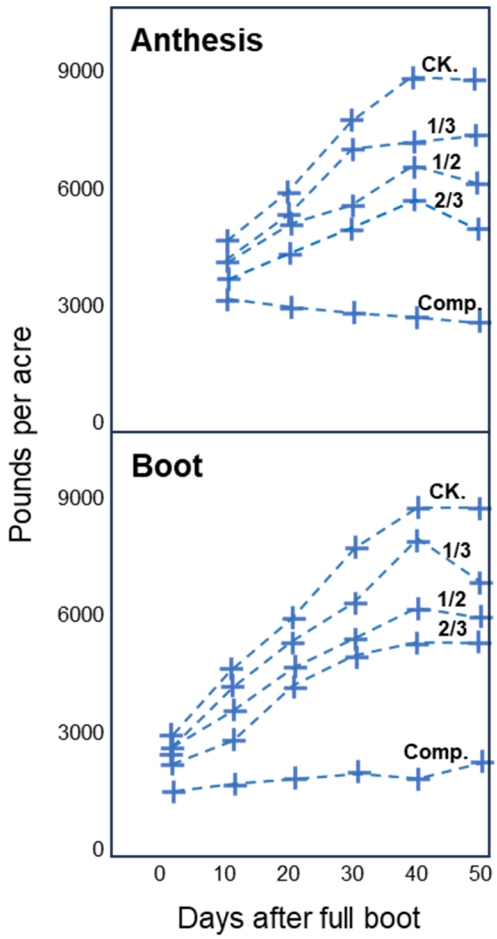
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Figure 4.1. Definition of yield levels and yield losses (from Zadoks and Schein, 1979)



Sources: Zadoks, 1967; Zadoks and Schein, 1979; Chiarappa, 1981.

Figure 4.2. Effect of mechanical defoliation on sorghum biomass (redrawn from Pauli and Stickler, 1961)



Mechanical defoliation was performed at anthesis and boot development stages.

Experiments involved five levels of defoliation: complete (Comp.), two-third (2/3), half (1/2), one-third (1/3), and none (check treatment, SK.).

Abscissa: time (days after full boot); Ordinates: biomass (pounds per acre).

Redrawn from: Pauli, A.W. and Stickler, F.C., 1961. Leaf removal in grain sorghum. II. Trends in dry matter, carbohydrates, and nitrogen following defoliation 1. Agronomy Journal, 53(2):102-105.

Table 4.3. Damage mechanisms associated with plant pathogens

Damage mechanism	Physiological effect	Examples of harmful organisms
Light stealer	Reduces the radiation intercepted by the crop canopy	Pathogens producing lesions on foliage.
Leaf senescence accelerator	Increases leaf senescence, causes defoliation	Foliar pathogens such as leaf-spotting pathogens, downy mildews.
Tissue consumer	Reduces the tissue biomass	Tissue-destroying pathogens; defoliating insects.
Stand reducer	Reduces the number and biomass of plants	Damping-off fungi.
Photosynthetic rate reducer	Reduces the rate of carbon uptake	Viruses, root-infecting pathogens, stem-infecting pests, some foliar pathogens.
Turgor reducer	Disrupts xylem and phloem transport	Vascular pathogens, wilt-causing pathogens.
Assimilate sapper	Removes soluble assimilates from host	biotrophic fungi exporting assimilates from host cells; sucking insects, e.g. aphids; some planthoppers.
Harvest destroyer	Prevents grain filling, reduces grain size and weight, or kills unripe heads, panicles, or cobs	Pathogens directly affecting harvestable tissues of cereals. Many pathogens causing fruit rots.

Derived from Rabbinge and Rijsdijk, 1981; Boote et al., 1983; Savary and Willocquet, 2020

5. Strategy for crop loss assessment

5.1. Steps as outlined by E.C. Large (1966)

In his 1966 article, E.C. Large laid out two phases of an overall strategy to assess crop losses to plant diseases (Large, 1966). The first phase involves:

a) "A close descriptive study of the gross morphology and course of development of the healthy crop plant from sowing to harvest, or from season to season." and
b) "A similar close study of the course of the disease on plants in the field, over the whole range of attack."

The first phase emphasises observation, leading to a collection of drawing and sketches, to which Large refers to as "the preliminary portfolio". The term "portfolio" is thus retained here. The second phase involves:

c) The design, based on the preliminary portfolio, first, "of a standard diagram or research key for the assessment of the disease", which later may be simplified as a "field key", which can be used by any observer;
d) "The conduct of a series of field trials, over a number of years, in which progress curves for the disease are plotted by the field key, and yields are recorded, for plots on which the disease is allowed to run its course according to the conditions of the season, and an equal number of check plots kept as nearly as possible free from the disease"; and
e) "The choice, from study of the progress curves obtained in the field trials, of the particular disease assessments that will best serve to define severity of attack when employed in survey work, and the calibration of these assessments in terms of reduction of yield." The accumulated data therefore is used to define when disease has to be measured in order to enable yield loss estimates.

5.2. Overall strategy for crop loss assessment

The material assembled here follows this overall strategy. Three remarks however are needed:

1. Large's (1966) strategy pertains to quantitative, biomass, losses. This strategy is here expanded to qualitative losses.

2. The pioneering work of Large (1966), and of many other scientists involved in the first stages of establishing methods for disease measurement, focused on foliage diseases. Much of the resources available today still strongly emphasises on diseases of the foliage, despite the importance of many diseases affecting other plant tissues, or entire plants. The present report aims to share methods for all forms of plant diseases, irrespective of the tissues affected.

3. The last stage (e) of the above strategy implies a fixed (non-linear) relationship between the progress of disease intensity and its physiological effect on a crop stand. Over the years, extensive research has shown that such relationship is not fixed, but instead, very flexible. While this, in reality, is still a field for ongoing and necessary further investigation, practical options exist to address the dynamic interaction of disease and crop physiology in crop loss assessment. This is addressed further in the present report.

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6. Development and use of host and disease portfolios: observation and assessment strategies

Assessing crop losses involves (1) observations on the crop itself (the individual plants that constitute a crop stand, their development over successive stages and growth in size and biomass, the various organs formed and their individual dynamics), as well as (2) observations on the disease (i.e., symptoms, signs, their locations on plant tissues, their dynamics and multiplication, their implications on both the individual plant and the crop stand physiology). These observations are assembled in the host portfolio and the disease portfolio.

This section describes (1) the development and use of portfolios including field keys, (2) steps to define sampling designs within nested spatial hierarchies, and (3) the methods and metrics to conduct assessments of disease injury.

6.1. The crop portfolio

Crop loss is the physiological translation of dynamic plant-pathogen interactions at the populational level. Measuring crop loss therefore requires a suitable documentation of the host crop: this entails considering both the scales of the individual plant and the plant population of a crop.

The physical features of individual crop plants result from a number of processes (see **Box 6.1.a**: Plant habits and ideotypes), from crop plant domestication, to plant breeding, and to crop management effects at the individual and crop scales. The physical features of a crop as a whole is in turn a reflection of individual plant attributes, and of the overall crop management, including tillage, crop establishment date and method, nutrient inputs, or irrigation (in annual crops), and planting geometry and density, fertilisation, or pruning (in perennial crops).

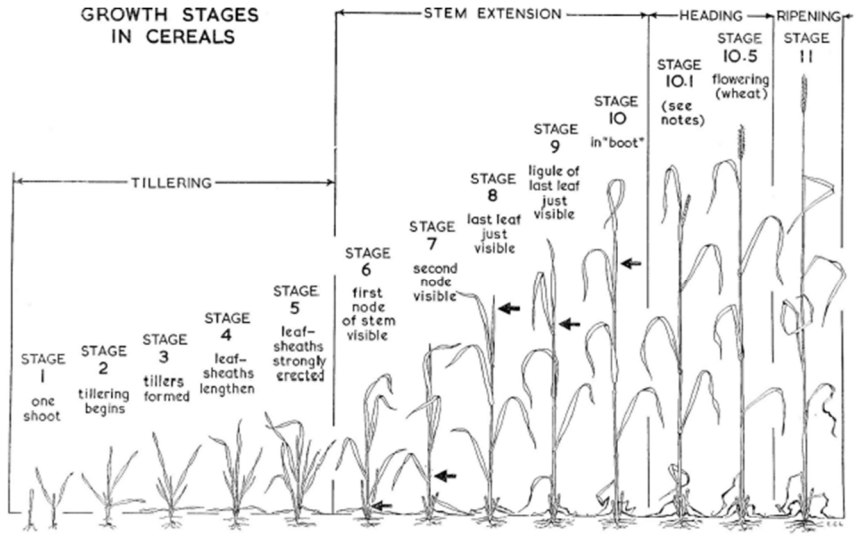
The physical features of both the individual plant and whole-crop stand have strong consequences on the physical environment (microclimate), which in turn influences the physiology of a crop stand, and thus the microbiological (phytobiome) environment. Both the physical and the microbiological environment, in turn, have multiple consequences on the dynamics of epidemics, on the injuries they produce, and therefore on the crop loss they cause. These interacting factors commonly lead to considerable spatial variability in crop growth, yield, and disease intensity (see **Box 6.1.b**: Within-field spatial variation of crop stand environments, performances, yield, and disease intensity). This has direct implications in sampling procedures and experimental designs.

It should be emphasised that (1) because of crop growth and (physiological) development, all these interactions and their effects on crop losses are dynamic, and (2) the nature and consequences of disease-generated injury necessarily change over the physiological development and duration of a crop, as a result of shifts in plant physiology occurring during plant and crop development. Both crop development and crop growth therefore need to be part of the crop portfolio.

Crop growth refers to the accumulation of plant tissues and of biomass, whereas *crop development* refers to the succession of physiological stages through which the individual plants of a crop stand evolve. Crop growth is quantitative and continuous, whereas crop development is qualitative and comprised of distinct stages. This is why, when referring to the evolution of a crop stand through its successive physiological stages, “development” is preferred to “growth”. **Figure 6.1** shows an early version of the many scales that have been used to describe the development process in the case of small grain cereals. Many other versions in describing crop development have been developed, in a wide diversity of crops, both annual and perennial. Although other drivers of crop development may occur, temperature is overwhelmingly the most important across cultivated plant species. Crop development is thus often measured along a thermal time (accumulated temperature) rather than on a mere chronological time basis.

Crop development is one central characteristic to describe the status of a crop stand. This is because crop development outlines the successive physiological plant stages during which host plants may become more, or less, susceptible to infection, and also during which different plant organs, as they appear and develop, may become vulnerable and exposed to disease injury. Crop development (**Fig. 6.1**) is typically measured at the individual plant scale. The state of development of a population of crop plants needs thus to be derived from a (random) sampling of individuals. In many cases, a sample of about 10 plants within a crop stand is sufficient, and the development stage of that crop stand is defined as the most frequent (statistical mode) stage encountered within the sample.

Fig. 6.1 Crop development stages in cereals (Large, 1954)



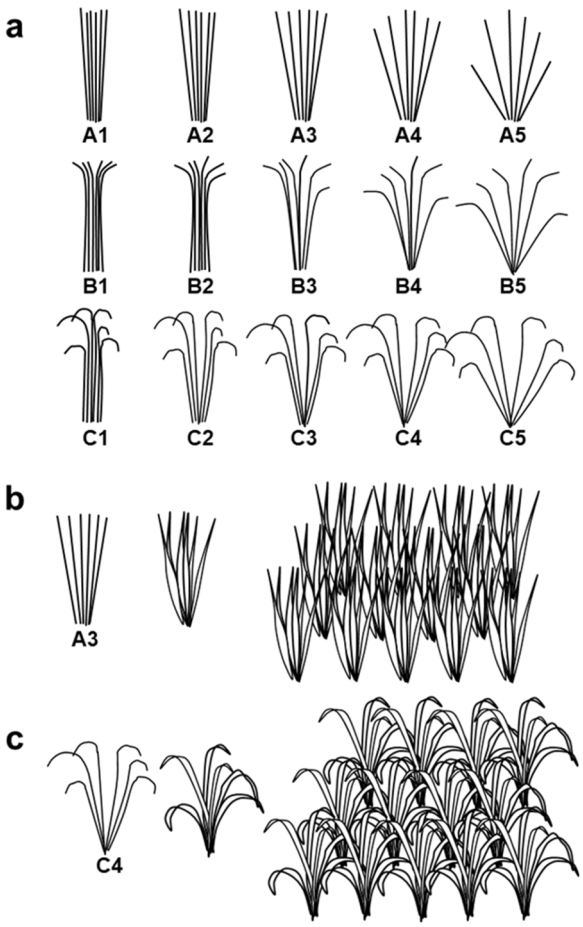
Box 6.1.a – Plant habits and ideotypes

The shape of plants: plant habits

As a result of physical shapes of individual plants that are assembled in a crop stand, shapes which change as a crop grows, the physical environment of that crop evolves at a micro-scale. Wide changes in wind speed, moisture, or temperature, which may occur in the meso-environment of a crop are being buffered. The very establishment of a crop and its further growth change its own environment above- and under-ground. The book by Monteith and Unsworth (2013) provides an entry point to the literature on the environmental physics of plant-based systems. Plant habits have much to do with the physical environment of crops, and therefore, with their biological environment, including plant pathogens.

Figure 6.1.a.1 considers the canopy of an annual field crop such as a cereal, which is generated by different shapes of individual plant habits. The morphological consequences of differences in shapes of plant habits are multiple. Habit A3 is well-adapted for a row crop, with a very effective interception of radiation. Such a habit is also very likely to lead, among other things, to a crop stand (1) which generates high air turbulences, increasing as crop (row) density decreases; (2) higher penetration of radiation (and generally, stronger heat exchanges with the atmosphere) within the canopy, leading to an overall warmer and drier canopy; (3) a canopy that is sensitive in its growth and performance to the orientation of rows (an East-West orientation leading to a higher radiation interception); and (4) a warmer, drier soil. The choice of A3 thus is bound to have consequences (i) on the crop physiology and its growth, (ii) on plant pathogens, whether soil-borne or affecting the canopy, and thus (iii) on crop losses.

Figure 6.1.a.1. Classification of plant habits in cereals



a: Redrawn from Broekhuizen, S. (1961) and from Zadoks and Schein (1979) (Fig. 8.1, page 249).

b and c: Consequences of differing individual plant habits on the physical structure of a crop canopy.

Reflecting on ideotype C4, for example, may lead to conflicting choices. A canopy that quicker and better protects the soil against erosion in the early stages of canopy deployment, and also retains more moisture, are all features that may be appealing in breeding programmes that are geared towards adaptation to climate change. However, these features also have plant health consequences.

Reflection on plant habits may also concern root systems in their relations with soil-borne diseases. In that case, key terms of reference would include the rate and extent of root growth and root branching in interaction with soil characteristics (both undisturbed and modified by tillage and crop establishment practices).

Reflection on plant habits also applies to perennial crops (e.g., fruit trees or grapevine). The ancient practices of pruning, for example, are critically important for annual growth and fruit quality, as well as for disease management and crop loss reduction – pruning is one age-old means for suppression of multiple diseases in such crops.

Designing plant shapes for a purpose: plant ideotypes

The design of plant ideotypes must have started with the domestication of crop plants. This has been a slow process in agricultural history, involving farmers' guided evolutionary efforts over thousand generations of plant improvement cycles. Plant ideotypes are today typically the result of a plant breeder's vision, with massive consequences, which also concern plant health and crop losses. Examples include the semi-dwarf varieties of wheat and rice, which were the foundation of the Green Revolution, or the design of a new rice plant type for the irrigated environments of Asia (**Figure 6.1.a.2**). Such choices, based on the strategic vision of possible agricultural futures by few gifted scientists, concern many millions of hectares, leading to major changes in crop performances, large consequences for societies and food security, as well as for the environment, as well as, for plant diseases and the crop losses they cause. It may be that future choices will be more targeted and tailored for specific environments and needs, using technologies such as gene editing.

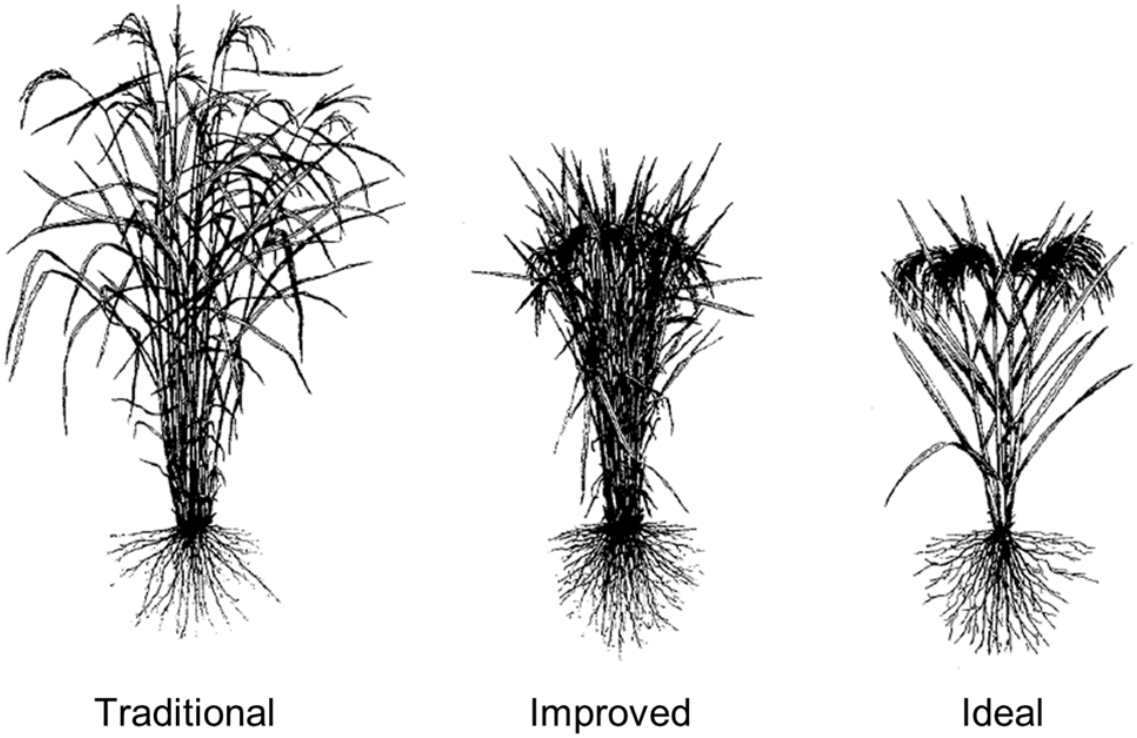


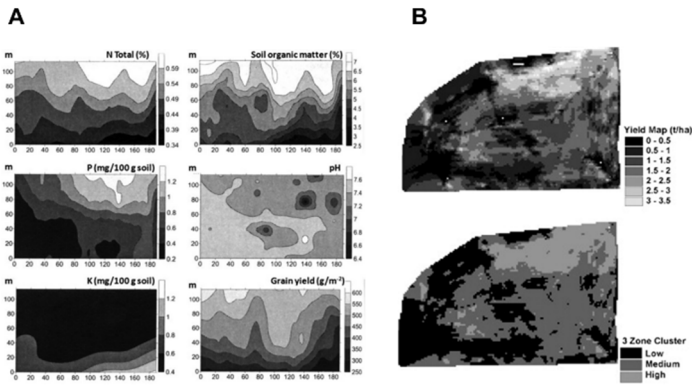
Fig. 6.1.a.2. A breeders' vision for an ideal rice ideotype for the irrigated rice-lands of Asia (Source: Khush, 1995).

Box 6.1.b – Within-field spatial variation of crop stand environments and performances

Spatial variability of soil properties and crop growth

The variability in soil properties and the associated crop growth and crop yield is the subject of a considerable amount of literature. Examples are shown in **Fig. 6.1.b.1** for oats in Germany and wheat in Australia.

Fig. 6.1.b.1. Examples of within-field variability of soil properties and crop yield.



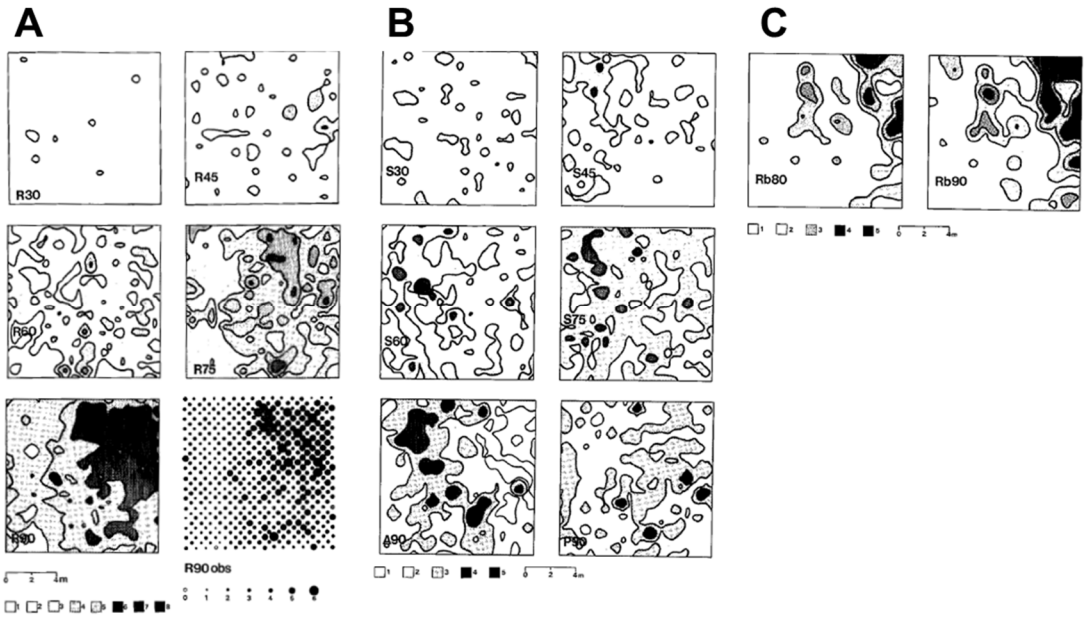
A: Spatial patterns of kriged estimates of selected soil parameters and oat grain yield in yield (g m−2) in Gränichen. In x and y direction distance is in meters (m). P = Soil-test P, expressed as P2O5, K = Soil-test K, expressed as K2O. (Source: Hausherr Lüder et al., 2018)

B: Within-field variability of wheat yield in Western Australia. Example of a (top) yield map, and (bottom) clustered yield map with three zones. (Source: Robertson et al., 2008)

Spatial variability of plant disease intensity

Considerable spatial variability of plant disease intensity is also commonly observed in crop stand. Spatial variability of plant disease intensity is related to a number of possible causes, including weather factors, the location of disease inoculum sources, crop stand structure, growth, and physiology, as well as (**Fig. 6.1.b.2**), as here, the simultaneous occurrence of multiple plant diseases.

Figure 6.1.b.2. Within-field variation of intensity in groundnut diseases (Source: Lannou and Savary, 1991).



A. Groundnut rust severity. Maps derived from observation of 481 plants. Entries (R30, …, R90) indicate assessment dates in days after sowing (das). Severity (%) isopaths are: 1: 0-0.5; 2: 0.5-2.5; 3: 2.5-7; 4: 7-20; 5: 20-45; 6: 45-60 7: 60-90%; and 8: 90- 100%. Two maps for t = 90 das are given, from automatic mapping (R90, left) and actual observations (R90 obs, right). For R90 obs, rust severity classes (0 to 6) are shown by dots of increasing size.

B. Severities of groundnut leaf spots. Maps are derived from observation of 481 plants. Cumulative severities are given from 30 das (S30) to 75 das (S75). Early leaf spot (A90) and late leaf spot (P90) are mapped for day 90. Severity (%) isopaths are: 1: 0-0.4%; 2: 0.4-2.0; 3: 2.0-6.0; 4: 6.0-15; and 5: 15-100%.

C. Intensity of Rhizoctonia blight. Maps are derived from 225 quadrats of four individual plants 80 das (Rb80) and 90 das (Rb90). Intensity is expressed as frequency of infected plants per quadrat. Isopaths are: 1: 0; 2: 1; 3: 2; 4: 3; 5: 4 plants infected per four-plant quadrat.

6.2. The disease portfolio

In their *Introduction to Plant Disease Epidemiology* (1990), Campbell and Madden state: "*The assessment of disease present at a given time is at the cornerstone of statistical analysis of the data, modelling efforts, and interpretation of pathosystem phenomena*." These authors also emphasise that the assessment of plant disease "*is one of the most important and often most difficult tasks in plant disease epidemiology*" (Campbell and Madden, 1990, p 107). What follows is offered as a guide to concepts and to the methods most frequently used to quantify disease in a host plant population. The choice of methods will be discussed. Challenges are encountered to undertake such effort; these include the labour force available, the costs entailed (training, transportation, time spent in measurement), and the actual efforts spent in data collection, sometimes under harsh conditions. At this stage it suffices to say that, while flexibility exists in the choice of methods, objectives must guide such choices. These include: the overall representativeness of the collected data, the ability to repeat and report the methods used, the accuracy of the data collected, and the precision that such data have.

The quantity of disease occurring in the host population is referred to as *disease intensity*. Disease intensity, in turn, may be expressed in terms of *disease incidence* or in terms of *disease severity*: the choice between these two metrics depends, first, on the nature of the disease considered, and second, on the anticipated use of data.

Disease incidence is defined as the proportion of plant units (plants or plant parts) that are diseased in a sample, irrespective of their individual disease severity (Kranz, 1988; see below for the definition of disease severity). The sample, in turn, may be: (1) plants chosen at random in a crop stand; (2) plant organs (roots, stems, leaves and leaf-like organs, or fruits) in a sample of organs, either directly selected at random in a host population (or crop stand), or chosen within a sub-set of selected plants (nested sampling, as for instance: fruits in a set of trees in an orchard, or leaves of plants randomly chosen in a crop). One then speaks of incidence at the plant scale in the first case or of incidence at the organ scale in the second case.

Disease severity is the fraction of area or volume that is diseased (Campbell and Madden, 1990; Kranz, 1988). Disease severity may thus be, e.g., the fraction or percentage of diseased leaf area, or of root area, or of fruit volume or area. Disease incidence, on the other hand, is based on counts of diseased vs. healthy organs: disease incidence refers to the fraction or percentage of diseased organs (e.g., of leaves, roots, fruits, plants).

A third quantitative measure of disease intensity is *disease prevalence*, the proportion of host populations that are diseased in a landscape, as, e.g., the proportion of fields that are diseased in a given area. Zadoks and Schein (1979) warn against the use of this measurement, because the distinction between "diseased" and "healthy" may be subjective (i.e., may depend on the observer), especially at very low disease levels. Disease may also be undetectable, and yet cause crop losses. Yet, many countries today report disease intensity in fraction of cultivated area (e.g., in a given administrative area) that is diseased. From the ecological perspective and at a scale larger than the individual plot in a given experiment, or the individual field in a landscape, one nevertheless should consider disease incidence as a relevant metric, if strictly defined operationally (including, e.g., the stage of host plant development, and the technology used to detect disease).

Disease incidence and disease severity are quantitative measures. They enable a wide array of powerful, hypothesis-testing or inferential, statistical methods. They are especially well-suited for experimental research, which constitutes the backbone of research dealing with crop losses, addressing, fully or in part, purposes 1 (Priorities for disease management), 2 and 3 (Research priorities for disease management), 4 (Plant breeding), and 5 (Chemical and biological control), and contributing as well to purposes 6 (Overall priorities in strategies for disease management), and 7 and 8 (Future research priorities for disease management) of **Table 2.2**. For these reasons, along with the necessity of quantitative, reliable, comparable, disease intensity measurements, seeking the use of quantitative

methods for measuring disease intensity is a priority, in plant pathology in general, and the quantification of crop losses caused by disease, in particular.

However, other forms of data collection exist in the field of crop loss assessment, which are not quantitative. Descriptive scales, which are briefly addressed here, constitute a class of disease intensity measurement tool which departs from the quantitative approach.

Table 6.2A illustrates an early example of a descriptive scale used by plant pathologists (British Mycological Society, 1947) for the assessment of disease intensity of potato late blight at the plot or field scale. This scale entails observation of leaves, leaflets, and stems; approximate counts of lesions per leaf or leaflet; the overall colour of the field; and its smell. This scale addresses the whole crop stand (but provision can be made to account for disease foci, such as, e.g., 1 + pf25, meaning an overall rating of 1%, however with a rating of 25% in the primary focus area). Similarly, **Table 6.2B** (Campbell and Madden, 1990) is an example of a qualitative scale for use in plant breeding to assess the intensity of the Maize Dwarf Mosaic and Maize Chlorotic Dwarf viruses syndrome (1 to 9 scales are commonplace in plant breeding practice). Use of this scale generates a qualitative, ordinal, variable. This scale refers simultaneously to foliage colour (mottling, chlorosis, and in general, discoloration), to plant size and therefore growth (stunting, collapsing of plant), and to harvestable plant parts (ear size, ear absence). As does the old potato late blight scale, this scale also focuses at the plot or crop stand scale.

Irrespective of other considerations (precision, accuracy, and reproducibility), a variable generated by the use of such descriptive rating scales cannot be analysed with conventional methods that are applied to continuous, quantitative, variables. However, strong cases have been made for the possibility of analysing and interpreting qualitative data (**Box 6.2a**).

Rather than tabulated qualitative descriptions, however, most of the assessments of disease severity are done using pictorial aids. Thus, much research in field plant pathology deals with the assessment of disease severity (Kranz, 1988) through the use of disease severity assessment scales. Disease severity assessment scales have been developed in many plant-disease systems, on a range of plant tissues, including tubers, stems, cereal heads, and foliage. The latter (see examples in Box 6.2b and Fig. 6.2b) has, in particular, received intense attention by multiple investigators. In this respect, the disease assessment scales (or assessment keys) developed by Clive James (1971) on an array of plant tissues for multiple plant diseases constitute till today a key reference. As discussed in Kranz (1988), these scales have the properties (1) of including a limited number of levels or classes of disease severity, making them easy to use, (2) of having more classes at low levels of severity, enabling a good precision of severity measurement at severity levels that are more relevant on both the epidemiological and crop yield reduction standpoints, and (3) of being carefully crafted images of the observer's experience of the disease symptoms appearance under field conditions – they constitute syntheses of the disease portfolios.

Hundreds of disease assessment scales have been developed over the years by plant pathologists. Only an overview can be provided here. Disease assessment scales are visual aids to conduct field observations (observations may also be made with these scales in controlled-experiment conditions – this, actually, would be most advisable, enabling the linkage between controlled-environment and field-condition research). The scales (or "keys" as called by Clive James, 1971) are intended to generate data that are standardised over successive measurements or over different experiments by the same observer, over different observers in the same or different crop stands, over different teams of observers working on the same disease at different locations. They also are devised in such ways that the resulting disease severity measurement be both accurate (leading to computing a mean observed severity that is close to the true mean severity) and precise (leading to limited variation around the true mean severity; Campbell and Madden, 1990).

The measurement of disease severity addresses the lowest, most detailed, level of hierarchy (see **Figure 6.3**) that a field plant pathologist considers. Therefore, these assessment scales must not be

considered in isolation from the higher levels of hierarchy of disease and crop loss assessment, which they are meant to document. This is why a disease assessment scale needs to be accompanied by instructions regarding the best way to use it. These instructions may concern the spatial, horizontal, distribution of disease in a crop stand (as in the case of late blight below), the spatial, vertical, distribution of disease (as in the case of groundnut rust below), or again the frequency with which, or the crop development stages at which, disease severity measurements should be taken. For instance, potato late blight epidemics in Western Europe and groundnut rust epidemics in West Africa are generally considered focal and general, respectively, in their structure. Epidemics may vary in their spatial structure as they evolve, as in the case of stripe (yellow) rust Western Europe (whether that is also true, e.g., in South Asia remains to be shown). The spatial structure of disease matters in the proper estimate of yield losses caused by plant disease (Hughes, 1988). Examples of disease severity assessment scales are provided in **Box 6.2b**; this topic is taken up again later in this report with additional resources.

Table 6.2. Examples of descriptive scales for disease intensity measurement

A. Field key for the assessment of intensity of potato late blight at the field (plot) scale

Blight (%)	Description
0	Not seen on field.
0.1	Only a few plants affected here and there; up to 1 or 2 spots in 12 yard's radius.
1	Up to 10 spots per plant, or general light spotting.
5	About 50 spots per plant, or up to 1 leaflet in 10 attacked.
25	Nearly every leaflet with lesions, plants still retaining normal form; field may smell of blight but looks green, although every plant is affected.
50	Every plant affected and about ½ of leaf area destroyed by blight: field looks green flecked with brown.
75	About ¾ of leaf area destroyed by blight: field looks neither predominantly brown nor green. In some varieties the youngest leaves escape infection so that green is more conspicuous than in varieties like King Edward, which commonly shows severe shoot infection.
95	Only a few leaves left green but stems green.
100	All leaves dead, stems dead or dying.

B. Rating scale for maize plants infected by Maize Dwarf Mosaic Virus and/or Maize Chlorotic Dwarf Virus

Code	Description
1	No apparent symptoms.
2	Top two or three leaves mottled, no stunting.
3	Entire plant above the ear mottled and/or discoloured; no evident stunting.
4	Chlorosis and/or discolouration above the ear; some stunting.
5	Leaves above the ear discoloured; plants stunted and ear reduced in size.
6	Upper three-quarters of plant chlorotic and/or discoloured; plant stunted and ear reduced in size.
7	Entire plant discoloured and stunted; small ear.
8	Entire plant discoloured and stunted; no ear produced.
9	Plant completely collapsed; no ear.

Sources: A: British Mycological Society, 1947 (cited in Zadoks and Schein, 1979, p. 255); B: Campbell and Madden, 1990 (p. 122). Scale B is intended for use 3 weeks after flowering.

Box 6.2a – Statistical methods for analysing and interpreting qualitative data in a quantitative way

Much of the plant pathological disease information actually collected is qualitative. For instance, the collection of disease intensity data generally follows pre-determined classes, which are successive categories of increasing levels of disease intensity described in a qualitative or semi-quantitative way: this is an example of qualitative ordinal data. McCool et al. (1986) highlighted the possibility of using bivariate frequency distributions (i.e., contingency tables), where counts of individuals associated with the successive levels of disease intensity in separate populations are considered (e.g., two or several varieties, from susceptible to disease to more resistant; different levels of fertiliser; or again successive levels of chemical protection). A contingency table enables the calculation of a chi-square value, which in turn (under simple assumptions; McCool et al. 1986; Savary et al. 1995) allows the testing of independence of the factor considered (varieties, fertiliser input, or chemical protection) with disease intensity levels: if such conditions are met a sufficiently large Chi-square value then enables rejection of that hypothesis at a given level of probability, that is to say, rejecting the (null) hypothesis that varieties, fertiliser input, or chemical protection have no relationship with the observed levels of disease intensity.

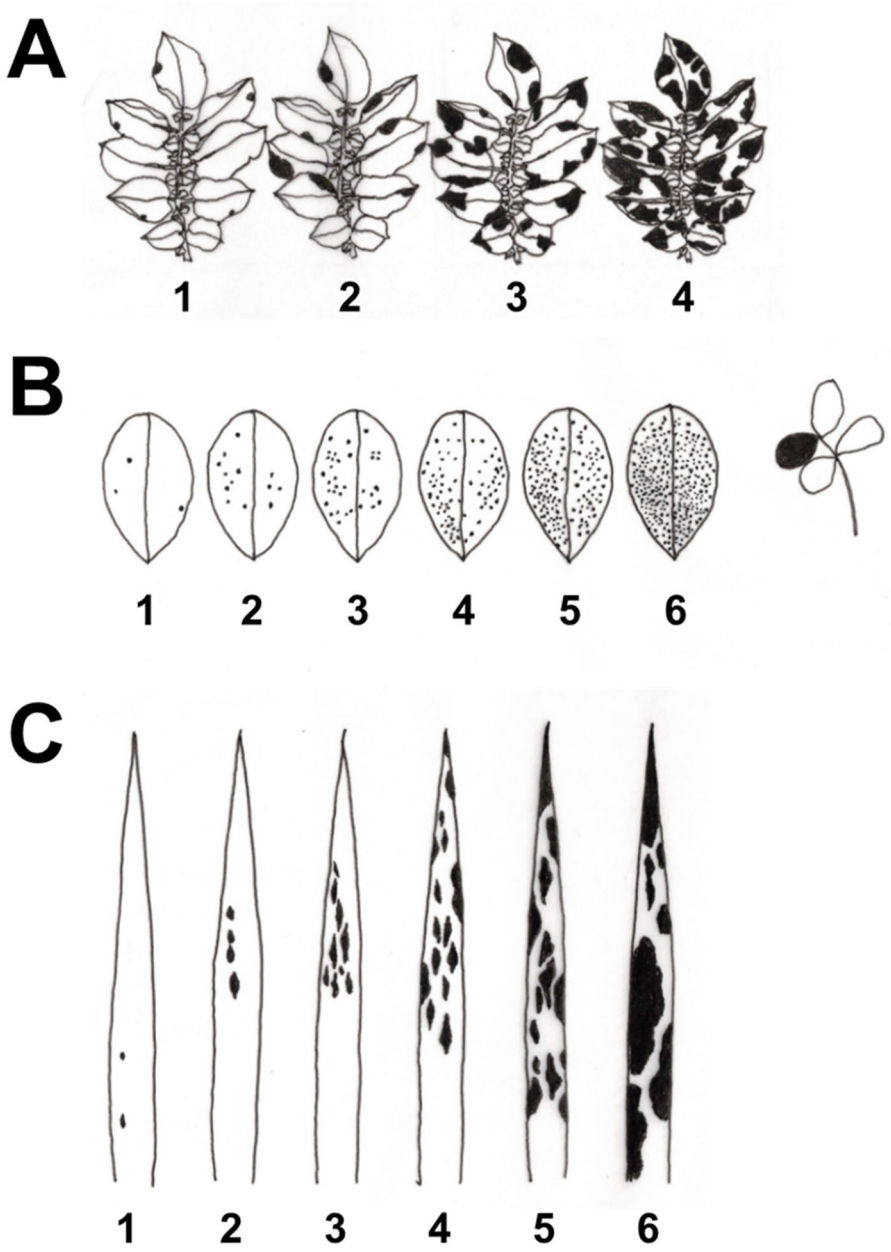
Use of categorical data in plant pathology (Savary et al. 1995) takes its full relevance when plant pathologists consider variables that inherently are qualitative. A plant genotype, a pattern of crop management (e.g., conventional or organic), a method of crop establishment (as, in irrigated rice, transplanted or direct-seeded) are typical of variables that are qualitative and cannot be ranked: a plant genotype, a crop management, or a crop establishment, is not larger, or heavier, than another. Such variables are thus termed cardinal variables, referring to systems element that inherently define them. Among populations of fields, the approximate (i.e., categorised) dates of crop establishment (relative to the mean crop establishment in a landscape: e.g., “early”, “average”, “late”), the amounts of fertiliser inputs (e.g., “high”, “average”, “low”), or the approximate durations of farmer’s labour (e.g., “long”, “moderate”, “fast”), may in turn be examples of qualitative variables that can be ranked. Such information becomes paramount in the analysis of plant disease epidemics, and therefore in the analysis of crop losses if the scale chosen is that of the agrosystem or landscape. A formal statistical analysis at such scales needs to mobilise such information. Multivariate, non-parametric, methods that enable considering heterogeneous data (quantitative, qualitative-cardinal, qualitative-ordinal), and which do not entail unrealistically restrictive distributional hypotheses, exist. This is addressed again when considering surveys in farmers’ fields.

Box 6.2b – Examples of disease severity assessment scales

Three examples of disease assessment scales on the foliage are provided here as illustrations. In each scale, severity values are expressed as % of the maximum possible severity. Observable severity levels are represented by successive categorised levels (0, 1, …, n), each of them referring to the median (mid-point value) of severity within each level.

In most foliage-infecting necrotrophic pathogens, the maximum severity is taken as the total area of a leaf. However, severity almost never reaches the total area of a leaf: complete necrosis of plant organ (leaf) sets in at severities that seldom exceed 60% of the organ area, so that severities exceeding this threshold are unobserved. This is why, in the case of potato late blight or of septoria blotch of wheat, the scale stops at mid-point values of 50 and 60%, respectively. By contrast, in the case of biotrophic pathogens such as rusts, 100% severity may be observed. Such a severity however corresponds to a much smaller fraction of leaf area visibly covered by pustules – about 30% of the leaf area. This is because of the actual size of a rust lesion, which includes the tissues that are colonised and exploited by the pathogen, and which exceeds the size of the visible pustule.

Fig. 6.2.b. Examples of foliage plant disease severity assessment scales



A. Disease severity assessment scale for potato late blight (redrawn from Clive James, 1971)

1: 1%; 2: 10%; 3: 25%; 4: 50% leaf area covered by lesions. This scale is intended for use in disease foci in the early stage of epidemics. A crop is to be surveyed for disease foci, when the date of initial infection is recorded. Disease severity at the crop scale involves: (1) an estimation of the average number of disease foci per unit area (e.g., ha); (2) a determination of the average area of foci; leading to (3) an estimation of the fraction area covered by foci where (4) within-foci disease severity is assessed using this scale.

B. Disease severity assessment scale for groundnut rust (redrawn from Savary, 1987).

1: 1.2%; 2: 5.1%; 3: 13.7; 4: 29.3%; 5: 58.6%; 6:100% leaflet area covered by pustules, corresponding to 0.36; 1.56; 4.24; 9.09; 18.2; 31.0 pustules.cm-2. Note the decreasing size of pustules as pustule density increases. This scale is intended for use in a random sample of individual plants (general epidemic) within a crop stand, and applied at several (usually, three) layers of the crop canopy.

C. Disease severity assessment scale for septoria leaf blotch on wheat (redrawn from Kranz, 1988).

1: 0.5%; 2: 2.0%; 3: 6.0; 4: 6%; 5: 30%; 6: 60% leaf area covered by lesions. This scale is intended for use in a random sample of individual plants (general epidemic) within a crop stand.

6.3. Levels of hierarchy in plant disease assessment

Methods for assessing disease depend on the nature of the host plant population (e.g., annual or perennial), on attributes of host plant populations, and on attributes of the host-pathogen interaction, i.e., of disease at the population scale. **Figure 6.3** provides an overview on how choices can be made to conduct disease assessments that enable assessing crop losses. **Fig. 6.3** is inspired by systems where disease of the aerial plant parts is the focus of interest, and in particular, the foliage. Similar diagrams could easily be developed for systems where the focus is root systems, or fruits, or underground harvestable plant parts (pods, roots, or tubers).

A main feature of the overall strategy for disease assessment is that a hierarchy (as in any ecosystem) is involved. In agricultural systems, that hierarchy includes plants, each being part of a human-managed population (a crop stand, a field, or an orchard), which in turn belongs to a landscape (agrosystem). The strategy needs to start with the latter.

Each level of the hierarchy involves requirements to be met in order to achieve disease measurements that correspond to the considered hierarchy level: prevalence at the landscape, incidence at the field scale, and severity or incidence (at the organ scale) at the individual plant (or tree) level. These requirements, in turn, need to account for attributes that are specific to the considered scale. Examples are given in **Fig. 6.3**:

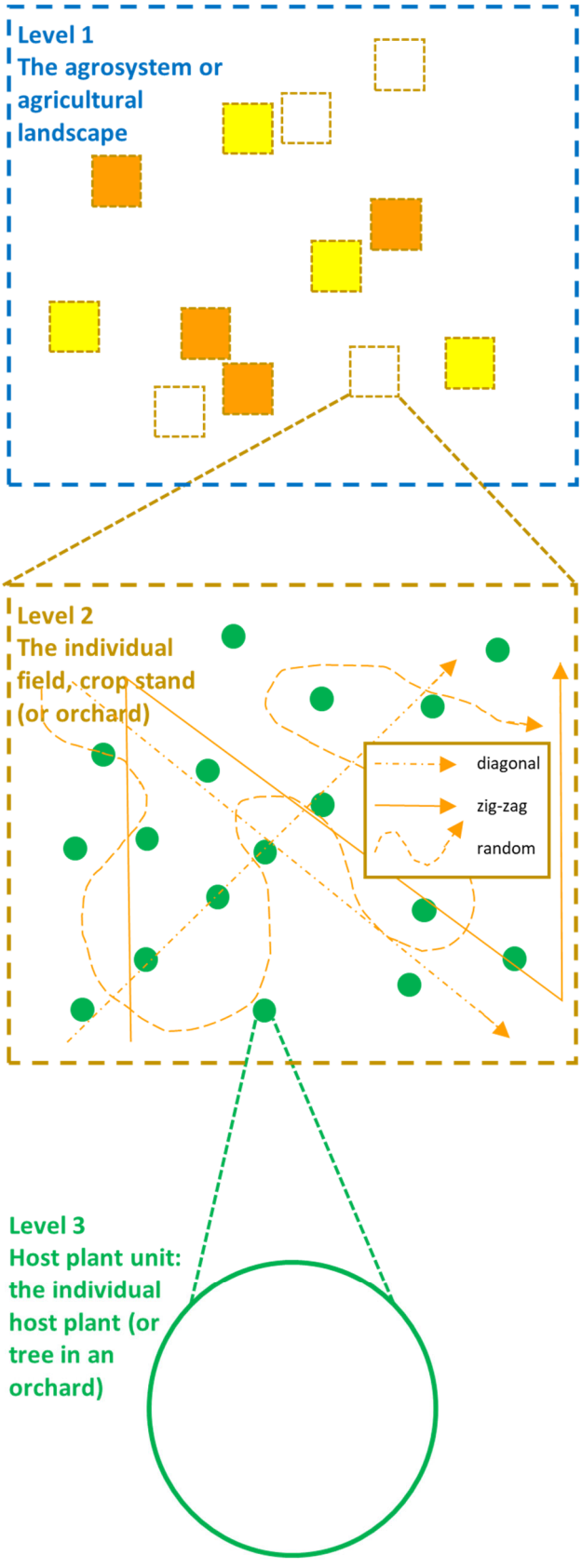
- Attributes such as crop establishment date, crop variety, crop management, or inputs, of course pertain to each individual field. These attributes, however, vary across an agricultural landscape, making each field (or crop stand, or plantation) similar to some others and dissimilar to other fields. Such differences strongly influence (1) disease levels, (2) crop performances, and therefore (3) crop losses. As a result, the sampling strategy at the landscape level depends on the diversity that the agricultural landscape contains in terms of such attributes.
- Within each crop stand (field, orchard), the development stage, and the status of plant growth, are important attributes to consider, among others. Note that the assessment of the development stage of a crop implies the use of a development scale which belongs to the host portfolio.
- Within each host plant, attributes include the number of stems, the total number of leaves produced, and the number of live and dead leaves. Fruits, if the focus of the assessment, would be addressed in a similar way. In perennials, exposure of branches to sunlight may be important: that too needs incorporation in the sampling strategy at the plant scale.

Disease assessment involves the consideration of nested scales shown in **Fig. 6.3** as levels. In order to derive disease assessment measurements, each level of the strategy entails a specific sampling strategy: there has to be a sampling strategy at the (1) landscape, (2) field, and (3) plant scales. Note that these strategies are not limited to just acquiring disease data, but other data as well, which pertain to attributes of the next-above scale (**Fig. 6.3**). In particular, information pertaining to the second and third levels (individual field and individual plant) is indispensable to the computation of disease intensities and the estimation of yield losses.

Sampling strategies, starting from the landscape (agrosystem) scale down to the individual plant unit are schematically illustrated in **Fig. 6.3**. Several authors have compared different paths within a crop stand to identify individual plants to be considered in assessments. These paths may roughly follow a cross, a zig-zag, or a random shape. Statistical considerations are at play in such choice, but convenience, effort, and labour time too are to be factored-in.

The frequency and timing of disease injury assessments also depends on the nature of the injury, and on its evolution during the crop cycle (i.e., on the speed of the plant disease epidemic). Injuries affecting harvested organs are in general assessed only once before harvest. Other types of injuries are in general assessed several (3-7) times, during a period that covers the span of epidemics. At each assessment, disease injury assessments need to be accompanied by assessments of the crop development stage.

Figure 6.3. Levels of hierarchy in disease and crop loss assessment



Relevant attributes to document (examples)
- preceding crop (or fallow period duration)
- tillage practices
- crop establishment date
- crop establishment method
- cultivar (perennials: cutting variety)
- inputs: nature, quantity, dates

Required:
- sampling strategy at the landscape or agrosystem scale
- representativeness: the sampling strategy may have to account for the diversity in attributes of individual crop stands (typology of cultivated fields or crop stands)

Target outcome variables
- disease prevalence
- crop performances (incl. crop yield)

Relevant attributes to document (examples)
- field size
- crop establishment and geometry (e.g., levees, flat, row arrangement)
- cultivar (perennials: cutting variety)
- inputs: nature, quantity, dates
- crop density (intercropping)
- overall state of plant growth
- spatial crop heterogeneity
- spatial disease distribution heterogeneity

Required:
- sampling strategy at the field scale (multiple designs)

Target outcome variables
- crop development stage
- disease incidence at the plant (host plant unit) scale

Relevant attributes to document (examples)
- characteristics of plant architecture
- number of nodes (perennials), leaves
- number of live and dead leaves per axis (main branches, main axis)
- numbers of main roots and their positioning

Required:
- sampling strategy at the plant (tree, root system) scale

Target outcome variables
- disease severity (if applicable: roots, fruits and harvestable plant parts, foliage)
- disease incidence (if applicable, at the relevant scale: branch, tiller, plant axes)
- if applicable: disease-associated defoliation

Caption for Figure 6.3:

Crop loss assessment involves considering three main, nested levels of hierarchy. Two sets of elements are to be assessed: disease intensity and crop losses. This diagram emphasises methods for the former element, disease assessment.

Each level entails a sampling strategy which is specific of that level, of the objective of investigations, and of the pathosystem considered. The sampling strategy also integrates information from the host portfolio and from the disease portfolio. Each level also entails consideration of attributes of the plant system at that level. These attributes guide assessment methods at the next lowest level of the hierarchy, including the disease (and crop loss) assessment methods used. These attributes also provide a basis for the analysis of disease and crop loss data.

Disease *prevalence*, *incidence*, and *severity* are, respectively, the typical target disease information to be collected at the agrosystem (Level 1), field (or perennial crop stand; Level 2), and host plant unit level (Level 3) of the hierarchy.

Disease assessment at the host plant unit level may involve both disease severity and incidence, or either one of these. An array of different types of incidence quantifications may also be considered, which address different levels of hierarchy within the structure of the host plant unit. One may, for example, consider at the host plant unit level:

On aerial plant tissues of annual crops: (1) axes or stems, (2) canopy layers (e.g., upper, middle, lower, and (3) leaves or fruits for diseases of the aerial part of host plants;

On aerial plant tissues of perennial crops, in addition to the above: (4) canopy parts with different orientation toward sun radiation (e.g., East vs West), (5) segment of twigs (e.g., earlier seasons twig growth vs within season twig growth

On underground tissues: (1) main roots, (2) strata of root systems (e.g., shallow, pivot, and other roots), or (3) segment of root (diseases of the underground part of host plants).

This framework can also be applied to experimental trials by replacing “landscape” (Level 1) by “trial”, where the sampling strategy is replaced by the experimental design of each trial. Level 2 then represents experimental plots within trials**.**

6.4. Metrics and instruments for disease assessment

The metrics and the instruments used to measure disease injuries vary depending on the type of injury considered. This is summarised in **Table 6.4**.

6.4.1. Systemic or whole-plant disease

In the case of systemic or whole plant diseases (e.g., barley yellow dwarf, cassava mosaic, or citrus tristeza),

- The metric commonly used is disease incidence (at the population or crop stand scale); this implies counts of healthy and diseased individuals;
- The instrument commonly used is visual examination, and sometimes a disease scale based on symptoms;
- The sampling procedure must account for the spatial heterogeneity of disease distribution at the population or crop stand scale.

6.4.2. Diseases of the root system

In the case of diseases of the root system (e.g., many root rot diseases on perennials caused by *Phytophthora cinnamomi*, wheat take-all, or the *Aphanomyces euteiches* root rot of pea, and many nematode injuries),

- Destructive samplings are necessary;
- The metric commonly used is disease severity (typically, the fraction of diseased root length);
- Instruments often used are visual examination and a disease severity scale;
- Two (nested) sampling schemes are necessary: (1) at the plant population scale to account for the spatial heterogeneity of disease distribution at that scale, and (2) at the root system scale to address the within-root system heterogeneity.

6.4.3. Diseases of underground harvestable tissues: roots and tubers

In the case of diseases of underground harvestable roots or tubers (e.g., Diplodia rot of cassava, or bacterial soft rot of potato),

- Samplings at harvest are necessary;
- Metrics commonly used are disease incidence or severity (with a severity scale);
- The instrument commonly used is visual examination and sometimes a disease severity scale.

6.4.4. Diseases of the vegetative aerial tissues

In the case of the many (mostly bacterial, oomycete and fungal) diseases affecting the foliage (leaf blades, ligules, and sheaths),

- The metric commonly used is disease severity (fraction of area of foliage units, e.g., leaves);
- Instruments often used are visual examination and a disease severity scale;
- Two (nested) sampling schemes are necessary: (1) at the plant population scale to account for the spatial heterogeneity of disease distribution at that scale, and (2) at the scale of the foliage of a plant unit to address the within-plant unit heterogeneity. For example, sampling at the plant unit scale may be consist of assessing leaf 3 (from the apex), leaf 5, and last [live] leaf on the main plant axes (shoot, branches, or tillers) of each plant unit (see below, Fig. 7.2.2).

6.4.5. Diseases of fresh above-ground harvestable fleshy tissues: fruits

Typical examples are apple or pear scabs, or several tomato diseases, or again dark spot of cabbage heads:

- Sampling is conducted at harvest;
- The metric may be disease severity at the harvested plant unit scale;

- The instrument then used is visual examination and a disease severity scale;
- in which case two (nested) sampling schemes are necessary: (1) at the population of harvested plant units, and (2) at the scale of the individual harvested plant unit.

6.4.6. Diseases of above-ground harvestable tissues: cereal heads, panicles, and cobs

In the case of injuries on cereal heads, panicles, and cobs, such as, e.g. Fusarium head blight of barley and wheat, or false smut of rice, and multiple diseases affecting maize cobs,

- The metric commonly used is disease incidence at whole harvestable part (heads, panicles, or cobs), or at the spikelet or grain scales (which also may be referred to as a severity);
- Instruments often used are visual examination and a disease severity scale (or its equivalent, as, e.g., fractions of grains or of spikelets affected);
- Two (nested) sampling schemes are necessary: (1) at the plant population scale to account for the spatial heterogeneity of disease distribution at that scale, and (2) at the scale of the harvestable plant tissue unit to address the within-unit heterogeneity.

The case of fusarium head blight is an especially important and difficult case: important because of the production of mycotoxins, and difficult because of the complex association between visible symptoms and mycotoxin production.

Table 6.4. Methods and metrics for injury assessment

Type of injury	**Systemic injury or infection affecting whole-plant physiology**	**Injury with multiple localised lesions of the root system**	**Injury with lesions on underground harvestable tissues: roots and tubers**	**Injury with multiple localised lesions on the vegetative aerial tissues**	**Injuries on fresh above-ground harvestable fleshy tissues: fruits**	**Injuries on dry above-ground harvestable tissues: cereal heads, panicles, and cobs**
Examples	Many viral diseases of annual plants; Vascular diseases of annual or perennial plants	Many (fungal, bacterial) diseases causing necrotic lesions on roots	Rots of underground roots or tuber; some diseases of underground fruits	Many leaf-spotting pathogens	Many diseases of fleshy fruits	Many diseases of cereal heads and panicles
Type of damage mechanisms induced	Stand reducers; Photosynthetic rate reducers	Tissue consumers; Photosynthetic rate reducers; Turgor reducers	Harvest destroyers	Light stealers; Leaf senescence accelerators; Photosynthetic rate reducers	Harvest destroyers	Harvest destroyers
Occurrence of losses in quality	Possible	No	Yes: Appearance; Chemical content; Mycotoxins	No	Yes: Appearance	Possible: Mycotoxins
Most frequent metrics	Incidence (plant scale)	Severity (at the root site scale)	Incidence (at the root scale) or severity (at the root or tuber site scale)	Severity (at the leaf, sheath, or stem scale)	Severity (at the fruit scale)	Incidence (at the organ scale) or severity (at the site scale)
Measurement instrument	Counts of diseased individual plant units in a sample	Severity assessment scale	Severity assessment scale, or Counts of individuals in a sample	Severity assessment scale	Severity assessment scale	Severity assessment scale, or Counts of individuals in a sample
Remarks	• Required: sampling scheme at the plant population scale	• Destructive sampling • Required: sampling schemes • (1) at the plant population scale • (2) at the root system scale	• Measurement at harvest • Required: sampling schemes at the plant population scale	• Required: sampling schemes • (1) at the plant population scale • (2) at the foliage system scale	• Measurement at harvest • Required: sampling schemes • (1) at the plant population scale • (2) within fruiting plant	• Measurement at harvest • Required: sampling schemes • (1) at the plant population scale • (2) within fruiting organs

6.5. Remarks on the assessment of disease severity

The measurement of disease severity, if its aim is to understand crop (yield) loss, quite differs conceptually from the measurement of disease severity that would be conducted for pure epidemiological purposes. The latter, plant disease epidemiology, pays for instance considerable attention to the notion of sporulating area, especially in the case of studies on fungal foliar diseases, in the case of diseases caused by (semi-)necrotrophic pathogens (e.g., Septoria-like diseases of wheat; Rapilly, 1983) or in the case of diseases caused by biotrophs (e.g., barley leaf rust; Teng and Close, 1978). Such questions, however, are not within the scope of yield loss analysis, where instead the focus is on the nature of the injuries (and the associated damage mechanisms) that are caused by disease lesions on the foliage. Lesions on the foliage (1) reduce radiation interception (this is the "light stealer" mechanism of **Table 4.3**, a reduction of radiation interception); lesions on the foliage may also (2) reduce the physiological efficiency of the radiation which is intercepted (i.e., reduce the radiation use efficiency, corresponding to the "assimilate sapper" mechanism of **Table 4.3**), and they often (3) contribute to leaf senescence (another form of reduction of radiation interception, corresponding to the "leaf senescence accelerator" mechanism of **Table 4.3**).

The concept of virtual lesion may be seen as an expansion of the "light stealer" mechanism. The physiological influence of a lesion on the foliage may expand far beyond the limits of what can be seen – beyond the limits of the visible leaf lesion. This may be because the physiology of tissues lying beyond the observable limits of a lesion is affected by the pathogen, reducing their photosynthetic activity, and which possibly may lead to cell death. Such is the case in the foliar form of rice blast (leaf blast), which is the disease from which the virtual lesion concept originates; Bastiaans 1991). In other pathogens, this physiological influence of a lesion beyond its observable limits may also result from the fact that the pathogen alters the anabolism of leaf tissues, which produce carbohydrates that are up-taken by haustoria formed by intercellular hyphae of the biotroph fungus. These carbohydrates then enable the production of propagules (as in rusts of dicots and cereals). In the latter case, "light stealing" is combined with, and even superseded by "assimilate sapping". These examples show that the measure of leaf disease severity only is an indicator of what the true physiological effect of the disease on the host is. Disease severity is quantitative; but it needs to be translated to express what the true injury is.

Considerable effort has been devoted to the measurement of disease severity, especially on the foliage of crop plants, with hundreds of assessment scales developed. This effort was initiated by the seminal texts by Large (1966), and the scales developed later-on by Clive James (1971) constitute the foundations of current methods. A wide array of disease severity scales exist on a number of different types of plant tissues, including stems and sheaths, roots and tubers, leaves, and fruits, for a number of different plant diseases of many crop plants.

The measurement of severity of disease on the foliage can sometimes be extremely challenging. Such is the case of powdery mildew of grapevine, for example: even expert pathologists sometimes have difficulties deciding whether a single leaf is diseased or not, let alone measuring the area covered by the fungus on a given leaf. In such hyper-specialised biotroph pathogens, symptoms are extremely tenuous. In such case, it may be useful to consider incidence at the leaf scale (proportion of infected leaves), which may be less prone to error.

A disease severity assessment scale with many classes may give the impression of achieving higher measurement precision. Experience however shows that the use of such many-class scales is cumbersome in field practice, and that a higher precision at a given organ scale may be achieved at the expense of better measurement accuracy. It is better to achieve a reasonably accurate measurement, even though with relatively low precision, than to achieve very precise measurement with a poor accuracy, that is, a very precise mean figure value which in fact is far from the true severity value. Replication of observations, in a satisfactory number of independent (injury level) replications, within a solid experimental or survey design, is a sound practical approach for field work.

A typical disease severity assessment scale consists of a limited number of categories, usually five to seven, starting with a “no disease” (0) level, followed by increasing levels of disease severity. These levels are represented by observed ideotypes, as Large (1966) suggested, which correspond to the centre (mid-value) of a given severity class. A disease severity scale usually is not linear. Instead, classes have narrow severity ranges at the lower levels of severity (low disease severity), becoming wider toward the mid-range levels of the scale (medium disease severity), and narrower again at the upper level of the scale (highest severity levels). Over the years, the effort has been widely expanded, with numerous scales for an array of plant diseases (diseases of the foliage representing the bulk of the scales developed). **Box 6.5** provides resources on the topic.

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Box 6.5 – Resources for disease severity measurement: disease severity assessment scales

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7. Frameworks and workflows for crop loss data acquisition: experiments and surveys

7.1. Setting the objectives for data collection

Investigations on host-pathogen interactions at the population level – the reasons why observations are taken at the field (crop stand), orchard, or vineyard scale – can address a wide array of purposes. The purpose of crop loss assessment requires specific observations, however. We start this section by listing some of the most frequent reasons for field collection of disease data. These include:

1. experimentally analyse the dynamics of plant disease in a given host plant population, or compare these dynamics in host plant populations which differ genetically or in terms of the contexts where they are grown (e.g., crop establishment or management); or
2. experimentally analyse crop loss consequences of plant disease epidemics which may have different patterns and may occur at varying crop development stages;
3. assess and interpret patterns of plant health (i.e., multiple diseases, not one disease in isolation, is considered) over time or space at various scales, from the small agricultural region to entire countries or world regions and from a single to multiple successive growing seasons;
4. assess the impacts of overall plant health, and thus account for the occurrence of multiple plant pathogens (and possibly along with an array of harmful organisms to be characterised) over time or space.

Each of these different objectives lead to different approaches (**Fig. 7.1**) and different measurement instruments. The first of these objectives corresponds to pure field-based plant disease epidemiology, and is not addressed in this material. The second objective may concentrate on the individual host plant, leading to the physiological study of the diseased plant (which also is not addressed here), or on the study of the of the diseased population of host plant as a, e.g., a crop stand, or on field-based crop loss experimental research. The third objective implies surveying plant diseases (and crop harmful organisms) and the quantification of the injuries these organisms cause in a range of contexts. If combined with field experimental work, survey work can lead to achieving the fourth objective.

While crop loss quantification needs to consider populations of host plants in single stands, many concepts pertaining to the individual plant scale are relevant in terms of processes (i.e., injury) and their dynamics. Process-based simulation modelling, which is not addressed here, uses the same conceptual basis. Setting aside technical considerations (parameter measurements and model evaluation), this is why research often combines field-based crop loss experiments and simulation modelling.

7.2. Experiments on crop loss assessment

The essence of experimental research on crop loss is the comparison between two crop stands growing under the same environment, which only differ in a single aspect, the occurrence of injury. Key to this effort is a healthy (un-injured) crop stand serving as a reference to crop stands (treatments) where disease develops and causes injury(ies), thus enabling comparison in performances (i.e., crop growth, crop development, biomass of crop yield, quality of crop harvest).

Experimental designs in crop loss studies broadly address two types of questions, which are reflected by the definition of their experimental treatments. The first set of questions (the most frequent) concerns the levels of losses associated with patterns of injuries. Experiments then consider injury dynamics that are artificially made different in their timing and/or their levels, relative to that of the host crop development. This first set of questions leads to producing time-dependent damage functions (i.e., functions relating yield loss to injury level at various crop development stages; Teng

1980; Zadoks, 1985) and the identification of injury levels leading to varying levels of crop losses. The second set of questions pertain to damage functions that may vary with production situations (Rabbinge, 1993), and therefore, with attainable yield.

The first set of questions and experimental designs lead to information that enable tactical, short-term decisions. Among other elements, the information generated leads to quantifying injury thresholds at the crop (e.g., field, orchard) and season scale. Thresholds (e.g., warning, action, economic thresholds; Zadoks, 1985), in turn, are the instruments for reasoning choices enabling disease control action, and so, play a central role in integrated disease management. Addressing the second set of questions leads to data enabling strategic, longer-term decisions pertaining to the cropping system scale, and to choices regarding for example crop management, the deployment of crop varieties and their diversification, the balancing of crop loss risks with levels of agricultural intensification, and research prioritisation.

7.2.1. Overall workflow in crop loss experimental research

There is a broad diversity of (1) agricultural contexts where crop loss experiments are conducted, (2) pathosystems with diverse consequences of diseases on crop performances, and therefore, (3) research questions which need addressing through crop loss experiments. **Figure 7.2.1** is an overview of the workflow typically followed in experiment-based crop loss investigations. The workflow includes four domains where choices are necessary.

Crop loss experiments must be representative of actual agricultural contexts. A first domain (**Fig. 7.2.1 A**) therefore involves the consideration of what farmer's practices actually are. What farmers do involves choices in terms of crop variety (or planting material), of crop establishment methods and date, of crop management in general, within cropping systems where such actions are implemented.

Paramount is also the purpose of agricultural production: there are very large differences in practices, in investments (inputs, labour, knowledge), and values (economic, social, cultural) between, for example, grapevine production for fruit or wine, or between maize production for human food, animal feed, or biofuel. Such differences in purpose are also directly linked with differences in financial crop value, and therefore loss value. Much of this knowledge can be derived from survey data, if available, or otherwise collected anew. Field experience generated by surveys can also provide very valuable information regarding the variability of disease intensity and crop performance in actual agricultural contexts. The type of disease dynamic and the type of injury caused by disease (type of disease 1) inform the ways disease treatments, that is, the levels of injuries, are to be defined (e.g., questions such as: should injury be established artificially or left to spontaneous infections; how should crop development and crop growth be addressed). Knowledge on disease spread and pathogen multiplication (type of disease 2) in turn is necessary to operationally define how un-injured controls are to be established and how injury treatments that are defined *ex-ante* are to be maintained throughout the experiment despite the ability of disease to spread.

The experimental design of crop loss experiments (**Fig. 7.2.1 B**) thus involves treatments (injury levels and un-injured controls) that are operationally defined. Decisions in the experimental design domain must also be made regarding the number of replications and the location(s) where the experiment will be conducted, as well as the number of growing seasons when the experiment needs to be conducted. All these elements derive from the overall knowledge of the experimental context.

The type of crop stand determines to a wide extent the nature of data to be collected (**Fig. 7.2.1 C**). Whether the host plant is perennial or annual, for instance, influences choices regarding sampling patterns in space and time, the host crop development stages that need targeting, and the way disease assessments are to be done.

The fourth domain (**Fig. 7.2.1 D**) is that of sampling methods and measurements. Choices first depend on whether one deals with above-ground or underground injuries; whether injuries affect harvestable plant tissues or not; whether the disease is polycyclic; and whether it is systemic. These

criteria lead to choices in the nature of sampling (destructive or not); in sampling frequency (once or several times); and in sampling timing relative to crop development. These criteria also lead to choices regarding the plant elementary units to be sampled, the choice of disease intensity metric to use (severity or incidence, and if the latter, at which plant tissue scale), and the choice of disease intensity quantification technique.

7.2.2. Experiments in research station

7.2.2.1. Experimental designs

Many experimental designs in crop loss experiments follow conventional designs, with Gomez and Gomez (1984) as a classic source. Designs may involve experimental treatments such as (1) multiple levels of disease injury for a given plant disease; (2) multiple dates of disease onset; (3) combinations of injuries caused by two or more pathogens (and or crop harmful organisms); or (4) multiple levels of attainable crop yields combined with varying levels of injury. Experiments commonly involve at least three replications, and repeating experiments (over successive growing seasons, or at multiple locations, or both) is a basic requirement for reporting.

7.2.2.2. Uninjured control treatments

All crop loss experiments are grounded on controls where no injury occurs, and where the performance of a healthy crop stand is measured. Typically, the performance measured is the yield Y of a crop stand, while controls enable measuring the attainable yield, Ya. Two questions need specific consideration. The first question concerns the size of a crop stand that may be considered suitable to measure yields in actual agricultural contexts. Dimensions exist for a number of plant systems which have been typically used in the literature (e.g., James and Shih, 1973; Walker, 1983), whether perennials (fruit trees, grapevine), field crops, or vegetables. The definition of a minimum size for a crop stand to reasonably measure crop yield implies specific knowledge of the crop ecophysiology in relation with the individual crop plant size. Elementary plots may be small for cereal crops such as wheat, rye, barley, or rice (a few m^2), are larger for other cereals such as maize or sorghum, larger still for potato, and much larger for cassava or plantain.

If the disease studied affects root systems, then individual plot sizes are considerably increased, since assigning areas for within-plot (random, multiple, and sequential) destructive samplings for root examination is required, along with buffer areas to prevent root-to-root growth interference, together with an area dedicated to measurements on final harvest. Crop loss experiments that address soil-borne pathogens and root diseases (as, e.g., in take-all of wheat; Schoeny et al. 2001) may be at least five to ten times larger in area than experiments dealing with diseases of the aerial plant organs.

A second question, which also concerns the definition of the control treatment, is to prevent these control crop stands from being injured. The question becomes very important in the case of diseases that are caused by pathogens with very strong dispersal ability (e.g., viral diseases transmitted by airborne vectors, or aerially dispersed fungal diseases of the foliage). This has been referred to as “inter-plot interference”, which can refer to (1) an excess disease develops in crop stands where it is not wanted, or not yet intended – in the case of treatments with varying time-span of injury (i.e., different epidemic duration), a positive interference, or (2) a deficit of disease intensity occurs, as a result of experimental units that are too small and/or of excessive propagule emigration, a negative interference.

Solution to this problem is often not the use of chemicals, except those which are known to not affect the physiology of the healthy crop stand. For instance, many fungicides have measurable growth-enhancing effects, in addition to their disease-suppressing properties, and should not be used if Ya is not to be artificially increased, leading to an over-estimation of yield losses. Several other approaches have been developed based on epidemiological knowledge of pathogen dispersal in specific pathosystems. A classic option is the use of borders where a non-susceptible host is grown. Another solution derives from the micro-field concept, borrowed from field-based epidemiological research

(Zadoks, 1972; Zadoks and Schein, 1979): a micro-field is (1) a crop stand that is large enough to reproduce the environmental conditions of a cultivated field, but which is small enough so that the desired level of injury (an epidemic) is artificially established, representing the pre-set treatment definition, especially the non-injury, control level, and which (2) is isolated from other micro-fields assigned to different treatments because micro-fields are established in a large, non-susceptible crop, enabling to minimise inter-plot interferences.

7.2.2.3. Treatment definition

Crop loss experiments imply different treatments which all are to be compared to the reference controls. These different treatments are meant to reasonably represent the dynamics of epidemics as they would occur in a field, and the resulting injury they generate. These treatments are often representing several nominal levels of injury. These nominal levels of injury are implemented in a number of ways, a main one being artificial infection directly within a given experimental plot, or the transfer of an artificially infected plant within a plot.

An important case, which reflects the actual context of agriculture, is that of experiments which aim at quantifying the interactions among injuries caused by different diseases (harmful organisms). A classic example is that of potato (Johnson et al., 1986), where different injuries interact, and where the dynamics of injuries interact as well. This occurs because the (manipulated) dynamics of a given epidemic may suppress, or enhance, the dynamics of another epidemic which is also part of the experimental research. While no within-field suitable solution to this problem exists, proper analysis (starting for instance with analysis of covariance) of experimental data involving both the actual, measured, levels of injury within each combination of treatments, and the measurement of resulting crop performance enables to produce extremely valuable results. Experiments involving three or more simultaneous epidemic dynamics can be conducted, too. Their analysis entails the use of multidimensional statistical methods (Savary et al., 2000a).

7.2.2.4. Treatment replication

Whether a crop loss experiment should necessarily follow the conventional design of agronomic experiments is a valid question. If the purpose of the work is aimed at producing a damage function, where successive levels of a given injury can be related to successive levels of crop loss, then, the priority lies with a large number of injury levels, not with a large number of replications of a few levels of injuries (Teng and Gaunt, 1980). This point, combined with the intent of possibly addressing simultaneously (1) multiple injuries, and (2) a range of attainable crop performances, needs to be considered in experimental designs.

7.2.2.5. Varying attainable yields and production situations

The fact that the levels of crop losses, especially of yield losses, may increase, or decrease, with attainable yield is one reflection of the dynamics of interactions between a growing host crop physiology and the dynamics of an injury (e.g., an epidemic or the dynamics of a harmful organism; Savary and Willocquet, 2020). Interactions between attainable yield and injury level on yield losses has far-reaching consequences, since this implies changes in vulnerability of production situations as these evolve.

Contrasting production situations cannot easily be considered as a treatment in factorial on-station field experiments; but attainable yield can be varied experimentally, e.g., by means of different crop, water, and input management. A convenient way to incorporate variable attainable yields in a crop loss experiment is to define “production situation” main statistical units, embedding a range of injury levels (including un-injured controls; Savary et al., 2000a).

Considering changes in attainable yield enables to address questions related to research priorities, and ultimately, to agricultural policies: some changes in production situations, involving, e.g., increases in attainable yield, may lead to crop losses that are not compatible with sustainable

agriculture or sustainable development – unless proper strategic action (e.g., breeding for host plant resistance) is taken.

7.2.2.6. Sampling for disease assessment in experimental plots

Disease assessment has to produce data that properly account for the physiological injury (and not for the state of epidemic dynamics) with which a crop stands actually is confronted to. This representativeness question has typically two scales: that of the injured host plant within a stand, and that of the crop stand as a whole.

At the individual injured host plant, sampling for injury takes very different levels of effort whether dealing with perennial or annual plants. In perennials, considerable efforts may be required (Seem, 1988). An experiment on crop losses caused by coffee rust, for instance, is likely to involve: (1) the level (upper, middle, lower) within a coffee plant canopy, (2) the orientation of branches (N, S, E, W) to be sampled, and (3) the age of leaves (earlier growth and latest flush) to be assessed. Such a stratified sampling necessarily has an implication in data analyses. Three groups of data are to be collected: crop growth (including defoliation or leaf senescence if the focus is on leaf disease), crop development, and disease data (Willocquet, Avelino, and Savary, unpublished).

In annual host plants, and still dealing with diseases of the foliage, a stratified sampling as shown in **Fig. 7.2.2** is usually convenient. This design can be applied in dicots such as groundnut (Savary, 1987) or mustard (Singh et al., 2024), or in cereals such as rice (Savary et al., 2000a). Using the stratified sampling scheme of **Fig. 7.2.2**, where three leaf layers are defined (3rd leaf from apex: L3, 5th leaf: L5; last living leaf at the axis base: LL), allows to quantify disease while crop grows:

- on a two-leaf axis, one leaf (LL) is assessed to represent the axis;
- on a three-leaf axis, one leaf (L3 = LL) is assessed to represent the axis;
- on a five-leaf axis, two leaves (L3 and L5 = LL) are assessed to represent the axis; and
- on an axis bearing 6 or more leaves, three leaves (L3, L5, and LL) are assessed to represent the axis.

A similar design, where different layers or categories of plant tissues are defined, may be applied in root diseases, such as take-all of wheat (Willocquet et al., 2008).

The assessment of injury caused by foliage diseases does not entail only the visibly diseased tissues, but also defoliation, if defoliation is induced by the pathogen. The intensity of disease-induced defoliation is often a varietal trait (which may amount to disease escape if very strong); it also can be strongly dependent on physical elements of the environment (drought and heat). Quantifying defoliation may be as important as quantifying visible disease intensity (severity, in most cases). Therefore, defoliation needs to be quantified (as, e.g., number of detached petiole scars on the main stem in **Fig. 7.2.2**), leading to the consideration of an additional layer of (shed) foliage. Although addressed from a pure epidemiological standpoint, the work done on coffee rust (Seem, 1988; Kushalappa and Ludwig, 1982) is exemplary of the way the issue is to be addressed.

The layer-based sampling of **Fig. 7.2.2** enables producing disease severity assessments for each layer of the crop canopy, and thus an average severity measurement, using one plant axis as a reference. This severity assessment is usually expanded with: (1) counts of diseased leaves and of healthy leaves (enabling an incidence assessment at the plant axis scale), and (2) counts of dead leaves (counts of shed leaves from petiole scars on the axis for dicots, or counts of dead leaves within a tiller for monocots). In annual crops, observations on a single axis of a plant thus enable generating: (1) average disease severity on that axis, (2) incidence at the plant axis scale, and (3) fraction defoliation at the plant axis scale.

7.2.2.7. Yield and crop performance assessment in experimental plots

While yield assessment may seem a trivial matter in terms of agricultural technology, the occurrence of injury may require that specific attention be devoted to it. This is especially so (1) if harvestable

tissues (roots, tubers, pods of some legumes) are underground and injured to varying levels, or detached, or again reduced in size, as a result of disease, (2) if injuries lead to downgrading the harvested produce (e.g., fruits) in various levels (e.g., grades of fruit appearance), and (3) if quality losses are induced by disease. Quality losses, such as spots on apples, are easily dealt with; however, the build-up of mycotoxins, sometimes in absence of any visible sign of the pathogen, is an altogether different issue, to be addressed separately.

7.2.3. Experiments in farmers' fields

Agricultural economists classify gaps in crop performances in type I and II for good reasons. Yield gap I is the gap between research station and farmers' field results, and yield gap II refers to the variability in crop performances under actual farmers' field conditions. Agricultural economists conventionally target the reduction of yield gap I, as it is considered as resulting from poor technology adoption.

There can be considerable differences between the conduct of on-station and that of farmers' field experiments addressing crop losses. The former context ensures better control of environmental conditions in the broadest meaning of the term, including crop rotation, crop establishment (crop history in perennials), or levels of inputs, for example, not to mention the establishment of treatments according to the planned design. The latter leads to consider actual farmers' practices in their diversity while precluding some operations, such as artificial infections. The former is likely to generate reliable and detailed results and specific details on experimental progress; the latter enables incorporating extremely valuable information on real practices and environments.

On-station may produce reference data describing damage functions, with wide application for disease management. However, networks of experiments in farmers' fields can also generate invaluable data sets, as for example extensive studies on losses to fusarium head blight in the USA (e.g., Madden and Paul, 2009) exemplify. The choice of experimental setting entirely depends on the agricultural contexts, on the pathosystem considered (simple or multiple), and above all, on the experimenter's goal.

7.3. Surveys in farmers' fields

7.3.1. Overall strategy

The workflow for surveys in farmers' fields follows the same overall structure as that of crop loss experimental research, with differences only in the first domains (**Fig. 7.3**). Ultimately, a survey in farmers' field broadly addresses the characterisation of production situations, of injury profiles, and the associated crop performances.

Despite the similarities, there is a fundamental difference between surveys in farmers' fields and crop loss experiments in terms of achieving a measure of yield losses. Crop loss experiments include a non-injured treatment, which generates a measurement of attainable yield, Ya, in a given production situation. It is impossible to have such a reference treatment in farmers' field: one cannot have simultaneously a fully healthy crop (Ya) and its twin crop where injuries occur leading the crop yield to be reduced to its actual, farmer-harvested, yield (Y). One approach to address this question is developed at the end of this section.

The first domain (**Fig. 7.3 A**) concerns the aims of the survey effort. Surveys of plant health and crop performances in farmers' field may be conducted by public and corporate institutions for a number of purposes:

- disease surveillance, definition of domains where new technologies may be deployed,
- identifying new needs addressing overlooked or new plant health problems,
- identification of impacts and markets for a new product (seed, technical advice, chemicals),
- identification of priority areas for improved plant health research,

- policies regarding technical infrastructure, education, or research.

A survey in farmers' field, because of the change in scale it involves, almost unavoidably will address two elements that cannot, or cannot easily or fully, be addressed in experimental settings. One is the production situations where farmers operate. Consideration of varying production situations entails considering elements such as production purpose (what kind of produce, intended to which usages), farm size, levels of production technology, landforms and variable access of production to natural resources (including water and soils), availability of agricultural labour (and its socio-economic and technological implications). A critical choice a survey project must face at its conception is thus the difficult question of representativeness (**Fig. 7.3 A**).

Representativeness may be from the agronomic and socio-economic standpoints. A survey on plant health may thus involve agronomy, soil science, or genetics, and economy or sociology, as much as it involves plant pathology. The question of a survey representativeness therefore goes far beyond the mere determination of sample sizes. The question, in reality, is directly related with the aim of conducting a survey in farmers' field.

The other element is termed injury profile. Similarly to equivalent public health studies, a plant health survey in farmers' field addresses individuals (farmers' fields, each different, with its own attribute), and an array of diverse plant health problems of varying importance. The pattern of plant health problems affecting a crop stand in the time-course of its development, from crop establishment to harvest, in a farmer's field is termed "injury profile". Medicine shows that anyone's health is strongly linked to anyone's way of life. Similarly, injury profiles and production situations have been shown to be strongly associated in an array of different cases, in the temperate and the tropical world alike. A survey in farmers' fields needs to address production situations in their diversity, so that the associated injury profiles are identified. Such a linkage has numerous applications, an important one being the identification of production situations where changes, sometimes small, may considerably improve plant health: this is a significant contribution to integrated plant health management, not at the individual field, but at the production situation scale.

Crop performances, especially crop yield, is the last yet important element to consider in the definition of survey aims. Measuring crop performance at the end of a growing season during which the build-up of injuries, crop development and growth, have been monitored is a major addition to a survey's agenda, enabling it to address impacts of plant health on crop performances. Measuring crop yield represents a considerable time and financial investment, including the engagement of farmers in the effort.

The second domain in the workflow is that of designing the survey protocol (**Fig. 7.3 B**). This implies a number of elements itemised in **Fig. 7.3 A**. Designing a survey protocol has similarities with the design of a process-based simulation modelling structure: too simple, it will fail to achieve the set objectives; too detailed, it will prevent survey implementation, owing to excessive work and time. As in modelling, an ideal survey procedure is one where each collected element has meaning, and will effectively be used in analyses that are specifically aimed at testing the hypotheses set forward in defining the aims of the survey.

The rest of the workflow is identical to that of experimental research, except for the measurement of crop performances (e.g., crop yield), in domain D (**Fig. 7.3 D**), i.e., in the choice of data to collect.

7.3.2. Computation of yield losses from multiple injuries in farmers' fields

The computation of yield losses caused by multiple injuries in farmers' fields involves two separate, complementary data components: first, data from a set of crop loss experiments where levels of each considered disease (or pest) injury are artificially manipulated, including a non-injured control (Ya), so that yield losses (Ya – Y) can be calculated (e.g., Savary et al. 2000a), and second, farmers' field survey data that cover a range of production situations and an array of observed levels of disease or

pest injuries, as they occur spontaneously in farmers' fields contexts (e.g., Savary et al. 2000b). The broader the range of production situations captured in the survey, and the more diverse the disease and pests, with their varying individual levels, the broader the conclusions will be in their representativeness of the diversity and causes for crop losses in actual agricultural contexts.

Field experiments may be conducted as described in the previous section (for small-grain cereals, an example is the design used in Savary et al., 2000a). Computation of yield losses in farmers' fields settings follows a principal component regression approach. This can be summarised as follows.

- Using the experimental yield loss data, a normalized principal component analysis is first conducted on the disease (or pest) injury variables, leading to the generation of a series of independent injury factors, Fi (which are independent linear combinations of injuries).
- Second, these factors, together with the attainable yield (Ya) values, are used in an upward, stepwise multiple regression analysis of variation in actual yield (Y), generating regression model that describes the actual yield response surface. The regression model has the following shape:

$$Y = aYa + \Sigma b_i F_i + \Sigma c_j Ya \times F_j + \Sigma\Sigma d_{k,l} F_k \times F_l \qquad [1]$$

  where the c_j $Ya \times F_j$ and the $d_{k,l}$ $F_k \times F_l$ terms account for interactions between attainable yield and injury factors, and among injury factors, respectively.

- Third, the resulting equation is assessed by aptness of residuals, coefficient of determination, and F test.
- Fourth – and then using data generated from survey work – the regression model is used to assess yield losses in various production situations. Estimation of yield losses for all production situation analyses entails back-computations using the yield response surface (equation [1]). Each factor value F_i is computed using its loadings and the considered (normalized) injury level(s); a preset attainable yield value is then entered in the equation; an estimate for actual yield is thus derived; and the difference Ya – Y, i.e., yield loss, is calculated.

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Figure 7.1. Selecting the objectives and the associated approaches for field collection of disease data

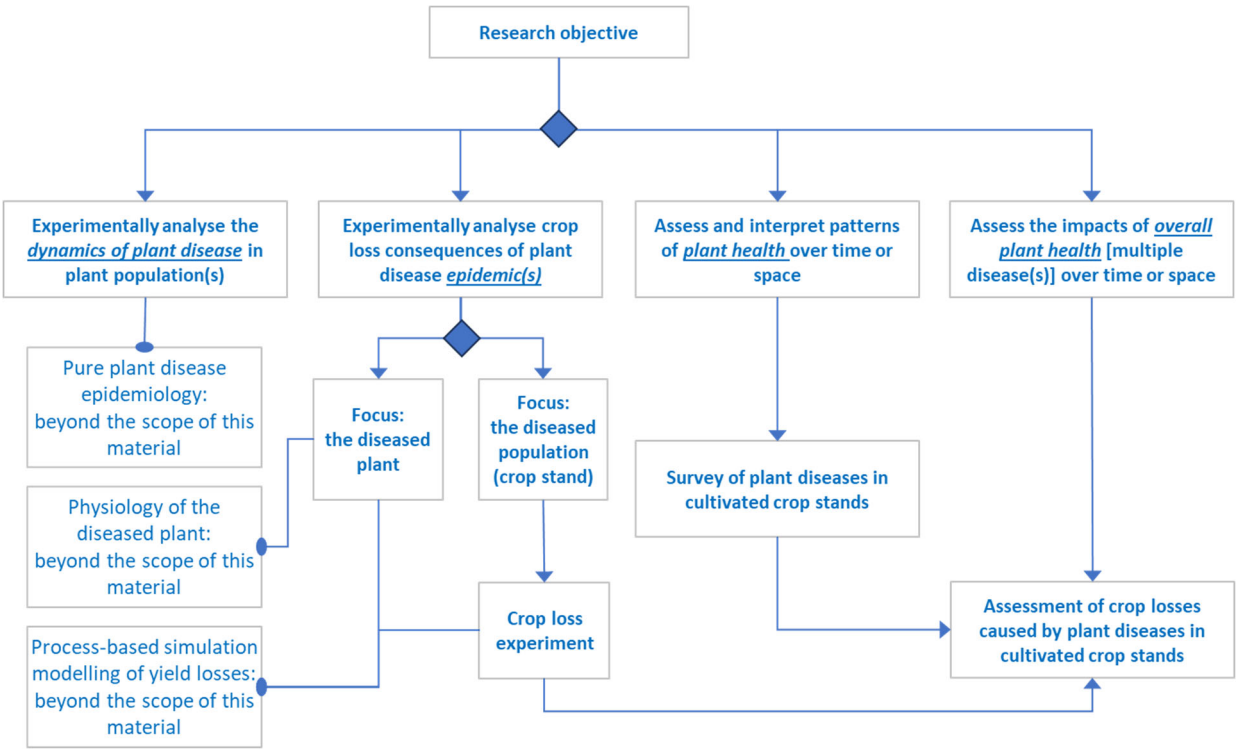


Figure 7.2.1. Workflow for crop loss experiments

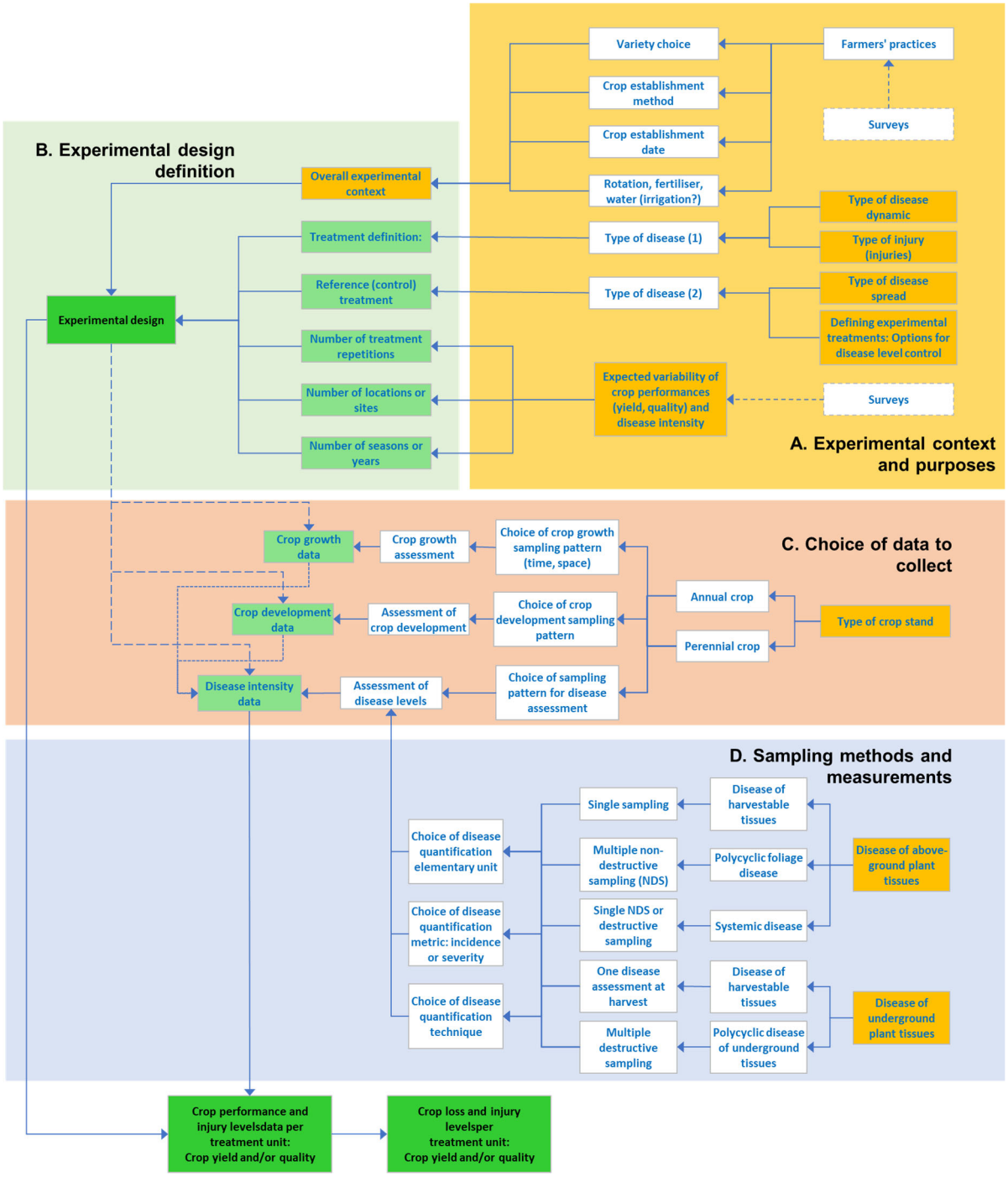
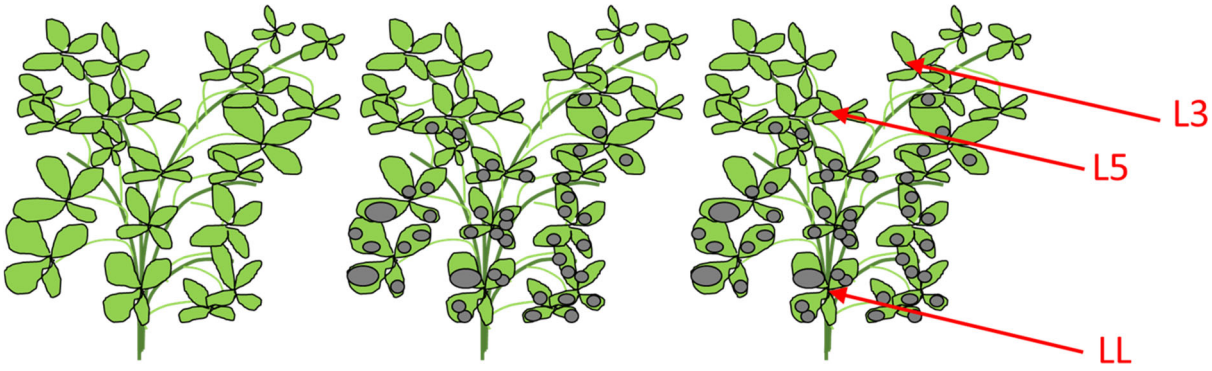


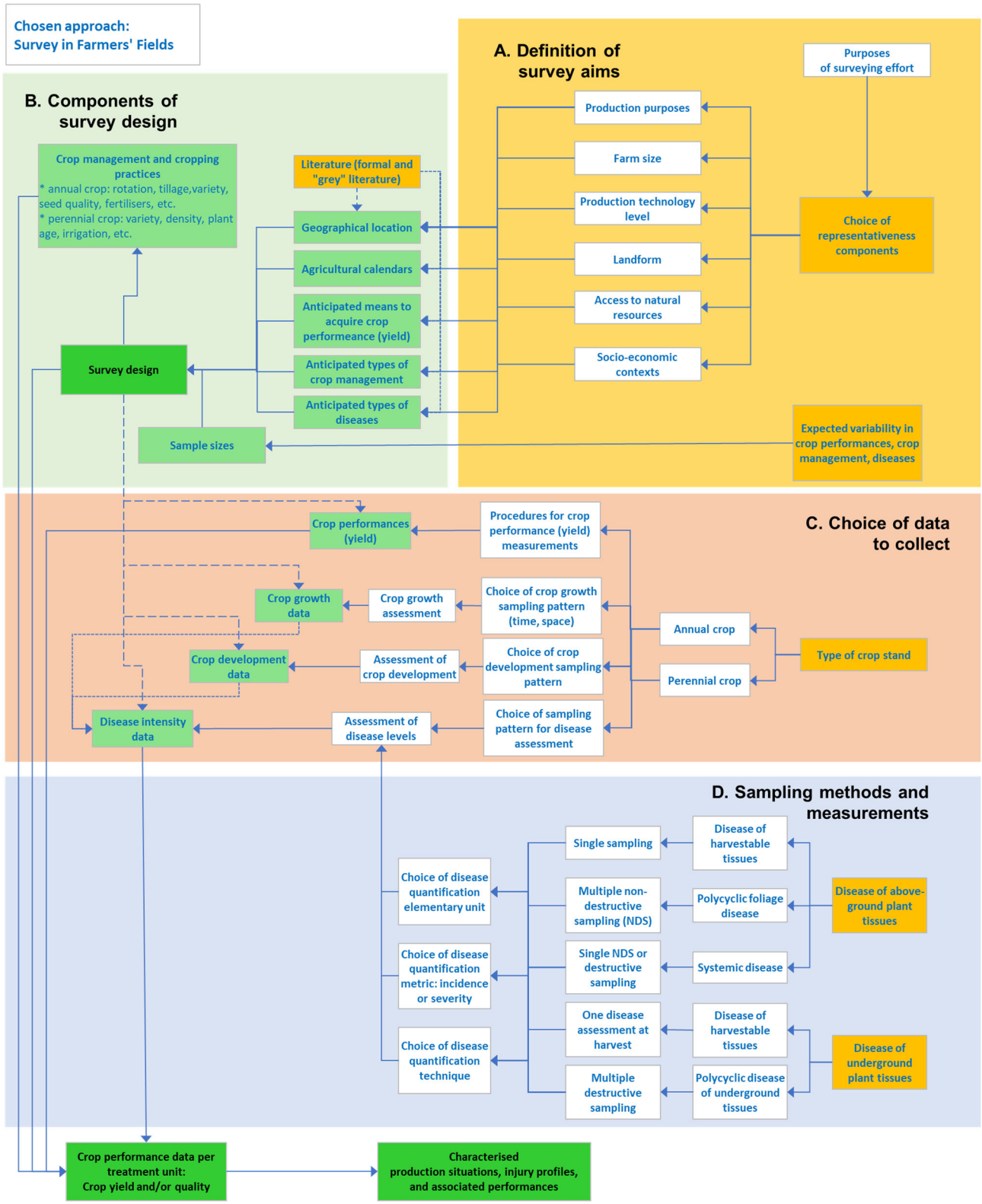
Figure 7.2.2 – Stratified sampling for foliage disease assessment in an annual crop – example on a dicot crop



Three leaf layers based on leaf age are sampled: 3rd, 5th, and last live leaf of a main vegetative axis. The disease assessment metric is usually disease severity, so that an unweighted average disease severity may be computed as: $(S_{L3} + S_{L5} + S_{LL})/3 = S_{plant}$. Weighing on different layers might be applied if prior knowledge of the contribution of each layer to crop yield loss were available (caution is advised if doing so due to changes with crop growth and differences among varieties).

These observations are often complemented on the same axis by: the numbers of healthy leaves, of diseased leaves, and of shed (defoliated) or dead leaves (from counts of petiole scars along the axis in dicots, or dead leaves in a tiller for monocots). Data on severity, incidence, and defoliation are thus generated at the plant axis scale.

Fig. 7.3. Workflow for crop health and crop loss surveys



8. Measurement of crop yield and yield components

Crop yield, a single figure, accounting for the performance of a crop on a given area, is the rough summary – a numerical net result – of many processes that unfold and interact over a growing season (in an annual crop), or a succession of seasons (in perennials). The interacting processes include: the host physiology, the physical environment (including the weather and abiotic stresses), and pathogens dynamics, to which one should add many other elements of an agrosystems (weeds, animal pests, or parasitic weeds, and the microbiology of soils and of the aerial environment). To this, further, should one necessarily add humans and their actions in influencing the agrosystem.

Standard texts exist that provide guidelines regarding the number of plants within a crop stand and/or the minimum plot size to be harvested in an annual crop (e.g., James and Shih, 1973; Walker, 1983). Analogous standards exist for perennials. Remarks are limited here to elements that have direct relevance to yield loss assessment.

The ecophysiology of a crop may, among a number of different ways, be characterised in the form of yield components. The number of yield components, that is to say, the elements which contribute to crop yield, vary widely among crops, reflecting their different development patterns in a summarised manner:

- five yield components are usually considered in small cereals (wheat, rice, barley, or rye, for example): (1) plants or units (tillers) per unit area; (2) heads per plant or unit; (3) spikelets per head; (4) grains per spikelet; and (5) weight per grain;
- three components are usually considered in potato: (1) plants per unit area; (2) tubers per plant; and (3) weight per tuber;
- three components are usually considered in cassava: (1) plants per unit area; (2) roots per plant; and (3) weight per root;
- and only two components are usually considered in sugar beet or cassava: (1) plants per unit area; and (2) weight per plant (root). (In sugar beet, sugar content is critical, but that is a yield quality, not yield biomass, attribute.)

Calculation of yield Y proceeds with a product of such components. For example, in small cereals:

Y = Number of plants or tillers per unit area * Number of heads per plant or unit * Number of spikelets per head * Number of grains per spikelet* Weight per grain

In broad terms, even in a healthy crop stand, a larger number of yield components is associated with both a plant-to-plant variation of each of the components, and a capacity for compensation (for example, a small plant will be surrounded by larger ones compensating its comparatively low yield).

Yield components often reflect the architecture of crop stands: much larger crop stands need to be harvested for a representative measure of crop yield in sugar beet, or cassava, compared to a small-grain cereal.

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9. Technical advances in crop loss assessment and open questions

Many directions could be taken to assess the implications of technical advances to better quantify crop losses. We chose only a few out of many lines of thoughts.

9.1. Technology gradients in agriculture

A very large fraction of the world's agriculture is conducted in small farms. Small-holding, defined as farms that are less than 2 ha in size, are still very numerous today. Small-holdings are the norm in much of East Asia, South Asia, Southeast Asia, and sub-Saharan Africa, as well as many parts of South America. While these farms are the main source of food for a growing population, they also are sources for multiple agricultural products, including staple (e.g., rice in India), or industrial products (e.g., cotton in sub-Saharan Africa). Excepting Argentina, Brazil, China, and India, the agricultural exports from the Global South (as defined by UNCTAD, the UN Trade and Development Agency) are small compared to that of the Global North, with its major agricultural exporters: the USA, Canada, Europe, and Australia.

Farms, worldwide, operate at very different levels of technology. This has tremendous consequences on production situations, and therefore on crop performances, diseases, and crop losses (**Fig. 4.1**). Small farms of the Global South strongly rely on human labour, farmers' experience and knowledge, and on the highly variable level of availability of natural resources. The latter often are extremely limited, but sometimes are quite adequate – some of the irrigation systems of South India are over 3000 years old, and still operate. The mu (亩), sometimes referred to "the Chinese acre", is a Chinese traditional unit of measurement for land area. In mainland China, one mu equals 666.67 square meters (0.0667 ha). The very existence of such an area unit is evidence of the way most Chinese farmers see their landscape. Access and consumption of chemical inputs is extremely heterogeneous in the Global South, as it depends largely on transport infrastructure, and on other types of public or private support. In contrast, large farms of the Global North, as well as in Brazil or Argentina, with their individual fields that commonly are in the range of 5 to 20 ha, or much more, in size suffer from a dramatic shortage of human labour; this is compensated by heavy machinery, considerable farmers' expertise earned through advanced education, and solid physical and non-physical infrastructure, including market organisation of both inputs and products. In many countries, extreme diversities of technology coexist, sometimes side by side – steep technological gradients occur. Both the Global South and North are homes to different forms of agricultures, aiming at products (sometimes luxury, or niche, or traditional – wine and organic products, and spices come to mind) and markets which largely govern what can, or cannot, be done in terms of plant production.

9.2. Technology gradients in agriculture change the way to see crop, diseases, and crop losses

Technology gradients are major drivers of agricultural change in rural landscapes, which accelerate shifts in production situations. While farmers in small-holding can easily scout their fields and detect if plant health issues seem to emerge, a farm manager in Brazil, in Eastern Europe, or in the USA, often is confronted with major challenges when it comes to exactly know what is happening in each of one's very large fields. A single such field may harbour extremely different micro-environments (see **Box 6.1.a** and **Box 6.2.b**) for crop growth, development, and health.

Very large expanses of land, certainly in the same large field, often in adjacent large fields, sown to the same genotype of the host, are designated targets for powerful and damaging epidemics. That risk is known by farmers, and they need the means to manage such risks. These fields are so large, the manpower so scarce, that monitoring becomes an acute issue. The rapid development of new instruments for detection and monitoring crop stands should not therefore come as a surprise. The

same applies to disease management (which is beyond the scope of this report): in many ways, precision farming actually refers to the management of space through short-term, tactical, and chemistry-oriented instruments in a context of labour scarcity.

Yet, irrespective of the position of a farm, a field, belonging to a given production situation along this technology gradient, the fundamental concepts documented in this report still hold. A given production situation is exposed to crop losses generated by an injury profile, which in turn is associated with attainable crop performances, and injuries. It appears logical to consider that the sustainable management of plant health and the limitation of crop losses will need to involve long-term strategic decisions, as well as short-term tactical ones.

9.3. Evolving techniques for disease assessment

The development of sensors in view of their application to plant pathology started over 40 years ago. Sensor-based methods are being developed to assess the level of disease injury. Sensors can involve RGB (i.e., the red, green, and blue primary colours of light) sensors, spectral sensors, thermal sensors, or fluorescent imaging sensors. Such sensors can be installed on a range of equipment: satellites, Unmanned Aerial Vehicles (UAVs, drones), tractors, or robots (Mahlein, 2016).

Use of these techniques as routine means for disease assessment still faces hurdles. This is because of current constraints in costs, level of (equipment) training in order to use a sensor and analyse information it generates (Shi et al, 2023), technical limits (accounting for variation in natural radiation and canopy architecture, spatial resolution; Tanner et al., 2022) - as well as vertical distribution of injury (see e.g., **Fig. 7.2.2**), and interactions with other diseases or abiotic stresses (see above section 4.2. Defoliation).

Such techniques are therefore not in most instances ready to be used on a routine basis *in the field*. The current and near-future practice to assess disease injury in the context of crop loss assessment mainly involves visual assessment, with the aid of diagram scales.

9.4. Open questions

Many questions come to mind on how to make crop loss assessment more useful for societies, for rural communities, for farmers, as well as for trade, local to global. Many of these questions should be seen as research areas. We offer here only a tentative short list.

- Mycotoxins in food is a global human health issue (Wild and Gong, 2010). Research on the relationships between symptoms (apparent, visible, quantifiable injuries – see the discussion on virtual lesions, on a very different aspect) and the real injury to harvest quality in the form of mycotoxins accumulated in the grain is a research priority. Work done by Madden and Paul (2020), with the concept of surrogate, applied to data produced over years of field work by a large network of farmers' field experiments, outlines a way forward.

- Too little is still known on the interactions among multiple injuries (i.e. components of an injury profile) on plant physiology and on the eco-physiology of a growing crop stand. Using proper metrics and methods for multiple pathosystems (multiple crop performance reducers) is necessary to enable management. It may very well be that such poly-injury systems become more common in many production situations, where such knowledge and methods will be needed. This theme is addressed again below from a different angle.

- Similarly, far too little is known of the nature and dynamics of interactions between abiotic stresses and plant pathogens, seen as crop performance reducers. This is an urgent need given the environmental shifts driven by climate change: There are growing indications on shifts in harmfulness of infectious plant diseases with climate change. Such fundamental knowledge is

bound to find direct applications in plant breeding, crop management, and plant health management. This theme is also addressed again below.

- Sharing data through open-access, international, and free data bases is a challenge, in part because of the need to establish internationally accepted data standards. But the challenge of the meta-data that need to accompany information that only concern injuries, yields, and crop losses (in quantity and quality) is even greater.

- Meta-data for crop loss information concerns production situations. While weather information is easily accessible in many cases, information on the social and cultural context is necessary, as much as information on agricultural practices, varieties, landforms, landscapes, or soils.

- Consider three frameworks: Framework 1: [one crop - one pathogen]; Framework 2: [one crop - several pathogens]; and Framework 3: [one crop - several pathogens - several physiological stresses]. The bulk of the crop loss literature deals with Framework 1. Some might consider this framework too narrow, even perhaps reductionist. Yet, Framework 1 allows to consider the dynamics of lesion accumulation on host plants in a crop; this accumulation of lesions may amplify their individual effect on plant physiology (more-than-additive effect), or reduce it (less-than-additive effect), in non-linear fashions. The dynamics of disease thus interacts with its harmfulness toward the physiology of the diseased plant. Further, a pathogen that develops onto or within the diseased plant is an integral part of the plant phytobiome, which influences the physiology of the diseased plant. Thus, the perspective of integrating the dynamics of physiological and biochemical interactions in a simple plant-system comes into play. In including the multitude of organisms of the phytobiome in Framework 1, it is true that this framework has been entirely changed. Yet, it also is true that simplicity does not imply absence of complexity: complexity results from the nature and strength of interactions of elements in a system, not from the number of elements. Complexity is a critically important feature of ecological (and other) systems: it is because of their complexity that emerging properties develop in ecosystems. Climate change, for example, triggers such emerging properties. Frameworks 2 and 3 are more complicated. They are closer to field realities, enabling science to come closer to its applications, and address important and new questions. Frameworks 2 and 3, too, can be, and generally are complex. Such frameworks can be addressed through solid, established, methods. One of them, process-based simulation modelling, is key, because it enables quantitative understanding – not just prediction – of how a given process influences the dynamics of a whole system. Process-based simulation modelling is central in enabling plant pathologists to address complexity.

- A key question for plant pathologists is the future of plant diseases, in terms of their possible impacts on crop performances. This is a vital question to consider, and also an exciting and challenging one. This question, in fact, overlaps those already listed. Climate change and shifts in crop management profoundly changes plant health worldwide; physiological (abiotic) stresses become increasingly grave and widespread – and their interactions with disease are well-recognised, even if they remain so poorly documented. Addressing the future impacts of plant diseases necessarily requires a sound base as a starting point – today. Investigating what could happen beyond today entails interdisciplinary work and quantitative approaches with which most plant pathologists are not familiar. Methods, also, exist to formally address the future. This will require plant pathologists to work with scientists from very different other fields. Yet, such questions, which actually are being widely addressed today in the science literature, only involve plant pathologists marginally. The contribution of plant pathology to such questions is necessary. Besides, it would not be the first time that plant pathologists make use of techniques derived from physics, mathematics, economy, or information technology.

What the above few points collectively indicate is that advances in crop loss – related research will depend to a large extent on methods which emerge from inter-disciplinarity. Inter-disciplinary exchange and progress has happened in the past in plant pathology. Central to such a question is to convey a vision of where science is necessary and at what scale – not of what techniques may accomplish. Plant pathology is a cross-road of sciences, and it progressed in the past mostly from inter-disciplinary exchanges.

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