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Protecting crops through plant diversity

Anaïs Tibi, Vincent Martinet, Aude Vialatte, eds

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The documents pertaining to this assessment are available on the INRAE websites (https://www.inrae.fr/).

The authors of the scientific report, which is the basis of this work, are all the members of the CSA workgroup listed at the end of the book. Unless otherwise specified, the figures and tables were produced by the authors. The websites mentioned in this book were accessed in June and July 2023.

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Summary

Introduction

In the post-WWII context, the advent of synthetic fertilisers and pesticides prompted farmers to specialise their farms in the most profitable crops, thus freeing them from environmental constraints (presence of crop pests, availability of nutrients in the soil, climate variability, etc.). While this agricultural transformation boosted production levels, it also resulted in the gradual loss of plant diversity, both cultivated (with shorter crop rotations and increasingly standardised fields) and semi-natural (removal of hedgerows in favour of larger fields). The environmental and health impacts of this dominant model and its interrelationship with global changes (climate change, biodiversity loss, changes in land use) are now well documented by the scientific community.[1] Facing such challenges, France and Europe are witnessing a strong public demand for agriculture that is more respectful of the environment and human health and less dependent on synthetic inputs.

The demand for alternative production methods to so-called 'conventional' systems is reflected in some European public policies (European Green Deal, Common Agricultural Policy) and national policies (see box 1). These policies set targets for reducing pesticide use, and, more generally, they promote a shift towards more diversified farming systems that place biodiversity and ecological processes at the forefront of production factors. However, despite the growing recognition of environmental issues in public policies, it should be mentioned that the shift towards low-pesticide cropping systems is far from being sufficiently advanced to meet the targets set (Guyomard *et al.*, 2020). Furthermore, while political and scientific circles view plant diversification as a significant lever for this transition, there is still a lack of critical perspective and overall vision regarding its effectiveness 'in the field', particularly concerning crop protection. Finally, plant diversification covers a broad range of situations and practices. While some are well-known and used by some farmers (i.e., varietal mixtures), others are little known (i.e., agroforestry in temperate environments), and many are—rightly or wrongly—perceived by certain operators as relatively ineffective or too restrictive.

Purpose and scope of the Collective scientific assessment

In this context, the French Ministries of Agriculture, Environment and Research commissioned the INRAE in late 2019 to carry out two collective scientific assessments (CSA) in parallel, one on the impact of plant protection products on biodiversity and ecosystem

1. i.e., the collective scientific assessments of INRAE and Ifremer on the ecotoxicological impacts of pesticides (Leenhardt *et al.*, 2022) and the INRA on the synergies between agriculture and biodiversity (Le Roux *et al.*, 2008), as well as the work of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES).

Box 1. European and French public policies on the use of pesticides and changes in agricultural production methods

At the European level, Directive 2009/128/EC, known as the SUD (Sustainable Use of Pesticides Directive), requires all Member States to draw up a general framework for action to limit the use of pesticides in the EU while encouraging farmers to use 'integrated pest management and alternative methods and techniques'. The recent European Green Deal, launched in December 2019, sets quantitative targets for 2030 through its strategic applications for agriculture (the 'from farm to fork' strategy) and biodiversity (European strategy for biodiversity). These targets include a 50% reduction in the use of pesticides,* an increase to 25% in the proportion of agricultural area used for organic farming, and a rise to 10% in the proportion of agricultural area used for 'high diversity landscape features' (buffer strips, fallow land, hedgerows, non-productive trees, etc.), which serve as a refuge for the natural enemies of crop pests. The main European policy that must be leveraged to this end is the Common Agricultural Policy (CAP) through its three environmental tools (cross-compliance, eco-schemes and agri-environmental and climate measures). While the CAP does not include an explicit target for reducing the use of pesticides, the re-diversification of farming systems has emerged as a challenge since the 2014 reform (one of the three greening measures) and is reinforced in the current programming.

In France, targets for reducing the use of pesticides are set out in a specific policy plan for pesticide use reduction, called the Ecophyto plan, launched at the Grenelle de l'Environnement in 2007. The Ecophyto plan is the French version of the SUD. Because the initial objective of cutting pesticide use by half between 2008 and 2018 ('Ecophyto 2018') was not achieved, French public authorities reviewed the Plan ('Ecophyto 2' then '2+') and pushed back the deadline to 2025. As a complement to the Plan, a Law on the Future of Agriculture, Food and Forestry (LAAAF for Loi d'Avenir pour l'Agriculture, l'Alimentation et la Forêt) passed in 2014.** As well as introducing the concept of 'agroecological' production systems into the legislation (without, however, defining their characteristics), it sets a target of 50% of French farms with agroecological practices by 2025. Parallel to agricultural policies, France's National Strategy for Biodiversity (which reflects the State's commitment under the Convention on Biological Diversity) includes in its 2022-2030 programme a commitment to promote the agroecological transition of agricultural production and food systems and to facilitate the implementation of agroecological infrastructures (to integrate ecological grids into land-use planning).

Finally, policies that target other issues may impact crop and landscape diversification. Examples include Directive 91/676/EEC on nitrates, which requires planting grassed strips along waterways; Directives 92/43/EEC on habitats and 2009/147/EC on birds, which aim to maintain the biological diversity of environments, particularly the (semi-)natural fraction of landscapes, and the national strategy on plant proteins, which encourages the introduction of legumes in crop rotations.

* The SUD Directive was due to be revised in the summer of 2022. Target that the EU has suggested including in the future Sustainable Use of Pesticides European Directive, thereby making it legally binding at the EU level. This project, however, failed at the end of 2023.

** It embodies the Projet Agroécologique pour la France (Agroecological Project for France), launched in 2012.

services (which conclusions were delivered in May 2022 - Leenhardt *et al.*, 2022), and one on the use of plant cover diversity to regulate pests and protect crops. The latter CSA, which is the subject of this book, responds to the need to assess the effectiveness of crop protection strategies based on plant diversification in agricultural fields and landscapes in light of published scientific results. It also aims to analyse the obstacles and levers to implementing such strategies by bringing together different disciplinary perspectives from the life sciences to economics and the social sciences. Finally, there is a need to clarify the role of plant diversity in providing other ecosystem services in synergy with the natural regulation of pests. This request is part of the Écophyto 2+ Plan.[2]

Since the mid-2000s, academic research has been increasingly active in analysing low-input production methods. Building in particular on the conceptual framework of ecosystem services popularised by the *Millennium Ecosystem Assessment* (2005), a body of evidence has highlighted the strength of the interactions between agricultural practices, biodiversity and the services provided by the latter to human societies (see, for example, Le Roux *et al.*, 2008). The 'EFESE-écosystème agricoles' survey carried out by the INRA has specifically highlighted the critical role of the nature and spatial organisation of plants in supplying all the services supporting agricultural production, including natural regulation of crop pests (Tibi and Therond, 2017). More recently, a growing number of studies have focused on the analysis of the benefits of plant diversification in agricultural fields and landscapes (such as the European projects under the aegis of the *Crop Diversification Cluster*). Similarly, several research endeavours are exploring avenues for eliminating the use of pesticides. The 'Écophyto R&D' survey carried out by the INRA (Butault *et al.*, 2010) showed that a target of reducing the use of pesticides by half could not be reached without the in-depth and sustainable redesign of production systems. The purpose of the CAS was to revisit and update this work by specifically reviewing the literature at the crossroads between plant diversification in agricultural systems and crop protection.

The CAS literature review is part of an ever-expanding scientific landscape. A European research alliance called *Towards a Chemical Pesticide-Free Agriculture* was created in 2020 at the initiative of the INRAE. Today, it brings together 34 research bodies from 20 European countries to foster transdisciplinary research and innovations. In France, the 'Cultiver et Protéger autrement' (alternative cultivation and protection methods) Priority Research Programme (PPR) was launched in 2018 to encourage research to design cropping systems free of synthetic pesticides. As the lead partner for this PPR, and in parallel to this CAS, the INRAE also carried out a foresight study proposing scenarios for the European Union's transition to pesticide-free farming methods by 2050 (Mora *et al.*, 2023).

The scope of the CAS encompasses all the spatial and temporal scales at which plant diversity can be rolled out or managed. Thus, at the field level, the focus is on the farmer's choice and method of planting species and varieties (varietal or species mixtures, grass

2. The CAS project received financial support from the Écophyto 2+ plan (*via* the Office Français de la Biodiversité—French Biodiversity Agency—which oversees the plan's funding) as part of its second area of focus on research and innovation.

strips, service plants, etc.) and the temporal dynamics of these plant cover crops (rotations). At the supra-field level (farm, landscape), the focus is on the effects of the composition and configuration of the vegetation as a whole, whether this concerns the farmed portion (cropping pattern, shape and size of land parcels) or semi-natural portion (nature and connectivity of agroecological infrastructures around the fields—hedges or borders—or which form islands in the landscape—woodland, permanent grassland, etc.).

The CAS scope includes all types of plant productions in France, whether field crops (for human or animal consumption, industrial use), perennial crops (arboriculture, vineyards) or horticulture. While the request addressed to the INRAE primarily aimed to gain a better understanding of the potential offered by plant diversification for the protection of cropping systems in mainland France, the systems in the French overseas territories have specific characteristics (in particular biogeographical, agronomic and socio-economic) that warrant a detailed analysis in the CAS. This analysis is presented in box 2.3.

The Collective Scientific Assessment (CSA) approach

The INRAE (formerly INRA) has carried out collective scientific assessment (CAS) activities since 2002. The CAS's institutional activity is covered by a national charter signed in 2011. The CAS involves analysing and collating scientific to inform public action. It aims to spotlight the scientific achievements, uncertainties, and areas of scientific controversy. The CAS does not provide advice or recommendations. Similarly, it does not provide practical answers to issues raised by managers. Instead, it provides as comprehensive a review of scientific knowledge as possible, using a multidisciplinary approach that combines the life sciences, economics and social sciences. It also identifies poorly documented issues that should be researched as a priority.

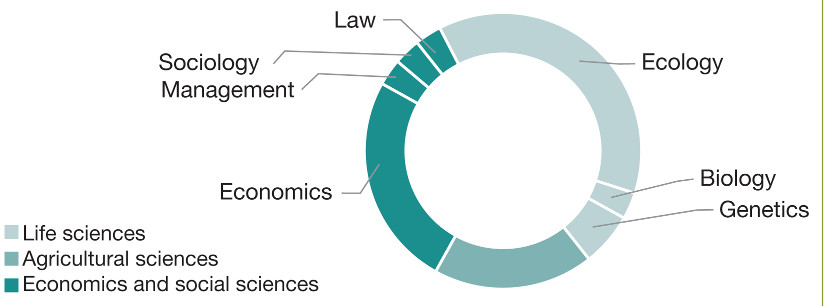
CAS operations are coordinated by the INRAE's DEPE (Directorate for Collective Scientific Assessment, Foresight and Advanced Studies) in compliance with an Institutional charter. The principles set out by the DEPE to guarantee the reliability of the findings of the work are described in a public booklet.[3] They include the competence of the experts (selected for their scientific publications), their plurality (they come from various public research institutes), the impartiality of the experts' committee (which relies on the examination of the experts' declarations of interest by the INRAE's ethics committee), the transparency of the methodology followed and the traceability of the actions and resources implemented during the operation.

INRAE brought together a committee of some thirty experts and scientific contributors with complementary disciplinary skills (figure I.1) to carry out this CAS. The members' list of the expert committee is included at the end of this document. Supported by two librarians, the experts compiled the scientific knowledge published to date on the various

3. https://www.inrae.fr/en/news/guidelines-collective-scientific-assessments-and-advenced-studies

issues addressed to INRAE, and extracted the relevant information to inform public decision-making. Two project managers were also recruited during the CAS to carry out complementary analyses to those produced by the scientific experts.

Figure I.1. Disciplines represented in the experts' committee



The figures show the number of experts in each discipline. Some experts are qualified in several disciplines.

Two librairians helped the experts' committee and project managers to identify and collect the scientific and technical references useful for the assessment (box 2). They conducted a bibliometric analysis of the final corpus supporting the scientific report.

The experts' committee was chaired by two scientific leads who set the CAS's scientific directions, oversaw the collective and multidisciplinary production, and checked the scientific robustness and integrity of the experts' conclusions. A team from the DEPE oversaw the general coordination of the CAS, the project's logistical and financial management, and the feedback symposium's organisation.

The CAS produced three deliverables. The analyses produced by the experts were initially compiled in a extended scientific report of some 1,000 pages, which includes the exhaustive list of references supporting the conclusions (cf. *infra*). Intended for a non-scientific but informed readership, the condensed report (presented in this document) compiles the main findings of the CAS report and provides a key to its interpretation. It should be noted that the 94 references quoted in this document are only a fraction of the bibliographical corpus of the CAS (only the references of figures, examples and data taken from publications are mentioned), as the extended report is based on 2,078 references. Finally, the CAS's main conclusions are presented in a twelve-page summary report in the most concise terms possible for a broad audience.

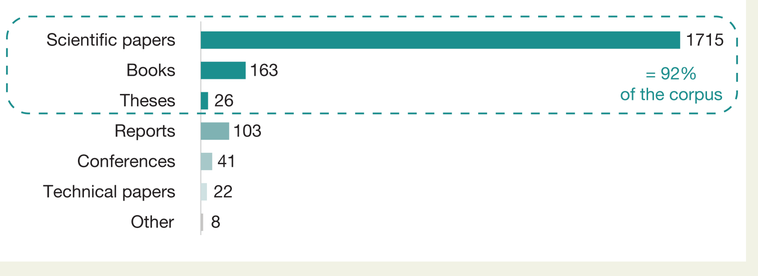
Box 2. The CAS bibliographic corpus

The expert's report is supported by a body of literature comprising 2,078 references, 94 of which are cited in this book. The librarians and the project leader have developed queries specific to each CAS topic in collaboration with the experts. These queries were used to search bibliographic databases (mainly the Web of Science, supplemented by Scopus for the economic and social sciences).*

The experts sorted the thousands of references from these queries and only selected those that could inform the questions in the request submitted to INRAE. The experts also enriched the corpus with references not captured by systematic searches of these databases (i), either because they are not referenced there (for example, academic references from journals not referenced in these databases and non-academic documents useful to the CAS, such as legal texts, specific reports, etc.), (ii) or because they are generic references, with research objects that are beyond the typical questions of the referral, but which enrich the CAS by providing structuring or discussion elements.

The final corpus comprises mainly scientific articles (83%)—the vast majority of which were published in peer-reviewed journals (78%)—supplemented by scientific books and theses, as well as reports (i.e. scientific reports or European Commission reports), information from scientific conferences, technical literature (mainly publications which include analyses of agricultural statistics) and other types of so-called 'grey' references complementing academic literature on aspects not covered by the latter.

Figure I.2. Nature of the references quoted in the CAS report



* These databases were last queried in late 2021.

A monitoring committee led by the DEPE met three times to liaise between the working group and the ministries and ensure that the work proceeded smoothly. It included representatives from the French Ministries of Agriculture, the Environment and Research, the INRAE's 'Agriculture' Scientific Division, the French Biodiversity Agency (OFB) and the Ecophyto Plan's Scientific Committee for Research and Innovation (CSO RI).

A Stakeholder Advisory Committee, facilitated by the DEPE, also met at the outset and conclusion of the CAS to inform stakeholders of the scientific directions and findings of the work and to collect the stakeholders' concerns, interests and questions regarding the operation. In addition to the members of the Monitoring Committee, several other stakeholders likely to be affected by the findings of the exercise and to use the results were invited to attend: stakeholders in the agricultural and food sectors,[4] environmental organisations,[5] consultancy firms,[6] local players,[7] etc.

4. Association de coordination technique agricole (ACTA-Agricultural technical coordination association), Réseau des Centres d'Initiatives pour Valoriser l'Agriculture et le Milieu rural (CIVAM-network of centres for initiatives to promote agriculture and the rural environment), Fédération nationale des coopératives d'utilisation de matériel agricole (FNCUMA-National federation of cooperatives for the use of agricultural equipment), La Coopérative agricole, Fédération nationale du négoce agricole (National federation of agricultural trade), Union des industriels de l'agroéquipement (Axema-Union of agricultural equipment manufacturers), Association nationale des Industries alimentaires (ANIA-National association of food industries).

5. Ligue pour la protection des oiseaux (LPO-Bird protection league), Office Pour les Insectes et leur Environnement (OPIE-French office for insects and their environment).

6. Solagro (a non-profit promoting practices and techniques to save natural resources in energy, agriculture and forestry), Flor'insectes (a consultancy specialising in the management of plant cover to encourage biodiversity).

7. Water agencies, National Forest Office (ONF).

PART 1

A few definitions

This part presents the objects and concepts studied in the CAS. First, the concept of pests and their impact on crops. Second, the natural regulation of pests, with a paradigmatic shift away from chemical control strategies.[8] Finally, the different ways of diversifying farmland vegetation; these differ according to the type of vegetation in question (cultivated or semi-natural), the temporal dimension of the diversification (crop season only or multi-annual) and the spatial scale of the roll-out (field, farm, landscape).

8. Used here to refer to pesticide use.

1. Pest, crop protection and natural regulation

Pest: from injuries to economic losses

Pests are living organisms whose actions on cultivated plants cause physiological or mechanical injuries. Such injuries may be characterised by an alteration in the growth or vigour of the plant, its morphology or that of its organs (lesions, changes in colour, deformations, necrosis, galls, etc.), or even its chemical composition (nutrient content, presence of toxins, etc.). The injuries may result in quantitative or qualitative crop losses[9] (damages) and ultimately in economic losses.

Various organisms can harm cultivated plants: phytophagous arthropods (insects, acarids, etc.), weeds (crop volunteers and spontaneous vegetation) or parasitic plants, pathogenic microorganisms (fungi, bacteria, viruses, phytoplasmas, etc.) that cause plant diseases, gastropods, nematodes, birds, mammals (rodents, moles, etc.). Some pathogens are transmitted to plants by carrier organisms (usually insects, but also acarids, nematodes, mammals, etc.). Although it does not always harm the plant, the vector is generally targeted by crop protection methods and is therefore viewed as a pest. Given the concerns that motivated this CAS, the analysis focuses mainly on the categories of pests that are chemically controlled: weeds and parasitic plants, pathogenic microorganisms, and micro-meso-macrofauna invertebrates (arthropods, nematodes, molluscs). Table 1.1 summarises the types of injuries caused by these different pests.

The CAS takes a two-pronged approach to weeds. They are qualified as pests when they cause yield losses (due to the competition they exert on crops) and a deterioration in the quality of harvested products (unwanted seeds present in the harvest). The weed flora is, however, part of the plant component of agricultural areas and contributes to plant diversity, which this CAS analyses regarding its potential to regulate pests.

Determining the entire chain of causality between the presence (abundance) of pests, the occurrence of injuries, the level of damages and associated economic losses is no easy task (figure 1.1). The relationship between the abundance of pests and the occurrence of injuries is not proportional, mainly because there are threshold effects for some pests. In addition, the relationship between occurrence of injuries and level of damages

9. It should be noted that losses can occur after harvest, during storage, even if the pest attack happened in the field (for example, the development of late blight on potatoes or certain fruit diseases).

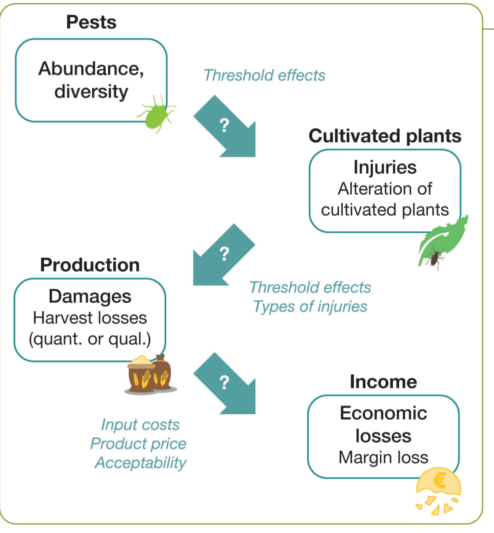
is typically not unequivocal. On the one hand, not all injuries leads to damage (i.e. when the injury does not target a harvested organ). On the other hand, crop yield and quality are composite variables resulting from various factors that interact, including meeting the crop's nutritional and water needs, making it challenging to identify and quantify losses caused by pests alone.

Table 1.1. Nature of injuries and potential damages caused by different types of pests on crops

Pest type	Injuries (observable symptoms)	Potential damages (crop losses)
Pathogens and phytophagous pests	Metabolic or mechanical alterations: – limiting plant rooting, germination and first stage of growth; – Interrupting (partially or totally) the absorption or translocation of water and nutrients (from roots or leaves to storage organs, fruit or seeds); – damaging the vital parts of the plant: storage organs, photosynthetic surfaces, reproductive organs, and support structures. → Alterations in the growth/vigour of the cultivated plant, its morphology (lesions, colour changes, deformation, necroses, galls, etc.), chemical composition (protein and sugar content, presence of toxins, etc.) or organs.	Failure of the cultivated plant to grow and/or deterioration of its organs, making it more challenging to harvest. → Yield loss. Downgrading of crop products due to non-compliance with organoleptic or health criteria. → Quality loss.
Weeds [1]	Competition with cultivated plants for resources (sunlight, water, nutrients). → Alteration in the growth of cultivated plants.	Hampered crop growth → Yield loss. Contamination of the harvest due to the weed seeds harvested at the same time as the cultivated plant. → Quality loss.
Parasitic plants [2]	Partial or total diversion of water and/or nutrients cultivated plants absorb. → Alteration in the growth or vigour of cultivated plants.	Hampered crop growth → Yield loss.

1 Crop volunteers and spontaneous plants.
2 Plants that live and develop at the expense of a host plant (e.g. sunflower broomrape).

Figure 1.1. The cascading effects of pests on crops

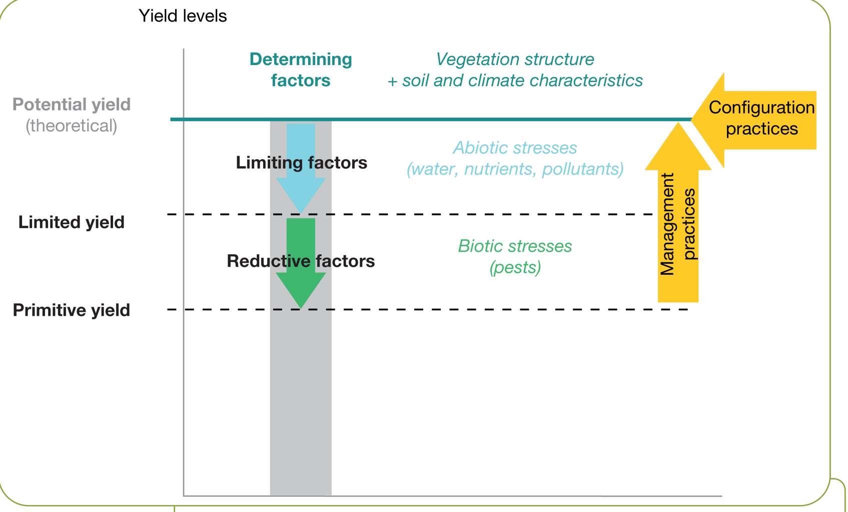


Estimates of damage caused by pests are fragmentary and only concern quantitative losses. This data comes primarily from technical institutes, which carry out yield measurements as part of controlled trials designed to assess the effectiveness of pesticides against certain types of pests. Data also comes from a few scientific papers, which provide estimates most often obtained through modelling. Such losses are evaluated in relation to potential (or achievable) yield, the maximum yield level that can theoretically be achieved when plants are not subjected to any biotic[10] or abiotic[11] stresses (figure 1.2).

Two types of yield loss estimates are available. Potential loss is the loss that could affect the crop in the absence of any protection against pests. It is typically measured by comparing plots that have been chemically treated/untreated for a given pest (or category thereof), other things being equal, and in both cases under optimised conditions regarding fertilisation and treatments against other pests. Hence, potential yield losses are overestimated by design and should be regarded as theoretical maximum values since they are obtained in a hypothetical situation of pesticide withdrawal, ceteris paribus (without implementing alternative management methods).

10. All interactions between living organisms: predation, cooperation, competition, parasitism, etc.
11. Physico-chemical factors in the ecosystem: soil characteristics, climatic, chemical and topographical factors.

Figure 1.2. Factors that determine, limit and reduce crop yield



Configuration practices define the ecosystem's structure: choice of plant genotypes (species, varieties), sowing dates and densities, and cropping sequences. Management practices aim to limit abiotic stresses (i.e., irrigation, fertilisation) and biotic stresses (such as pesticide treatments). Adapted from van Ittersum and Rabbinge (1997).

Actual loss corresponds to loss incurred despite implementing a protection strategy, often chemical, since the estimates available focus on conventional systems built around synthetic inputs. Compared with potential losses, estimates of actual losses indicate the effectiveness of current biocontrol methods. However, these estimates are fraught with uncertainty insofar as the yield also depends on the nutrient and water status of the crop, which may not be optimal (unlike the trials described above).

Table 1.2 summarises potential and actual loss estimates collected under the CAS.

Finally, the link between damage and economic loss is not a systematic one: damage only leads to financial loss if it results in a margin loss for the farmer. Yet this level of loss depends on a range of socio-economic factors such as the characteristics of the cropping system, the cost of inputs, the outlets for harvested products, and their price (which can increase when the damage affects a significant part of the sector, compensating in part for the loss of income in terms of quantity). The level of loss acceptable to the farmer is also influenced by psychological and economic factors (mainly financial or insurance-related).

Table 1.2. Orders of magnitude of average annual losses linked to pests reported in the literature

Crop	Ref.	Potential yield losses (in the absence of any protection against pests)	Actual yield losses (despite the implementation of a crop protection strategy)
Wheat	1	**Weeds**: 2.6 t/ha/year on average over 1993-2015	No data
	2	**Fungal diseases**: 1.6 t/ha/year on average over 2002-2020	No data
	3	**All pests**: 2 to 2.3 t/ha/year compared with actual yield over 1995-2012 (= 24.3 to 33% of actual yield)	No data
	4	**All pests**: 44% over 2001-2003 *including **weeds**: 18 to 29%, depending on the region* *including **diseases**: 12 to 20% depending on the region*	**All pests**: 14% over 2001-2003 *including **weeds**: 3% (or approximately 0.25 to 0.3 t/ha/year)*
	5	No data	**All pests except weeds**: 0.5 t/ha/year over 2009-2019 (or 5 to 10%, depending on the department) *including **septoria**: 0.2 t/ha/year*
	6	No data	**All pests except weeds**: 24.9% over 2010-2014 *including: **septoria** 5.5%; **yellow rust** 5.8%; **dwarf yellows** 3.2%; **brown rust** 2.5%; **powdery mildew** 2.2%; **tan spot** 1.9%; **fusariosis** 1.8%*
	7	No data	**Fungal diseases**: 0.8 t/ha/year over 2004-2008 period including ***septoria**: 0.66 t/ha/year (the rest being rusts, fusariosis, powdery mildew)*
Barley	2	**Fungal diseases**: 1.51 t/ha/year on average over 2002-2020	No data
	8	**Diseases**: 12% over 1996-1998	**Diseases**: 5% over 1996-1998
	5	No data	**Fungal diseases**: non-significant over 2009-2016
Maize	9	**Helminthosporium**: 0.6 to 0.8 t/ha/year **Fusarium head blight**: 1 to 1.4 t/ha/year	No data