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Douadia Bougherara, Céline Nauges, François Salanié and Fabienne Féménia

Toulouse School of Economics

Self-protection and self-insurance in pest management: The role of risk preferences and beliefs

Douadia Bougherara* Céline Nauges† François Salanié‡ Fabienne Féménia§

Abstract

Farmers worldwide manage yield risk mostly by applying pesticides, with possible negative impacts on human health and the environment. To analyse these decisions, we set up a two-period model in which a farmer first decides whether to adopt preventive measures that lower the risk of pest infestation (self-protection), before deciding *ex-post* about pesticides application (self-insurance). These two decisions are found to be substitutes in most cases. Under some conditions, we show that more risk-averse farmers apply more pesticides (i.e., more self-insurance) and exert fewer preventive efforts (i.e., less self-protection). We illustrate these theoretical findings using simulations calibrated from real data on crop producers from France. Decisions seem primarily driven by the costs of prevention and pesticides and by farmers' risk beliefs, while farmers' risk aversion plays a relatively minor role.

Keywords: risk; prevention; self-insurance; risk aversion; beliefs; pesticides

JEL: D81; D91; Q12

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*Corresponding author. CEE-M, Univ Montpellier, CNRS, INRAE, Institut Agro, Montpellier, France. ORCID: 0000-0001-9976-8543. E-mail: douadia.bougherara@inrae.fr

†Toulouse School of Economics, INRAE, Université Toulouse Capitole, Toulouse, France. ORCID: 0000-0002-5407-3630

‡Toulouse School of Economics, INRAE, Université Toulouse Capitole, Toulouse, France. ORCID: 0000-0001-7062-9208

§INRAE, UMR1302 SMART-LERECO, F-35000 Rennes, France. ORCID: 0000-0001-7804-1847.

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1 Introduction

Most agricultural production worldwide is nowadays highly dependent on pesticides, with attendant possible negative impacts on human health and the environment. How a farmer manages pesticides constitutes a classical example of decision-making under uncertainty: the farmer decides on his own, and under changing conditions, such as weather. The literature has so far mostly focused on static models. In this paper, we propose to consider more precisely the dynamics of this process.

Every year, for each field planted with crops, a farmer has first to decide whether to use agronomic practices (put in place before planting) that reduce the probability of pest infestation of crops later in the season. Such preventive practices (e.g., crop rotation, the management of previous crop residues) can be seen as self-protection tools. *Ex-post*, the farmer receives some information such as weather conditions, and decides whether or not to apply pesticides. This second decision is described as a self-insurance tool, since the application of pesticides reduces crop losses induced by the disease, if the disease occurs.

The distinction between self-protection and self-insurance dates back to a seminal article by Ehrlich and Becker (1972). This paper laid the ground for a series of contributions on this topic, mostly theoretical. Peter (2024), in his survey on the economic analysis of self-protection, claims that: "The biggest shortcoming of the literature is the lack of empirical work on self-protection." Even if major progress has been made on the (theoretical) understanding of the link between risk preferences and self-protection (Dionne and Eeckhoudt, 1985; Jullien et al., 1999; Eeckhoudt and Gollier, 2005), Peter (2024) points to the need for further evidence from the field, in particular regarding the role of potential behavioural biases (probability weighting, loss aversion etc.). This paper aims to provide both a theoretical study and an empirical illustration of a dynamic problem of decision-making, in which a self-protection decision is followed by new information coming (weather conditions), and finally by a self-insurance decision.

We develop a two-period model that builds on the literature studying self-protection and self-insurance decisions (Ehrlich and Becker, 1972). After the choice on self-protection has been made but before the decision on self-insurance is taken, the farmers receive some new information (here, a weather bulletin on expected rainfall) that is taken into account when they make their self-insurance decision (i.e., applying pesticides or not). We then study how costs, benefits, beliefs and risk preferences determine the level of self-protection in the first period (here, preventive practices) and of self-insurance in the second period (pesticides). As in Ehrlich and Becker (1972), we provide conditions under which the two efforts are substitutes: hence, the availability of pesticides deters preventive efforts, a case of moral hazard. We also provide conditions under which a more risk-averse farmer exerts more self-insurance efforts (a classical result in the literature), but also exerts fewer preventive efforts: this original result stems from the fact that these efforts are substitutes.

This theoretical model then serves as a basis for simulations. The model is calibrated from observed self-protection and self-insurance practices by French crop farmers. Observations come from a primary survey of 59 wheat producers from Northeast France. The farmers were surveyed on their knowledge and beliefs regarding the risk of a fungal disease, namely Fusarium Head Blight or FHB, one of the most devastating diseases of cereal crops (Moonjely et al., 2023) which impacts both wheat yield and quality. The farmers are found to be well informed about the role of preventive practices in lowering the risk of FHB on average, but we observe significant heterogeneity in their self-protection and self-insurance decisions, as well as in their risk beliefs. The simulation results confirm the theoretical predictions regarding the substitution between self-protection and self-insurance. We find that risk aversion has a moderate influence on the optimal strategies while economic conditions (i.e., the cost of the preventive practices, the cost of pesticides, and FHB-induced economic losses) and subjective risk beliefs are important drivers of farmers' behaviour.

This case study is highly relevant in the context of the growing concern worldwide on the impact of pesticides on health and the environment.[1] In Europe for example, ambitious targets to be achieved by 2030 have been set, including a 50% reduction in the use and risk of pesticides (see the EU Farm to Fork strategy and the European Green Deal).[2] One of the proposed paths to achieve this goal is to shift to alternative models of production that put more weight on preventive practices with the hope of inducing a lower dependence on pesticides (Vialatte et al., 2025). Our results suggest that the use of agronomic preventive practices as a substitute for pesticides depends on economic conditions (notably the price of pesticides and the cost of prevention effort), farmers' risk preferences and risk beliefs. Recall also our result that more risk-averse farmers may use more pesticides but also exert fewer preventive efforts. This differential effect of risk-aversion is not commonly considered by those advocating preventive agronomic practices as an alternative to pesticides; it may mean that these practices may not be as effective for more risk-averse farmers.

[1] https://www.eea.europa.eu/publications/how-pesticides-impact-human-health

[2] The objective of reducing pesticide use by 50% might be revised following the latest farmers' protests.

We review the relevant theoretical and empirical literature in Section 2. In Section 3, we explain why FHB is relevant to an empirical study of self-protection and self-insurance strategies by farmers. In Section 4, we develop and study the theoretical model that describes farmers' decisions under uncertainty while allowing for non-neutral risk preferences. Section 5 builds on the findings from the theoretical model and observations from a recent survey of 59 crop farmers from France to run simulations and assess the relative importance of economic conditions, risk preferences and beliefs on farmers' self-protection and self-insurance in pest management. Section 6 concludes.

2 Literature review

The theoretical model builds on the theoretical literature studying decisions on self-protection (or prevention) and self-insurance (Ehrlich and Becker, 1972). Self-protection, which in our case refers to the use of preventive practices, is aimed at reducing the probability of a loss, while self-insurance (the application of pesticides in our case) is aimed at reducing the size of the loss. The main result from Ehrlich and Becker (1972) is that risk aversion increases self-insurance but the impact on self-protection (or prevention) is ambiguous; the intuition being that self-protection is costly and this cost comes in addition to the loss in the bad state of Nature. Jullien et al. (1999) provide more general results, which we use in our theoretical analysis of the decision model. Eeckhoudt and Gollier (2005) show that not only risk aversion but also prudence (or aversion to downside risk) influences self-protection. Bleichrodt (2022) attributes the lack of prevention efforts to three factors: prudence; likelihood insensitivity (the perceived probability is a flat transform of the true one); and loss aversion.[3] In this article, we focus on two behavioural factors, namely risk aversion and risk beliefs. As in Ehrlich and Becker (1972), we provide conditions under which the two efforts are substitutes: hence, the availability of pesticides deters preventive efforts, a case of moral hazard. We also provide conditions under which a more risk-averse farmer exerts more self-insurance efforts (a classical result in the literature), but also exerts fewer preventive efforts: this original result stems from the fact that these efforts are substitutes.

Our analysis of self-protection and self-insurance in crop farming complements empirical studies that try to link agronomic practices such as crop choice, genetic diversity, soil management with subsequent chemical input use and the purchase of insurance products.

[3]See also Peter (2024) for a recent survey.

The evidence is mixed: using data from French crop farms, Bareille and Letort (2018) and Sodjahin et al. (2025) find that crop diversity lowers pesticide use and herbicide use, respectively, on cereals. However, farmers who planted legumes before cereals were not found to reduce their subsequent use of nitrogen, despite the well-known nitrogen surpluses delivered by legumes (Sodjahin et al., 2025). Di Falco et al. (2014), using a sample of Italian farms, find that crop diversification, by enhancing the provision of ecosystem services, induces lower adoption of financial insurance. The use of crop diversification (or biodiversity in general) as a substitute for insurance products is also discussed in Baumgärtner (2007) and Quaas and Baumgärtner (2008).

When repeated over time, agronomic practices have a positive impact on the stock of nutrients, soil structure, pollination, and biological control. Even if not explicitly described as self-protection, such practices effectively build productive capacity over time. Thomas (2003) designs a dynamic optimization model of nitrogen management that accounts for nitrogen carry-over from previous crops. He studies the possibility of farmers substituting nitrogen accumulated in the soil through previous land allocation decisions for current fertiliser applications. Chen et al. (2025), using data from a 35-year cotton field experiment in West Tennessee, develop a stochastic dynamic programming model to investigate optimal cover crop adoption policies taking into account cumulative effects on soil fertility, and they derive conditions under which cover crop adoption can induce savings in fertiliser expenditure. Bontems and Thomas (2000) studies the role of risk attitudes and value of information in a model describing farmers' optimal decisions on fertiliser use when random shocks occur between subsequent production stages.

Our paper also relates to the vast literature on risk and uncertainty in agriculture. The question of risk preferences in agriculture has led to the publication of numerous studies, and there has recently been a growing interest in farmers' risk perceptions or beliefs, with authors calling for the necessity of distinguishing between objective and subjective risk assessments (Hardaker and Lien, 2010). In the present article, we consider both farmers' risk preferences and farmers' risk beliefs.

Risk preferences have long been identified under the assumption that agents form rational and "objectively-correct" beliefs (Manski, 2004). However, if agents misperceive risks and form subjective (biased) beliefs that cannot be observed, then risk attitudes cannot be separately identified. One very nice illustration of the discrepancy between farmers' objective and subjective beliefs and its impact on the estimation of their risk attitudes can be found in Fezzi et al. (2021).[4] This article provides evidence that farmers are more likely to underestimate probability of events that are more distant in the past, an instance of the so-called "recency bias". Other types of biases that have been recently identified in the literature studying farmers' beliefs include "motivated beliefs". Arora and Feng (2024) observe misperceptions of past weather changes (in terms of temperature, precipitation, and drought) for a vast majority of the US crop farmers that they surveyed. The direction of the bias suggests that farmers' perceptions are driven by "motivated beliefs" in the sense that their incorrect beliefs help justify their past decisions in terms of land use.[5]

3 Context: the case of Fusarium Head Blight on wheat

The case study that inspired this article is focused on farmers' management of Fusarium Head Blight (FHB), a quite common fungal disease worldwide, that is described as "the most destructive and economically significant wheat disease in the world" (Al-Hashimi et al., 2025). It also provides a textbook case for studying self-insurance and self-protection behaviours.

FHB is well known by French wheat growers since it is relatively common, especially in wet years.[6] FHB impacts both grain quality and yield, leading to non-negligible economic losses. In France, yield losses can reach 2-2.5 tonnes per hectare (ha), hence possibly one third of the average wheat yield. FHB also generates mycotoxins that pose health risks to humans, animals, and the ecosystem (Al-Hashimi et al., 2025). When grains exceed the legal mycotoxin limit, wheat is downgraded from food to animal feed and hence it sells at lower prices.

Weather information before flowering is crucial information for farmers. Indeed, FHB is more likely to develop when there is an excessive amount of cumulative rainfall over the seven days before and seven days after wheat flowering[7] (40mm of cumulative rainfall over the 14-day period around flowering is the critical threshold).[8] Field trials have

[4]Evidence of discrepancies between objective (or rational) probabilities and subjective beliefs when choices are made under uncertainty has been found in other domains as well, see e.g., Wiswall and Zafar (2015) or Hendren (2017).

[5]Other related literature that is not discussed here includes farmers' beliefs updating (Barham et al., 2015; Lybbert et al., 2007).

[6]In France in 2017, around one-third of the surface planted with wheat was exposed to a significant risk of FHB (Vialatte et al., 2023).

[7]Fungal spores that are splashed up the plant or move from leaf to leaf are the main source of infection. Contamination through wind is less common.

[8]Source: Arvalis technical institute. See for example advice to farmers from Northeast France on

shown that the risk of FHB can be moderated by agronomic practices: the incidence of FHB is lower on parcels that were planted with straw cereals before growing wheat, and on parcels where soil debris were ploughed or buried (Moonjely et al., 2023). On the contrary, growing wheat after maize or sorghum and leaving residues on the surface increase the incidence of FHB. In addition to the use of preventive practices, farmers can eradicate the disease (and avoid any loss) by applying fungicides at the time of flowering, after getting updated weather forecasts. The FHB risk level conditional on practices and cumulative rainfall is summarized in Table 1.

Table 1 FHB risk level conditional on practices and cumulative rainfall (source: Arvalis)

Practices		**Risk level 1 to 7 scale**	**Recommendation in terms of fungicide application**	
Crop planted before wheat	Residue management		Rainfall < 40 mm	Rainfall > 40 mm
Straw cereals (SC)	Ploughed/buried (BR)	1	No	No
	On surface (RS)	2	No	No
Maize/Sorghum (MS)	Ploughed/buried (BR)	2-3	No	Yes
	On surface (RS)	5-6	Yes	Yes

Notes: The risk level corresponds to a wheat variety of average sensitivity to FHB. In the original Arvalis ranking, there is a distinction between low-, average-, and highly-sensitive wheat varieties. In our sample, farmers reported planting varieties that are classified by Arvalis as being of an average sensitivity to FHB (mostly CHEVIGNON and KWS-SPHERE). Also, risk levels when maize or sorghum was planted before depend whether maize is used to produce grains or fodder. Source: Arvalis Institute, cf. original table in Appendix A.

The information shown in Table 1 comes from a FHB risk assessment made by Arvalis, a technical institute that specialises in research and development on arable crops and that provides advisory services to farmers.[8] The FHB risk level is evaluated on a scale of 1 to 7, depending on the combination of practices and cumulative rainfall. Arvalis recommends applying fungicides when maize or sorghum (MS) was planted before wheat and previous crop residues were kept on the surface (RS), whatever the level of rainfall (very high risk, estimated at 5-6 depending whether maize is used to produced grains or fodder); and when maize or sorghum was planted before wheat (MS), previous crop residues were buried (BR), and cumulative rainfall exceeds 40 mm (risk estimated at 2-3). The technical institute does not recommend any chemical treatment when straw cereals were planted before wheat (SC). In this case, the FHB risk is at its minimum (1) when previous crop

FHB management, link [in French].

residues were buried (BR) and just slightly higher (2) when residuals were left on the surface (RS).

4 How to prevent FHB–or fight it: A theoretical model

In order to understand the key trade-offs, we set up and study a decision model of a farmer, with two periods, and two decisions: first about preventive practices, then about fungicides application.

4.1 The main framework

A single farmer manages a given crop field over the course of one farming year. In the first period, typically in fall, the farmer selects some or none of the preventive practices discussed in Section 3, with an associated cost $x \geq 0$. In the second period, say in spring, the farmer is informed about the amount of rainfall r, drawn in some known distribution. The farmer then makes another decision with cost y, about whether to apply fungicides ($y = y_1 > 0$) or not (and in this case $y = 0$). Hence, this decision is binary, in accordance with the actual management of FHB. Note also that when choosing y, the farmer only knows x and r, and does not know whether FHB will ultimately develop.

We assume that fungicides are a powerful tool: if the farmer applies fungicides, FHB will not develop. Otherwise, FHB occurs with a probability $p(x, r)$, that depends on the use of preventive practices and on the amount of rainfall. We have underlined previously that more rain makes FHB more likely to occur, while the effect of preventive practices is the opposite. We thus assume:

Assumption 1 *The probability $p(x, r)$ of occurrence of FHB, conditional on the first-period effort x and rainfall r, is weakly increasing in r and weakly decreasing in x.*

If FHB occurs, and in this case only, the farmer bears a fixed loss $\overline{L}$. To make the problem interesting, we assume

$$0 < y_1 < \overline{L},$$

so that (given x), the farmer's payoff can only take one of three values, that are ordered as follows:

$$W_0 - x - \overline{L} < W_0 - x - y_1 < W_0 - x.$$

Note that the use of fungicides reduces the risk borne by the farmer, since it replaces a risky lottery with extreme payoffs by a certain, intermediate payoff. As argued in Jullien et al. (1999), this property in fact defines self-insurance. By contrast, the first-period decision about preventive practices is a self-protection effort: a higher value for x reduces the probability that FHB occurs, but it also reduces the farmer's revenue in the case that it occurs nevertheless.

4.2 Substitutability, and a blackbox

One interesting question is whether the two efforts are substitutes: does an increase in the price of fungicides favour the use of preventive practices? Or equivalently, in this two-decision setting: does a reduction in the use of fungicides favour the use of preventive practices? It turns out that the answer depends on the information the farmer has at the time of the decisions.

The blackbox we want to open here is linked to the definition of the probability $p(x, r)$. The statistical foundation for it is based on the existence of a state of nature s, drawn initially by Nature, and which determines the occurrence of FHB, together with x and r. Hence, the FHB occurs if and only if the triple (s, x, r) belongs to some given set, and $p(x, r)$ is the conditional probability of this event, given x and r. Assumption 1 simply requires that this set grows with r and decreases with x.

By opening this blackbox, we uncover an important source of heterogeneity. Intuitively, s is a measure of whether a particular field is prone to FHB. This depends *inter alia* on the previous crop grown in that field, an element which practitioners control for. This also depends on other elements, such as the past occurrences of FHB, that only the farmer may have observed. Hence, it is likely that different farmers have different evaluations of the probability $p(x, r)$.

In addition, we are now able to define precisely the notion of substitutability. The farmer's payoff can now be represented by a stochastic production function that depends on (x, y, r, s), as in Quiggin and Chambers (2001). As a thought experiment, suppose that the farmer knows from the start the values of s and r, so that there is no uncertainty. Then the farmer has to decide a value for x, and a value for y. Clearly, switching from $y = 0$ to $y = y_1$ makes preventive measures unproductive. Conversely, increasing x so that one switches from a state in which FHB occurs to a state in which it does not, makes fungicides irrelevant. Thus, in this thought experiment, x and y are clearly substitutes: increasing one of these variables reduces the marginal payoff associated with an increase in the other variable.

However, in our framework, the farmer initially ignores both s and r, and both decisions have to be taken under uncertainty. Then substitutability does not follow directly from our technological assumptions: this property depends on the farmer's risk attitude, as we now show.

4.3 The case of expected utility

We assume in this section that the farmer is a risk-averse, expected utility maximizer. Let the concave function U represent their preferences. This will allow us to derive formal results; some of which can be extended to Rank-Dependent Utility frameworks.

The second-period problem: In the second period, after the farmer has chosen the preventive practices x and has learnt the rainfall r, they have to choose whether or not to apply fungicides. This amounts to comparing the expected utility from a lottery

$$p(x,r)U(W_0 - x - \overline{L}) + (1 - p(x,r))U(W_0 - x)$$

to the sure payoff

$$U(W_0 - x - y_1).$$

Clearly, fungicides will be applied more often if the loss $\overline{L}$ is higher, or if their cost y_1 is lower. It is also easily seen that the farmer applies fungicides if and only if rainfall is high enough; this is because $p(x,r)$ increases in r. Finally, we expect a more risk-averse agent to favour the sure outcome over the risky lottery. A direct application of Proposition 5 in Jullien et al. (1999) indeed leads to the following result:

Lemma 1 *For the same initial choice of x and the same rainfall r, if a farmer decides to apply fungicides, then (ceteris paribus) every more risk-averse farmer also applies fungicides.*

Lemma 1 underlines that the second-period decision also depends on risk aversion, which is a personal characteristic of the farmer. While Table 1 gives some experts' recommendation on this threshold, and how it should vary with preventive measures, a given farmer may legitimately disagree, depending on their aversion to risk. Heterogeneity now manifests itself through the channel of risk aversion; we emphasized the role of private information about p in the previous subsection.

Finally, one may wonder whether the two efforts are still substitutes in the presence of uncertainty. Based on our Expected Utility framework, the analysis in Appendix B distinguishes two effects. The first effect is technological: an increase in x reduces the probability of occurrence of FHB and thus makes fungicides less useful. For a risk-neutral farmer, this is the only effect, and it clearly supports the idea that the two efforts are substitutes.

The second effect is trickier: an increase in x is costly and makes the farmer poorer. And it is plausible that a poorer farmer be more risk-averse, a property known as Decreasing Absolute Risk-Aversion (DARA). Under DARA, it is thus theoretically possible that an increase in x leads to an increase in y for some values of r, thus rejecting that these efforts are always substitutes. For example, if pre-harvest measures are financed by debt, and FHB implies a very costly bankruptcy, then one understands that a farmer may in the end apply fungicides in order to get rid of the uncertainty. Still, this scenario does not seem plausible, and one can also wonder whether this effect is relevant for optimal decisions: it does not seem very consistent to implement costly preventive practices if the farmer anticipates with a high probability that they will apply fungicides.

We summarize this discussion by proposing that these wealth effects are small, and certainly not large enough to overcome the first technological effect discussed above. Technically, this amounts to adopting the opposite assumption to DARA. Note that by doing so we still encompass the case of a risk-neutral farmer, as well as the case of Constant Absolute Risk Aversion (CARA) for which wealth effects vanish:

Lemma 2 *Suppose the farmer's risk-aversion is weakly increasing with wealth. Then the two efforts are substitutes.*

The first-period problem: In the first period, the farmer does not know the value of future rainfall, and consequently he chooses x to maximize an expected utility:

$$E \max \Big(U(W_0 - x - y_1), p(x,r)U(W_0 - x - \overline{L}) + (1 - p(x,r))U(W_0 - x) \Big).$$

It is no surprise that spending more on preventive practices is warranted only if this reduces the need for fungicides. It thus follows that the optimal value for x is higher if the cost of fungicides y_1 increases, or if the loss $\overline{L}$ is lower. Appendix C formally establishes these properties. It also provides assumptions under which the sensitivity of the farmer's revenue to r is reduced by a higher x. Then we can once more apply Proposition 5 in Jullien et al. (1999) to obtain:

Lemma 3 *Suppose that more rain makes preventive practices less effective, i.e., the cross-derivative* p_{xr} *is weakly positive. Suppose also that the farmer's preferences exhibit CARA. Then (ceteris paribus) a more risk-averse farmer spends less on preventive measures, and applies fungicides more often.*

The first assumption is purely technological and allows, for example, for the case when p is a difference, as in $p(x, r) = a(r) - b(x)$, a and b being two increasing functions. The CARA assumption implies in particular that the two efforts are substitutes. Overall, the result might seem paradoxical: intuitively, we expect risk-averse agents to make more effort to reduce the risk. In fact, we know since Ehrlich and Becker (1972) that this sort of comparative statics exercise yields ambiguous results. The intuition here is as follows. The second-period effort is a self-insurance effort, and we know that more risk-averse agents choose higher self-insurance efforts, as proven in Lemma 3. Moreover, when rainfall is higher the best practice is to apply fungicides, and our technological assumption dictates not using preventive practices in such states. Hence, this assumption reinforces the substitution between the two decisions, and this provides a channel through which a more risk-averse farmer reduces his self-protection effort x.

4.4 Beliefs distortions and rank-dependent utility

We have already mentioned that farmers may have different beliefs because they possess more information about past practices and past occurrences of FHB. It might also be that farmers are more or less pessimistic, a psychological feature that would impact their decisions.

For the second decision on fungicides application, the case is rather simple: either one applies fungicides, and then the risk disappears; or one does not, and then the risk is measured by the probability $p(x, r)$, with two possible outcomes, bad or good. Belief distortion here is equivalent to Rank-Dependent Utility because the ranking of these two outcomes is always the same: the event with probability $p(x, r)$ is the bad outcome.[9]

A similar result holds for the first period decision, if one proceeds as follows. Given x and a strategy $y(r)$ of application contingent to r, there are only three possible outcomes, with a given ranking:

$$W_0 - x - \overline{L} < W_0 - x - y_1 < W_0 - x.$$

[9] Diecidue and Wakker (2001) provides a simple discussion of Rank-Dependent Utility. Harrison (2024) and Harrison and Ng (2019) survey applications of behavioural decision-making under uncertainty.

The probability of the first outcome is simply the probability that x, r and s are such that $y(r) = 0$ and the FHB does not occur, while the probability of the third outcome is that FHB does occur; the probability of the second outcome is simply the probability that $y(r)$ equals y_1. The key is that the ranking of these outcomes is always the same, so that once more Rank-Dependent Utility is equivalent to a distortion in these probabilities. Our simulations below will explore the role of changes in beliefs on the farmer's optimal decisions.

4.5 To summarize

This study of this two-period model has shown how economic conditions, risk preferences, and risk beliefs determine optimal decisions. Self-protection and self-insurance appear to be substitutes. Under risk aversion and a CARA utility function, more risk-averse farmers are found to use pesticides more often (self-insurance strategy) and to exert less prevention effort, under some reasonable conditions on the technology. This is a novel result in this literature. In the following, we will use simulations calibrated using real farm data to assess the relative role of these three main drivers on farmers' optimal behaviour.

5 Empirical illustration

5.1 Primary survey of wheat growers

The empirical illustration builds on a primary survey of 59 wheat growers from Northeast France.[10] The survey, which focuses on farmers' management of FHB in wheat, was run during the winter of 2023-24 in collaboration with CERFRANCE-ADHEO.[11] This company, which provides accounting services for farmers, sent the survey to its clients and shared with us complementary farm-specific information including farm size, crop-specific land area and chemical input use and costs, revenues, size of animal herd, farmer's age etc.

[10]Farms are located in three neighbouring *départements* in the north-east of France: Marne, Meurthe-et-Moselle, and Meuse.

[11]The survey protocol has been pre-registered on the OSF platform View link to preregistered report. Our survey complies with General Data Protection Regulation (GDPR). Informed consent was provided by all survey participants. The sample might seem small to the reader. An original database containing both economic data and behavioural data for farmers was built using answers gathered from a primary survey. For such surveys, farmers are commonly reached through partnerships with mediating institutions such as accountancy firms, cooperatives or technical institutes. In our case, the pool of farmers to be reached through the accountancy firm CERFRANCE-ADHEO was about 250. Thus, the response rate was good (about 24%).

The 59 farmers were surveyed on their beliefs regarding the effectiveness of agronomic practices (here choice of the crop planted before wheat and management of the previous crop residues) in reducing the risk of FHB in wheat, conditional on the amount of cumulative rainfall around the time of flowering. We also asked about the incidence of FHB on their farm and their recollections regarding the occurrence of excessive rainfall (cumulative rainfall exceeding 40 mm) over the last 10 years. Farmers were also questioned on their habits regarding their use of preventive practices and their use of fungicides on their largest field planted with wheat.[12] Finally, information on socio-demographics, attitudes, and risk aversion was collected.

The farm-specific data were matched with daily information on rainfall provided by the national meteorological institute (Météo-France) at the municipality level, from 2015 to 2022. In each year from 2015 to 2022, we measured the amount of rainfall in each municipality over the 14-day period around wheat flowering. Flowering time in each year was taken from information bulletins published on a regular basis by the regional office of Arvalis.

5.2 Main findings from the primary survey

Farmers declared experiencing FHB on their wheat field 1.8 times over the last 10 years on average (varying from 0 to 10 times, with standard deviation equal to 1.6).[13] The reported FHB incidence is in line with observed rainfall over the period 2015-2022: for the municipalities where the farms are located, the total amount of rainfall over the 14 days around flowering time exceeded 40 mm three times for one farm and twice for 51 farms.[14]

Figure 1 illustrates farmers' statements about their usual practices in terms of crop choice and soil residues management, and their use of fungicides over the last 10 years. Each dot represents a farmer. On the vertical axis, the practices are ordered based on their effectiveness against the risk of FHB (see Arvalis risk level in Table 1). Planting wheat after straw cereals and burying residuals (SC + BR) is considered to be the most effective

[12]The 59 farmers were asked about their habits in terms of planting straw cereals or maize/sorghum before wheat and in terms of residues management. We consider that a practice is "commonly used" by a farmer if they reported using it "often" or "very frequently" (other possible answers were "sometimes", "rarely", and "never").

[13]Nine farmers reported no occurrence of the disease, 18 farmers indicated a single occurrence, 20 farmers reported two occurrences, eight farmers reported three occurrences, and four farmers reported four occurrences or more over the last 10 years.

[14]The weather conditions were really bad in 2016 (all farms in the sample recorded a total amount of rainfall above 40 mm) and in 2018 (about two-third of the farms were affected by excessive rainfall).

preventive practice against FHB (risk estimated at 1 on a 1 to 7 scale by Arvalis). Risk level equal to 2 on the vertical axis corresponds to farmers who usually plant wheat after straw cereals but leave the residuals on the surface (SC + RS). Farmers usually planting wheat after maize or sorghum face high levels of risk. Farmers who bury residuals (MS + BR) face a risk estimated at 2-3 and farmers who leave residuals on the surface (MS + RS) a risk estimated at 5-6 on 1 to 7 scale. The latter combination of practices is considered to be the least effective against FHB.

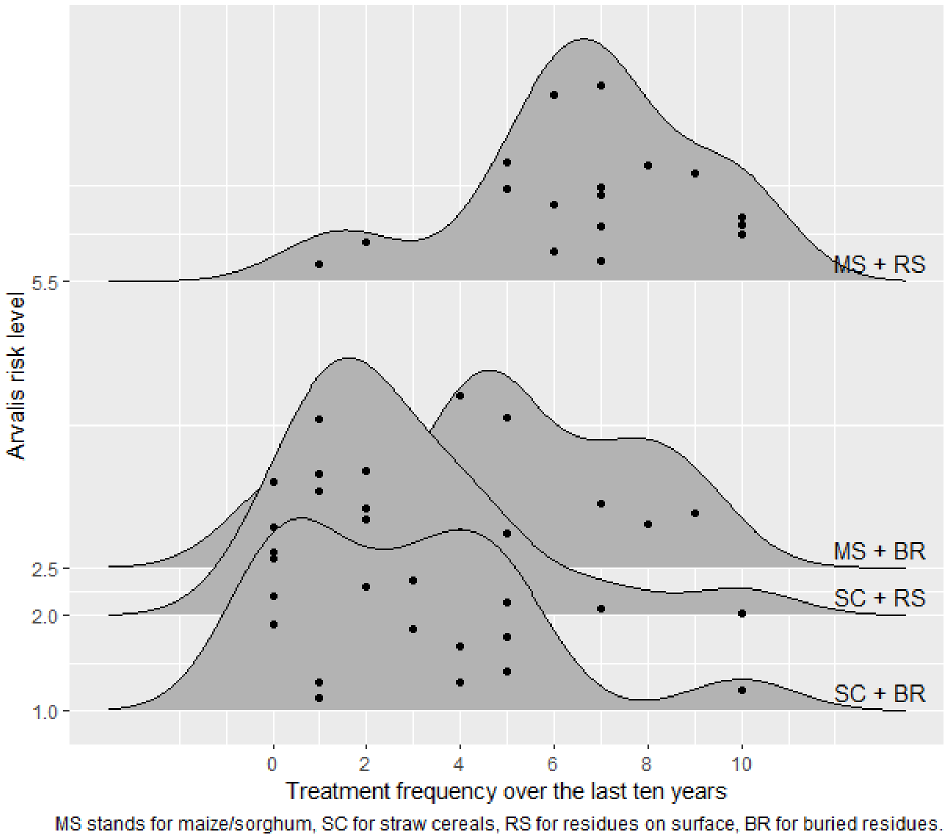

Fig. 1 Practices and frequency of treatment (59 farmers)

Farmers appear to be generally well informed about the FHB risk associated with the various agronomic practices: the farmers who use preventive practices that lower the risk of FHB use fungicides less often, on average (Figure 1): the 33 farmers who commonly plant straw cereals (SC) before wheat, applied fungicides on average 2.8 times over the last 10 years, while the 26 farmers who planted maize or sorghum before wheat (MS), applied fungicides six times on average over the last 10 years. However, we also observe that farmers adopting low-risk practices (SC + BR or SC + RS) still apply fungicides on a regular basis (even if not each year), even if chemical treatment is not supposed to be necessary (see Arvalis' recommendations in Table 1).

Farmers, on average, are found to be well informed about the relative risk of various practices and the role of rainy conditions. Each farmer was shown eight scenarios corresponding to the four possible combinations of practices (either straw cereals or maize/sorghum before wheat, combined with either buried residues or residues left on surface), and two rainfall conditions (low rainfall vs. excessive rainfall, i.e. above 40 mm) and was asked to assess FHB risk in terms of disease incidence over 10 years. Table 2 shows the average risk assessment across the four combinations of practices and two levels of rainfall.

Table 2 Average farmers' beliefs about the frequency of FHB over 10 years as compared to FHB risk level assessed by Arvalis

Practices		**Risk level 1 to 7 scale** (Arvalis)	**Average farmers' beliefs**[a] **according to rainfall**	
Crop planted before wheat	Residue management		< 40 mm	> 40 mm
Straw cereals (SC)	Ploughed/buried (BR)	1	1.7 (1.5)	4.9 (2.4)
	On surface (RS)	2	2.4 (1.6)	5.7 (2.2)
Maize/sorghum (MS)	Ploughed/buried (BR)	2-3	3.5 (2.1)	6.8 (2.3)
	On surface (RS)	5-6	4.3 (2.2)	7.9 (2.0)

[a] Farmers' beliefs are measured on scale of 0 to 10. These columns show mean and standard deviation in parentheses.

On average, farmers consider that cumulative rainfall above 40 mm always increases the probability of FHB, whatever the preventive practices. The average ranking of the four preventive practices is also consistent with Arvalis' own ranking. However, the standard deviations also indicate significant heterogeneity in beliefs (or subjective risk assessments) among the 59 farmers.

Farmers' average belief of FHB incidence is 5 out of 10 when planting straw cereals before wheat if there is excessive rainfall, which is consistent with the observation that farmers using these practices treat more often than that recommended by Arvalis (cf. SC + RS and SC + BR in Figure 1). Farmers' beliefs about FHB risk are found to be positively correlated with their stated frequency of fungicides application over the last 10 years, with correlation coefficients varying from 0.3 to 0.7 depending on farmers' usual practices.

The vast majority of farmers have accurate recollection of the number of very bad years in terms of rainfall: a total of 43 farmers declared experiencing at most three years of excessive rainfall (cumulative amount above 40 mm around the time of flowering) over the last 10 years. Among them, 19 declared getting excessive rainfall twice, which is in line with the meteorological data indicating two very bad years for most of the farmers: 2016 and 2018. However, there is a share of farmers who stated having experienced at least four very bad years, which suggests there may exist some upward-biased recollection of bad conditions. The latter observation may echo findings in Arora and Feng (2024) about farmers' motivated beliefs: an upward-biased belief in terms of bad weather conditions may be used by farmers to justify their decision to use pesticides in the past. The 43 farmers who claimed experiencing three or fewer years with high rainfall at flowering stated using pesticides 3.7 times over the last 10 years, on average. The nine farmers who claimed experiencing bad weather conditions during at least four years used pesticides six times over the last 10 years, on average.

Finally, farmers were asked about their willingness to take risks in their farming activity, on a scale of 1 (definitely not willing) to 10 (very much willing) (global assessment as in Dohmen et al., 2011). The average risk-taking indicator is 5.2 on the sample and the median is 5, varying from 1 (for one farmer) to 10 (for three farmers). The sample gathered 10 farmers aged between 25 and 34 years, 16 farmers aged between 35 and 44, 20 farmers aged between 45 and 54, 11 farmers aged between 55 to 64, one being above 65 and the last one not being willing to respond.

5.3 Simulations

The framework for the simulations builds on the theoretical model described in Section 4. In the following, we determine farmers' optimal strategies in terms of self-protection (use of preventive measures) and self-insurance (use of fungicides) under different economic conditions, risk preferences, and beliefs. We follow the model in Section 4: farmers decide first on the use (or not) of preventive practices. They then receive a weather bulletin which informs them about the level of rainfall r at the time of flowering, and finally decide whether or not to apply fungicides. We are particularly interested in evaluating the conditions under which the farmers switch from using preventive practices (self-protection) to using fungicides (self-insurance).

We make simplifying assumptions for the model to be tractable and to reflect actual farmers' choices. We assume only two cases regarding rainfall r, the so-called "good" or "low rainfall" case which corresponds to a total of cumulative rainfall over the 14-day period around flowering of less than 40 mm, and the so-called "bad" or "high rainfall" case when total rainfall is above 40 mm and the risk of FHB is at its highest (which reflects the assumption that p is increasing in r).

Regarding fungicide application y_1, we can safely assume that farmers either apply one single dose or no dose.[15] If fungicides are applied at cost y_1, then FHB does not develop and the farmers incur no loss, whatever the level of rainfall and the use (or not) of preventive practices. There is a fixed cost $y_1 > 0$ linked to treatment which farmers incur only if they decide to treat.

Regarding prevention effort x, we assume two sets of practices: x_0 that represents low-cost practices with the least effectiveness against FHB, and x_1, high-cost practices that are the most effective to lower the risk of FHB. We classify as preventive practices ploughing or burying residues (whatever the crop planted before) as well as leaving residues on the surface if straw cereals have been planted before wheat. This corresponds to pre-harvest practices with a risk level equal to or lower than 3 on the Arvalis scale. For these practices, treatment is recommended only when there is high rainfall and maize was planted before. If, on the contrary, maize or sorghum was planted before wheat and residues were left on the surface, we consider that farmers decided not to adopt preventive practices. In this case, the risk level is estimated at 5-6 and Arvalis recommends treating whatever the level of rainfall (see Table 1).

We use farmers' accounting data provided by CERFRANCE-ADHEO and rainfall data at the municipality level from METEO-FRANCE to set relevant benchmark values for the model parameters. In the benchmark case, we have:

- W_0, initial wealth: 600 euros per ha;
- y_1, the cost of fungicides (self-insurance): 40 euros per ha;
- $\overline{L}$, we estimate the loss induced by FHB at 100 euros per ha;
- x, the cost of prevention effort (self-protection). For simplicity, we assume $x_0 = 0$ and $x_1 > 0$. Since the use of preventive practices may induce some opportunity cost that is difficult to measure and may vary across farmers, we will consider that x_1 can vary from 10 to 100 euros per ha;[16]
- $p(x, r)$: the probability of FHB conditional on the use of preventive practices and the level of rainfall (low or high). This probability can take four values, as described

[15]From the authors' discussions with Arvalis' experts.

[16]For mixed crop-animal farms, not growing maize before wheat can entail some opportunity cost since maize is primarily used to feed the cows.

in Table 3;

- the probability of a low rainfall state is set at 0.80, while that of high rainfall is set at 0.20. These probabilities were calculated from rainfall records over the 2015-2022 period for the municipalities covered by the survey.

The assumptions made on $p(x, r)$; that is, the probability of FHB conditional on the use (or not) of preventive practices and the level of rainfall, are crucial. We explain in Appendix A how we derived the four probabilities in Table 3.

Table 3 Probability of FHB conditional on prevention efforts, x, and level of rainfall, r

Use of preventive practices (x)	**Level of rainfall around flowering (r)**	
	≤ 40 mm	> 40 mm
YES	0.1	0.5
NO	0.5	0.9

These probabilities are based on Arvalis' risk level assessments and can be seen as objective risk probabilities for France. As discussed earlier, there is heterogeneity in farmers' beliefs on FHB occurrence (cf. Table 2). This heterogeneity may be explained by farmers' being more knowledgeable about local conditions, and/or behavioural biases (e.g., farmers being more or less pessimistic).

In Section 5.3.1 and Section 5.3.2, we assume that the farmers make their decisions based on objective risks as defined in Table 3. Under these assumptions, the effectiveness of preventive practices is the same whatever the level of rainfall (that is, using preventive practices lowers the probability of FHB by 0.4 probability points under both low and high level of rainfall, cf. Table 3).

In Section 5.3.3, we check how optimal strategies change under different assumptions on risk probabilities.

5.3.1 The role of economic conditions

We test the sensitivity of farmers' optimal strategies in terms of prevention and application of fungicides to the main economic variables: the economic cost of prevention x, the loss $\overline{L}$, and the cost of fungicides y_1 (cf. Figure 2). For now, we focus on the case of risk neutrality (Figures 2-a and 2-d) and we discuss farmers' optimal strategies for the per ha cost of preventive practices x varying from 0 to 100 euros and the per ha loss $\overline{L}$ varying from 100 to 300 euros. All other variables are set at their benchmark levels.

For any given loss, the farmers will use preventive practices and apply fungicides under high rainfall conditions (green area on the graph) as long as the cost of prevention is below some threshold. Above this threshold, the farmers will stop adopting preventive practices and they will use fungicides whatever the level of rainfall (red area), which illustrates that self-protection and self-insurance are substitutes under risk neutrality (cf. Section 4.2). For example, if the loss is equal to 150 euros per ha, the farmers use preventive measures (along with fungicides only in high rainfall condition) as long as prevention costs are lower than 20 euros. For a higher cost of prevention, the farmers stop using preventive practices and apply fungicides whatever the level of rainfall.

In Figure 2-d, we show farmers' optimal strategies for x varying from 0 to 100 euros and y_1 varying from 0 to 100 euros. The loss is set at 100 euros per ha. The set of optimal strategies is more complex in this case. As expected, the use of preventive practices depends on its cost (dark and light green areas correspond to cases where preventive practices are used). When the prevention cost exceeds 40 euros, the farmers stop using preventive measures (i.e., no self-protection) and their use of fungicides depends on their cost: if the cost of treatment is lower than 50 euros, the farmers apply fungicides whatever the level of rainfall (red area). For a cost y_1 above 50 euros and below 90 euros per ha, the farmers apply fungicides with high rainfall only (orange area). If the cost of treatment exceeds 90 euros per ha, the farmers do nothing (this corresponds to the grey area on the graph with no preventive measures and no treatment).

Economic conditions influence farmers' strategies under the assumption of risk neutrality, and farmers' choice in terms of preventive measures and application of fungicides follows basic economic intuition. In the next section, we discuss the role of risk preferences.

5.3.2 The role of risk preferences

We assume a CARA utility function with two different levels of risk aversion: a rather risk-averse farmer (equivalent to a coefficient of 2 in a CRRA utility function) and an extremely risk-averse farmer (equivalent to a coefficient of 4).[17] In Figure 2-b, we show optimal strategies for x varying from 0 to 100 euros and $\overline{L}$ varying from 100 to 300 euros, for a rather risk-averse farmer, while Figure 2-c shows the same for an extremely risk-

[17] We adopt the terminology of Anderson and Dillon (1992).

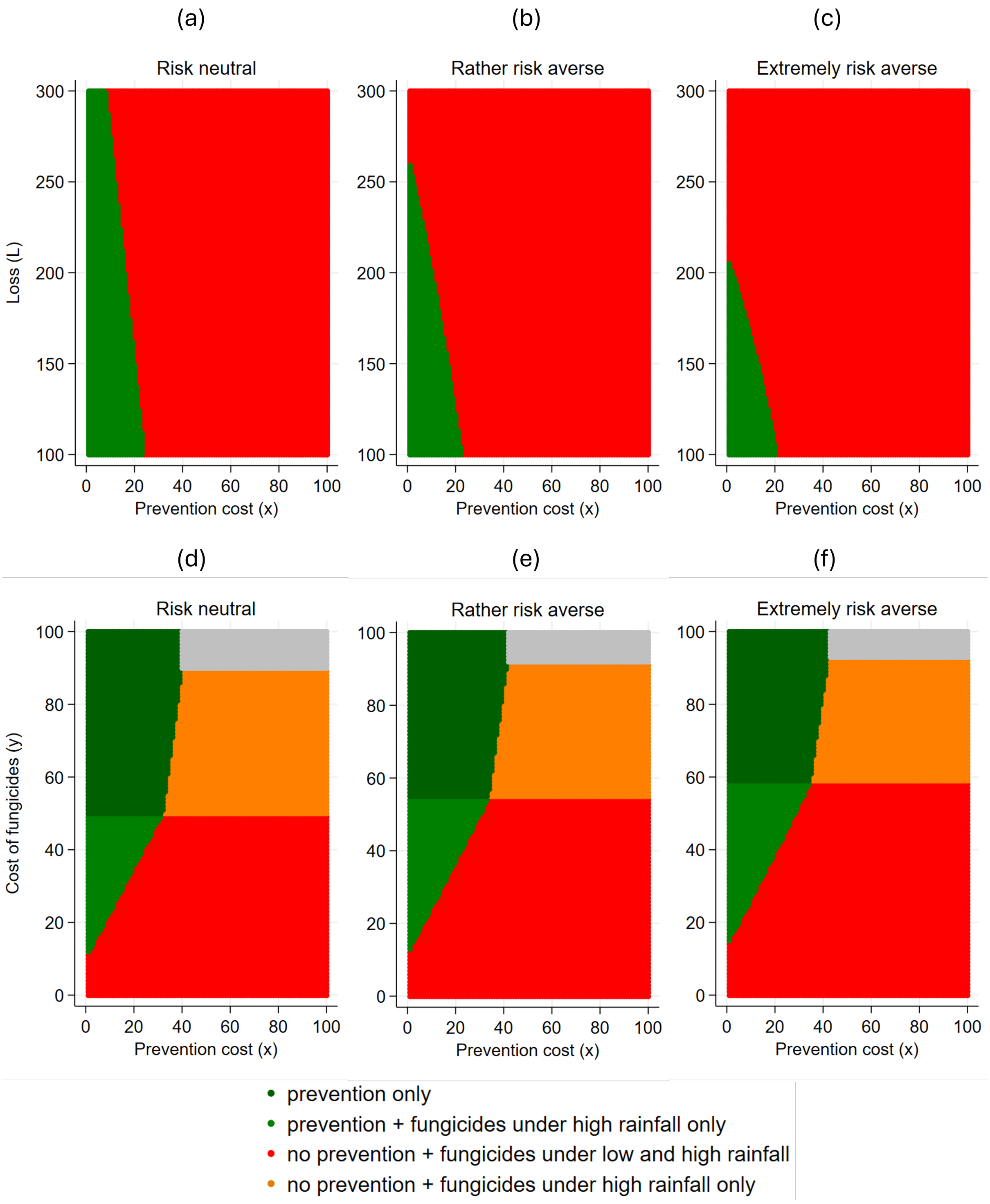

Fig. 2 Optimal strategies for varying economic conditions: prevention cost (x), losses ($\overline{L}$) and cost of fungicides (y_1) (in euro per ha) and for varying levels of risk preferences

averse farmer. In Figure 2-e, we show optimal strategies for x varying from 0 to 100 euros and y_1 varying from 0 to 100 euros, for a rather risk-averse farmer, while Figure 2-f is for an extremely high risk-averse farmer.

In line with Lemma 3, a more risk-averse farmer is found to switch earlier to self-insurance (i.e., the use of fungicides) and to make fewer preventive efforts than a less risk-averse farmer. Even if optimal strategies do depend on risk preferences, our simulation results show that the magnitude of the impact remains moderate even for an extremely risk-averse individual.

5.3.3 The role of beliefs

We assume probability beliefs vary with magnitude + or - 0.2, in the range of observed standard deviations of farmers' beliefs as measured in the survey (see Table 2). The new set of probabilities of FHB occurrence is shown in Table 4. We assume a lower risk of FHB (probability of 0.7 instead of 0.9) in the worst-case scenario (no preventive practices and high rainfall) and a higher risk of FHB (0.3 instead of 0.1) in the best-case scenario (preventive practices and low rainfall). Under these assumptions, we still have the property that the effectiveness of preventive practices is the same whatever the level of rainfall.[18]

Table 4 Probability of FHB conditional on prevention efforts, x, and level of rainfall, r, with new set of probabilities

Use of preventive practices (x)	**Level of rainfall around flowering (r)**			
	$\leq$ 40 mm		$>$ 40 mm	
	benchmark	new set	benchmark	new set
YES	**0.1**	**0.3**	0.5	0.5
NO	0.5	0.5	**0.9**	**0.7**

In Figure 3, top panel, we show farmers' optimal strategies for x varying from 0 to 100 euros and $\overline{L}$ varying from 100 to 300 euros. In Figure 3, bottom panel, we show farmers' optimal strategies for x varying from 0 to 100 euros and y_1 varying from 0 to 100 euros.

[18]There is no evidence that the actual effectiveness of the preventive practices varies with the amount of rainfall.

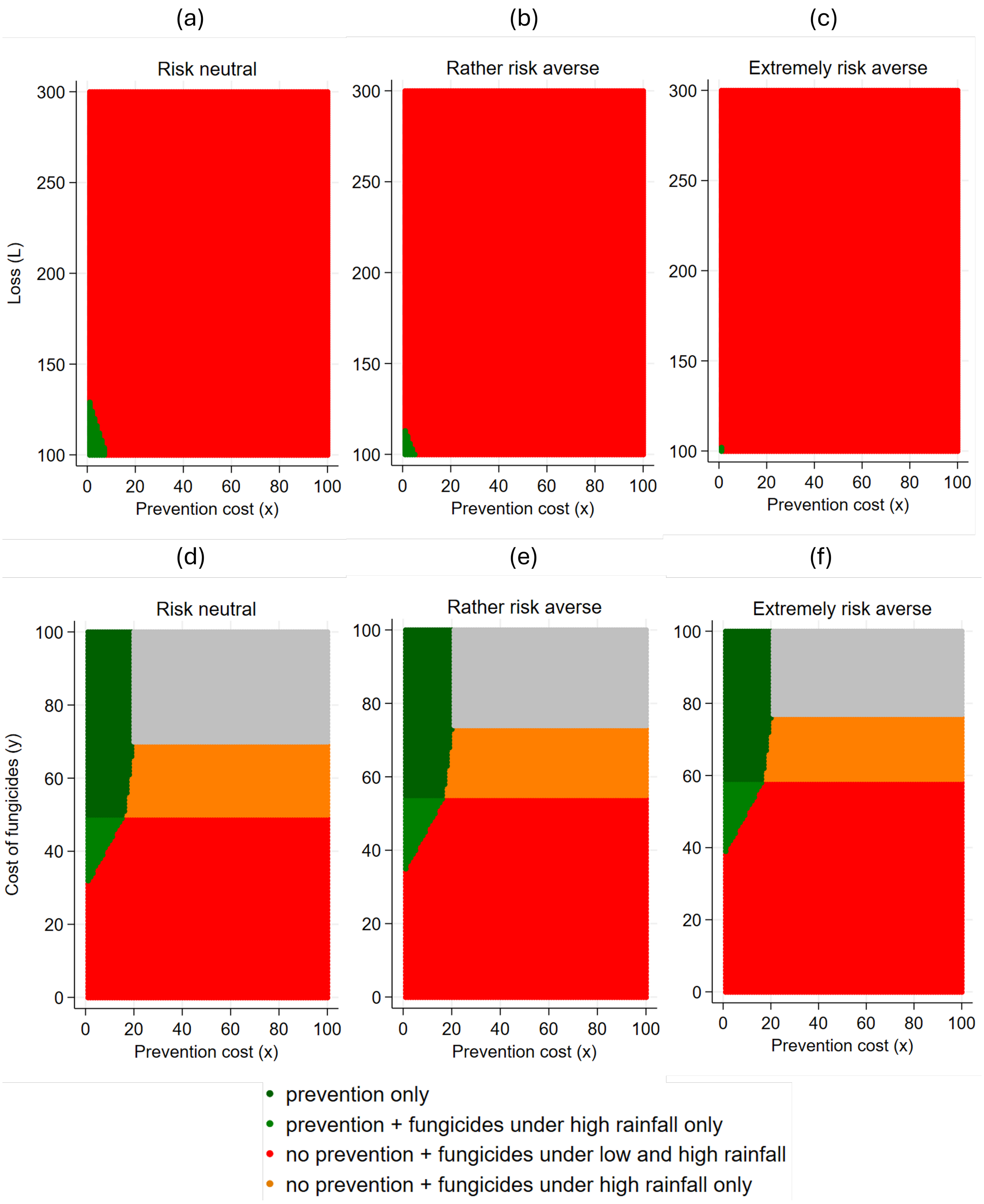

Fig. 3 Optimal strategies for varying prevention cost (x), loss ($\overline{L}$), and cost of fungicides (y_1) (in euro per ha), and for varying levels of risk preferences, with new set of probabilities

Increasing the probability of FHB occurrence from 0.1 to 0.3 in the case of low rainfall when preventive practices are used, and lowering the risk of FHB from 0.9 to 0.7 with high rainfall when no preventive effort is made, make preventive practices almost useless. Farmers switch to fungicides application for very low values of the prevention cost and small values of the loss (cf. red regions in the top three graphs), even more so for more risk-averse farmers. In the bottom panel of Figure 3, we also observe that farmers reduce prevention efforts and switch earlier to fungicides: the dark and light green areas indicating use of preventive practices shrink, while the red, orange, and grey areas (which corresponds to fungicides application) expand.

Hence, for this particular case of wheat farmers from Northeast France, heterogeneity in farmers' beliefs about the risk of FHB and economic conditions (cost of treatment, cost of the prevention effort, and FHB-induced loss) are found to be more important drivers of farmers' decision than risk preferences. Risk aversion is found to induce a lower level of self-protection and a higher level of self-insurance, but only for extremely risk-averse farmers.[19]

6 Conclusion

Self-protection and self-insurance tools have been studied theoretically but analyses of such behaviours using real observations remain rare. The use of pesticides in crop production provides a relevant illustration. Farmers have the possibility of making preventive efforts early in the season in order to reduce the risk of disease on their crops. Later on, at the time of the growing season when weather information arrives, they have the possibility of using fungicides in order to eliminate the risk completely.

Using a two-period model, we characterize theoretically the set of conditions under which self-protection in the first period (here, preventive practices) and self-insurance in the second period (pesticides) are used by farmers in relation to their risk preferences and their risk beliefs. We show that these two strategies are substitutes in most cases. In particular, under CARA utility and specific conditions on the technology, we find the rather counter-intuitive result that more risk aversion may lead farmers to exert less prevention effort to reduce the risk in the initial period.

Our simulation model, calibrated on real data from 59 crop farmers, shows that economic conditions (prevention cost, cost of fungicides, and loss) and subjective beliefs (which may differ from objective ones) are important drivers of farmers' decisions in terms of self-protection and self-insurance, while risk preferences matter only in the case of extreme risk aversion.

[19]We also simulated optimal strategies for farmers who are pessimistic about the probability of high rainfall. We assumed that farmers believe the probability of a high rainfall state is 0.4 (instead of 0.2). In such a case, farmers switch earlier to treatment and make fewer preventive efforts. Results are not shown here but are available upon request.

Pesticides are used today as a risk management tool by farmers. However, the social cost induced by pesticides due to their impact on health and the environment requires finding alternative production models. Encouraging the adoption of preventive agronomic practices, which is today often advocated as a means of lowering farmers' dependence on pesticides, may not be effective if targeted at risk-averse farmers. Indeed, even if preventive practices reduce the risk of disease on crops, we show that, somewhat paradoxically, the optimal strategy for more risk-averse farmers may be, under some conditions, to exert less prevention effort and to keep using pesticides.

Our article contributes to the literature on self-protection and self-insurance, with novel evidence from real data. Our results emphasize the important role of beliefs, hence calling for further consideration of behavioural biases in theoretical modelling.

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A Probability of FHB conditional on preventive practices and level of rainfall

Table 1 is a simplified risk level assessment based on Arvalis documentation (see original table in Figure 4). We use this table to derive assumptions on the probability of FHB conditional on using or not preventive practices and the level of rainfall, $p(x, r)$.

We classify as *preventive practices* ploughing or burying residues (whatever the crop planted before) as well as leaving residues on the surface if straw cereals have been planted before wheat. This corresponds to the first three cases of Table 1. For these practices, the risk level varies between 1 and 3 and treatment is recommended only when there is high rainfall and maize as a precedent (see detailed recommendations after the Arvalis table in Figure 4).

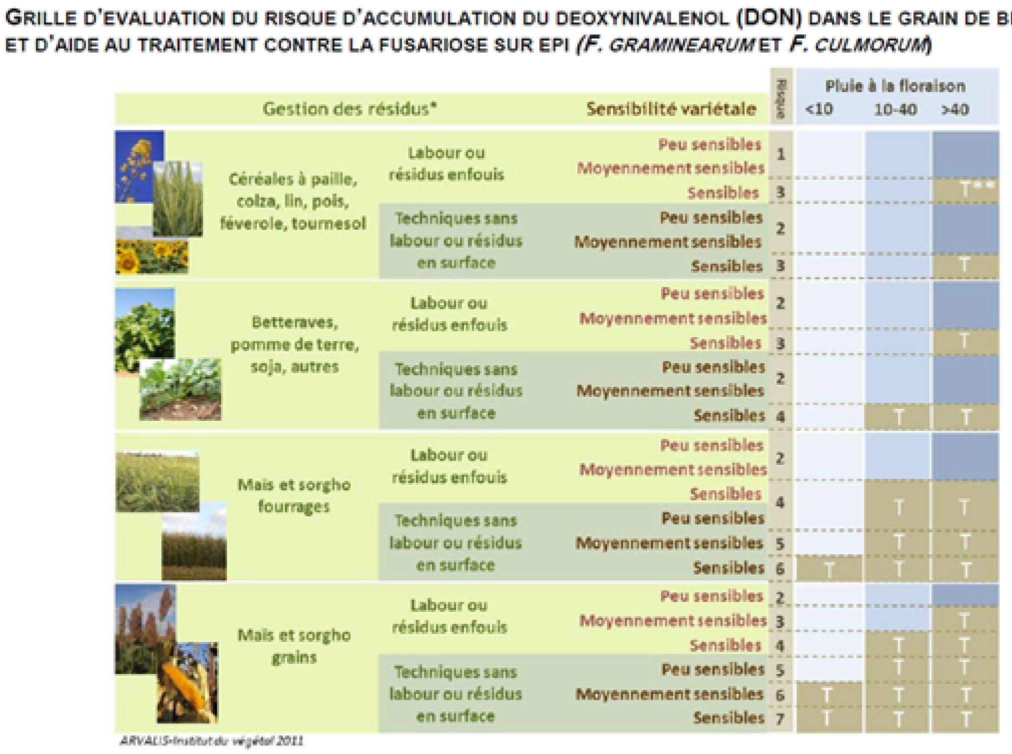
If maize or sorghum was planted before wheat and residues were left on the surface, we consider that farmers decided *not to adopt preventive practices.* In this case, the risk level is estimated at 5-6 on a 1 to 7 scale and Arvalis recommends treating whatever the level of rainfall.

The risk is said by Arvalis to be "minimal" with preventive practices and low rainfall, so we assume a probability of FHB of 0.1 (see Table 5). Treatment is recommended when there is high rainfall so we assume this means (for Arvalis) a probability around 0.5 of occurrence of the disease. In case of no preventive practices, Arvalis recommends treating in all cases but the risk is still higher if rainfall is high. We assume a probability of 0.5 with low rainfall and 0.9 with high rainfall. In such a setting, the usefulness of the preventive practices is the same with low and high rainfall.

Based on Arvalis risk level estimates, not using preventive practices induces a risk level of 5.5 on average, which is about 2 to 3 times higher than the risk faced when using preventive practices. Here the probability of FHB is assumed to be 0.3 on average with preventive practices and 0.7 on average without preventive practices (not taking into account the probability of low and high rainfall), which makes the probability of disease without preventive practices 2.3 times more likely than the probability of disease when preventive practices are used.

Table 5 Probability of FHB conditional on prevention efforts, x, and level of rainfall, r

Use of preventive practices	**Level of rainfall around flowering**	
	≤ 40 mm	> 40 mm
YES	0.1	0.5
NO	0.5	0.9



Recommendations depending on risk level. **1 and 2**: The risk of Fusarium Head Blight (FHB) is minimal and indicates good grain quality. No specific treatment is required for FHB under any climatic conditions. **3**: The risk can be further minimized by choosing a less susceptible variety. Treat specifically for FHB in humid climates (cumulative rainfall $>$ 40 mm during the period surrounding flowering). **4 and 5**: It is preferable to plant a less susceptible variety or to plough the field to reduce the risk level. If this is not possible, chop the crop as finely as possible and incorporate the residues quickly after harvest. For these two risk levels, consider specific treatment for FHB, unless the climate is very dry during the flowering period (cumulative rainfall $<$ 10 mm during the approximately 7 days surrounding flowering). **6 and 7**: Modify the cropping system to return to a lower risk level. Ploughing or finely chopping crop residues with rapid incorporation after harvest are the most effective technical solutions and should be considered before any other solution. Choose a variety with low susceptibility to FHB. Treat systematically with an effective FHB treatment.

Fig. 4 Original Arvalis table (in French only) - Translation in figure notes.

B Proofs of Lemmas 1 and 2

The second-period problem consists in comparing the expected utility from the lottery

$$p(x,r)U(W_0 - x - \overline{L}) + (1 - p(x,r))U(W_0 - x)$$

to the sure outcome

$$U(W_0 - x - y_1).$$

It is clear that one uses more fungicides when their cost y_1 is lower, or when the loss $\overline{L}$ is higher, or when the farmer is more risk-averse (Lemma 1). To go further, let us define the certainty equivalent $w(x,r)$ associated with the decision not to use fungicides:

$$U(w(x,r)) \equiv p(x,r)U(W_0 - x - \overline{L}) + (1 - p(x,r))U(W_0 - x). \tag{B.1}$$

Then one uses fungicides if and only if

$$w(x,r) \leq W_0 - x - y_1. \tag{B.2}$$

In particular, we have[20]

$$U'(w(x,r))w_r(x,r) = p_r(x,r)(U_0 - U_1),$$

where we have used the notations

$$U_0 \equiv U(W_0 - x - \overline{L}) < U_1 \equiv U(W_0 - x).$$

Since $p_r > 0$, this confirms that more rain favours the use of fungicides, as announced in the main text. Finally, the two efforts are substitutes if and only if an increase in x discourages the use of fungicides. From (B.2), this is equivalent to $w_x \geq -1$. From (B.1), we get

$$U'(w(x,r))w_x(x,r) = p_x(x,r)(U_0 - U_1) - pU_0' - (1-p)U_1',$$

so that the condition becomes:

$$p_x(x,r)(U_0 - U_1) + U'(w(x,r)) - pU_0' - (1-p)U_1' \geq 0.$$

[20] Subscripts denote partial derivatives.

The first product is the technological effect, and it is always positive, being the product of two negative terms: indeed, an increase in x reduces the probability of occurrence of FHB and thus makes fungicides less useful. For a risk-neutral farmer, this is the only effect. For a risk-averse agent, it remains to be checked that

$$U'(w(x,r)) \geq pU_0' - (1-p)U_1'.$$

Define the function $\varphi \equiv U' \circ U^{-1}$. Then the inequality becomes

$$\varphi(U(w)) \geq p\varphi(U_0) + (1-p)\varphi(U_1).$$

Using the definition in (B.1), we obtain

$$\varphi(pU_0 + (1-p)U_1) \geq p\varphi(U_0) + (1-p)\varphi(U_1).$$

This holds if $U' \circ U^{-1}$ is concave, by Jensen's inequality. This amounts to the absolute risk aversion $-U''/U'$ being nondecreasing with wealth, as set out in Lemma 2.

C Proof of Lemma 3

The expected utility of the agent is $EU(z(x,r))$, where $z(x,r) \equiv \max(w(x,r), W_0 - x - y_1)$, and w is defined in (B.1). z decreases in r because w decreases in r. To show that a more risk-averse farmer chooses a lower value for x, we only have to show that an increase in x reinforces this dependency on r, i.e., z_r decreases in x. We have

$$z_r = \begin{cases} w_r(x,r) < 0 & \text{if } \; w(x,r) > W_0 - x - y_1 \\ 0 & \text{if } \; w(x,r) < W_0 - x - y_1 \end{cases}$$

Conditions for Lemma 2 are satisfied, so that a higher x goes against the use of pesticides. Therefore, an increase in x leads to a reduction in z_r at the margin, since z_r switches from 0 to $w_r < 0$. It only remains to show that w_r is decreasing in x. Under CARA, we have

$$U(w) = \frac{1 - \exp(-Aw)}{A},$$

,

and Definition (B.1) yields

$$w(x,r) = -\frac{1}{A}\log\left(p\exp(-A(W_0 - x - \overline{L})) + (1-p)\exp(-A(W_0 - x))\right)$$

or equivalently

$$w(x,r) = W_0 - x - \frac{1}{A}\log(Kp+1),$$

where $K \equiv \exp(A\overline{L}) - 1$ is a positive constant. Note that wealth effects have disappeared. We obtain

$$w_r = -\frac{1}{A}\frac{Kp_r}{Kp+1}$$

Since $K > 0$ and p decreases in x, w_r decreases in x as soon as p_r is weakly increasing in x. In this case, a more risk-averse farmer thus must use fewer preventive practices, and since the two decisions are substitute the farmer applies fungicides more often. This proves the result in Lemma 3.