Why farmers consider pesticides the ultimate in crop protection: economic and behavioral insights

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Abstract:

The observed dependence of current crop production on chemical crop protection is largely due to economic and technological factors. High yield and specialized cropping systems require high crop protection levels and pesticides allow achieving such protection levels at reasonable (private) costs. The main aim of this article is to show that behavioral factors may reinforce the effects of these economic and technological factors on farmers' considering pesticides the ultimate in crop protection. Choice mechanisms described by Kőszegi and Rabin (2007) imply that individual attitudes toward a given risk are endogenous in the sense that they depend on the best available means to cope with this risk. Building on this extension of Prospect Theory, we show that farmers exhibit strong aversion toward crop health risks when pesticide prices are relatively low. Indeed, the cheaper the pesticides, the higher the crop protection levels farmers refer to when considering pesticide sprays, and the more they feel that choosing low crop protection levels entails unacceptable risk taking. Our analysis also suggests that pesticide prices play a more important role in farmers' crop protection choices than previously recognized. In particular, we show that pesticide taxes would unambiguously reduce farmers' pesticide uses, by reducing pesticide profitability as well as farmers' aversion toward crop health risks.

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JEL Codes: Q12, D21

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Keywords: Prospect Theory, reference point, loss aversion, personal equilibrium, pesticide use, risk aversion, pesticide taxes

JEL Codes: D21, D81, D90, Q53

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As the adverse effects on human health or on the environment of chemical pesticides are now considered as major concerns, reduction of agricultural pesticide use has become an important political objective in most industrialized countries. However, most regulation policies implemented until now have achieved limited pesticide use reductions. These policies have been mainly based on market access restrictions, funding public research efforts on alternatives to pesticides and subsidies aimed to disseminate pesticide saving crop production practices. While economists generally advocate implementation of pesticide taxes for internalizing the negative external effects of pesticides, public decision makers are reluctant to use taxes owing to their potential impact on farmers' income.[1] Crop production technologies being generally considered strongly dependent on pesticides, pesticide taxes are expected to significantly impact farmers' income with limited impact on pesticide uses.[2]

As a matter of fact, pesticides are key production factors in the crop production technologies used by farmers in industrialized countries (see, *e.g.*, Matson *et al*, 1997; Tilman *et al*, 2002; Aubertot *et al*, 2005; Lin, 2011). Conventional crop production practices aim to achieve high yield levels that are worth protecting. Moreover, production practices targeting high yield levels and based on short crop rotation schemes tend to increase pest, disease and weed risks and, as a result, call for high protection levels. Farmers using conventional production practices often choose chemical pesticides for protecting their crops because these inputs are easy to use and effective for achieving high crop protection levels.[3] Indeed, conventional crop production practices have been designed while taking for granted that high crop protection levels can be achieved at reasonable (private) cost with chemical pesticides (see, *e.g.*, Aubertot *et al*, 2005; Vanloqueren and Baret, 2009).[4]

Farmers' reluctance to reduce their pesticide uses can thus be explained to a large extent by the economic efficiency of chemical pesticides as crop protection inputs in current crop production practices. Following the seminal work of Feder (1979) agricultural production economists consider farmers' attitude toward risk as another major driver of agricultural pesticide uses (see, *e.g.*, Antle, 1988; Gong *et al*, 2016). Because they reduce production loss risks, pesticides are expected to increase the mean and to decrease the randomness of crop yields. As a result, farmers' risk aversion, as it is defined in the Expected Utility Theory (EUT), may explain their adoption of high chemical crop protection levels.

The main aim of this article is to revisit the links between farmers' attitude toward risk and pesticide uses, with a special focus on the role of pesticide prices. In particular, we aim to show that availability of relatively cheap and effective chemical pesticides has stronger impacts on farmers' crop protection choices than previously recognized. Obvious arguments related to farmers' economic rationality imply that the economic efficiency of chemical pesticides tend to foster their use.[5] But, these standard profitability effects are likely to be magnified by behavioral factors. Indeed, specific behavioral mechanisms imply that availability of relatively cheap and effective chemical pesticides can impact farmers' attitude toward crop health risks.

We uncover these later impacts by analyzing farmers' pesticide treatment decisions based on the analytical framework proposed by Kőszegi and Rabin (2006, 2007). According to these authors, decision makers' attitude toward a given risk depends on the "best" available means to manage this risk, and not only their "exogenous" preferences toward risks as assumed when relying on EUT. Indeed, when preparing to make a risky decision, individuals determine their "best" risk management option given their initial perception of the considered risk. They tend to consider this best available option as their reference choice when making their actual decision, even after having updated their perception of the considered risk. Referring to a given risk management option strongly determines the actual choices of decision makers. The safer their reference risk management option, the more their actual decisions display risk aversion features.

Our main results can be stated considering a simple dichotomous treatment decision. When farmers have to decide whether to spray a pesticide or not, their actual decision depends on the choice they are prepared to. Farmers anticipating to protect their crop may implement self-insurance pesticide sprays while those anticipating not to protect their crop only implement sprays with positive expected returns. Availability of a cheap and efficient pesticide against a pest risk leads farmers to consider the spray of this pesticide as their reference choice. This in turn renders them risk averse toward the considered pest risk when making their actual crop protection decisions. Pesticide prices play a crucial role in this analysis. They directly determine the economic efficiency of pesticide sprays as crop health risk management options and they indirectly impact farmers' attitude toward crop health risks through their effect on their reference crop protection choices.

The analytical framework proposed by Kőszegi and Rabin (2007) extends the Prospect Theories (PT) proposed by Kahneman and Tversky (1979) and Tversky and Kahneman (1992)[6] by describing how loss averse decision makers determine their reference income level in risky choice situations. The reference income plays a crucial role in PT models. It distinguishes gains from losses from the decision maker viewpoint and, as a result, the attitude of this decision maker toward the considered risk. In standard applications of PT, the reference income level is exogenously, and more or less arbitrarily, defined by the analyst. Kőszegi and Rabin (2007) proposed a "personal equilibrium" search process for describing how decision makers endogenously determine their reference income and demonstrated that the resulting modelling framework yields better predictions in important choice situations.[7]

The originality of our results on farmers' pesticide use decisions lies in the fact that they make explicit the role of farmers' reference crop protection levels, namely the protection levels which farmers use as benchmarks when deciding the actual protection level of their crops. The higher farmers' reference crop protection level, the more farmers exhibit risk aversion toward the considered crop health risks. If preventive pesticide treatments allow achieving high crop protection levels at reasonable cost then farmers are led to take these crop protection levels for granted. This in turn make them very reluctant to choose low crop protection levels, whether by reducing their pesticide uses or by using alternative crop protection techniques.

Agricultural pesticide use has led to an extensive literature (see, *e.g.*, Fernandez-Cornejo *et al*, 1998; Sexton *et al*, 2007; Skevas *et al*, 2013). Previous studies considering farmers' crop health management relied on the standard EUT and most of them considered pesticide uses at a rather aggregated level. These studies primarily aimed to investigate two specific features of pesticides: their protective role in agricultural production (see, *e.g.*, Lichtenberg and Zilberman, 1986; Chambers *et al*, 2010) and the impact of farmers' risk aversion on their use (see, *e.g.*, Feder, 1979; Antle, 1988; Pannell, 1991).

The effects of pesticides on yield risk and the relationship between risk aversion and pesticide uses were empirically investigated – albeit to a very limited extent owing to the diversity of contexts in which pesticides are used (Sexton *et al*, 2007) – with mixed results. Studies confirm the intuitive wisdom (see, *e.g.*, Antle, 1988; Saha *et al*, 1997; Liu and Huang, 2013; Gong *et al*, 2016) while other do not (Shankar *et al*, 2008). Yet, empirically investigating farmers' pesticide use is particularly difficult, due to data limitations in particular.[8] In most empirical and theoretical studies pesticide uses are analyzed by considering pesticide expenditures at the crop (or farm) level and by relying on EUT. This aggregation level involves farmers' global crop protection strategy, and more generally farmers' global crop management. This requires considering multiple risks and integrating the use of other inputs (see, *e.g.*, Pannell 1991; Horowitz and Lichtenberg, 1994).

To rely on EUT emphasizes the roles of the curvature of the marginal utility function and on how pesticides affect the probability distribution of yield levels (see, *e.g.*, Ramaswami, 1992). This in turn leads to ambiguous results. For instance, Feder (1979) and Leathers and Quiggin (1991) showed that a tax on pesticides may increase pesticide uses under two widely accepted assumptions: pesticides are production risk-reducing inputs and farmers' exhibit decreasing absolute risk aversion. This result is particularly puzzling for economists as it suggests that pesticide taxes might not "work" for reducing pesticide uses under admittedly reasonable assumptions.

We address simpler issues in this study. As in Feder (1979), we focus on single pesticide use decisions: to spray a pesticide against a given pest or not. Single pesticide use decisions are of primary interest because pest management involves a sequence of such decisions.[9] Our analysis of the mechanisms underlying crop protection choices yields original results because we assume that farmers' single pesticide use decisions can be analyzed suitably as isolated risky choices that can be affected by psychological biases. In that, we refer to choice patterns that are now extensively documented in economic psychology and behavioral economics: narrow bracketing, loss aversion and reference-dependent risk attitude (see, *e.g.*, Wakker, 2010; Kahneman, 2011).

Our analysis aims to provide new insights into farmers' pesticide uses by considering a PT analytical framework. We feel that our results are more intuitive than many EUT based results.[10] These results also have direct implications on the analysis of pesticide regulation policies. Our most striking result shows that farmers' attitude toward plant health risks does not only depend on farmers' preferences toward risk but also depends on economic factors. It suggests that pesticide taxes would be more efficient than usually considered. While EUT analyses of the effects of pesticide prices on pesticide uses are mostly inconclusive, our results imply that pesticide taxes would decrease farmers' pesticide uses. More generally, they suggest that pesticide taxes should be the keystone of any policy aimed at reducing agricultural pesticide uses.

The outline of the article is as follows. The second section presents the basic choice problem we consider and discusses the application of PT to this problem. The third section describes our analysis of single pesticide use decisions in a risky context and provides simple comparative statics results. The fourth section provides numerical results aimed to illustrate and to provide potential orders of magnitude of the effects uncovered by our theoretical analysis. Policy relevant issues are considered in the fifth section. The last section presents concluding remarks.

The results presented in the article are purposely based on a simple modelling framework. They are fairly easy to prove and to interpret (as well as to use). The Appendix provides supplementary results demonstrating that the main results presented in the article continue to hold when considering more general modelling frameworks.

Pesticide spray decisions, reference situation, and loss and risk aversion

It is now widely accepted that large stake risky decisions tend to be rational while small to modest stake risky decisions tend to be affected by psychological biases that are now extensively documented (see, *e.g.*, Wakker, 2010; Kahneman, 2011). Individuals pay more attention to large stake decisions. Also, if large stake choices – such as the choice of a global pest management strategy – are suitably analyzed by relying on EUT, modest stake choices require a different analytical framework (see, *e.g.*, Rabin, 2000; Kőszegi and Rabin, 2007).

Farmers' pest management involves a sequence of single pesticide use decisions: to spray a pesticide against a given pest or not. Each of these risky choice situations involves moderate stakes, at least when compared to the stakes involved in acreage or investment decisions. Moreover, many pesticide use decisions need to be made relatively rapidly, if not in a hurry.[11] This suggests that farmers' single pesticide use decisions are likely to be subject to the so-called narrow-bracketing effect affecting moderate stake and quick risky decisions. Accordingly, we assume that farmers analyze each of their single pesticide decision in the narrow context defined by what they know about this specific choice situation. Importantly, PT decision makers pay special attention to downside risks. This enables us to focus on losses due to crop health risks.

Pesticide treatment choice situation

In order to be able to obtain results in closed form solutions and to highlight interesting features of farmers' pesticide uses, we analyze a simple choice situation. We consider a single crop yielding the sure return y when free of any pest damage. Farmers are assumed to face a dichotomous pest risk. According to their perception, the considered infestation occurs with probability p_i – with $p_i \in (0,1)$ – and implies an economic loss of δ – with $\delta > 0$.

A pesticide spray at a given dosage allows reducing the pest damage when it occurs at cost w – with $w \in (0,\delta)$. The pesticide treatment is assumed to be perfectly efficient. If farmers decide to spray the considered pesticide ($s = 1$) then their crop return is certain and equal to $\pi_{s=1} = y - w$. If farmers decide not to spray the pesticide ($s = 0$) then their crop return $\tilde{\pi}_{s=0}(p_i)$ is random. It is equal to $y - \delta$ with probability p_i (damaged crop) and equal to y with probability $1 - p_i$ (healthy crop).

Of course, risk neutral farmers implement the pesticide treatment if and only if the expected return of the pesticide treatment is non-negative, that is if and only if $w \leq p_i \delta$.

PT and reference crop protection level

PT has emerged as the leading alternative to EUT for analyzing moderate-scale and/or quick risky choice in economics (see, *e.g.*, Barberis, 2013). In agricultural production contexts, Bocquého *et al* (2009) found that PT does a better job at explaining experimental risky choices of a sample of French farmers. Babcock (2015) showed that PT is more suitable than EUT for describing US farmers' choices of insurance contracts.

As in many applications based on PT, our analysis primarily makes uses of two key features of this modelling framework: its dependence on a reference point that distinguishes gain from losses and the loss aversion assumption.[12] Individuals conforming to PT evaluate risky prospects by distinguishing losses – below the reference point – from gains – above the reference point – and tend to overweight losses – loss aversion. These features can explain risk averse choices as avoiding a loss generates more value than a corresponding gain.

A crucial question arises when using the PT model for analyzing risky decisions: what is the reference point of the decision maker in the considered choice risk situation? The reference situation is often defined by the analyst as the one defined by the *status quo* choice, as in EUT. In the choice situation considered here, this would imply that farmers' reference situation is the ''unprotected crop'' situation. Indeed, at a first glance, this reference situation appears to be rational. Yet, the ''unprotected crop'' situation raises two problems as a reference situation. The first one is technical: how to accommodate the PT model for accounting for random reference income such as the one obtained by farmers not protecting their crop? As will be shown below this question is addressed by Kőszegi and Rabin (2007).

The second problem raised by assuming that farmers choose the ''unprotected crop'' as their reference situation is by far the most important. Indeed, our analysis demonstrates that farmers are likely to refer to the "protected crop" situation when cheap and efficient pesticides are available against the considered pest risk. This hypothesis is supported by results of studies investigating farmers' crop protection choices by means of interviews and surveys. Agronomists or sociologists analyzing farmer's pesticide uses generally observe that most farmers plan their pesticide sprays far in advance. Typically, they define their spray schedule and purchase pesticides at the beginning of the cropping season. Moreover, farmers tend to use more pesticides than recommended by crop protection experts (see, *e.g.*, Jorgensen *et al*, 2008; Bürger *et al*, 2012). Indeed, farmers seem to stick to their predetermined pesticide spray schedule partly because many of them struggle with deciding not to treat their crop in relatively low pest risk situations (see, *e.g.*, Lamine, 2011). This suggests that farmers' initial intention is more often to protect their crops rather than not to protect them, suggesting that their reference situation is the "protected crop" for many of their pesticide treatment decisions.

Farmers' question related to a treatment against a given crop health risk can be formulated as "Is this treatment useful?" or as "Is this treatment useless?". These questions are equivalent from a rational – EUT – viewpoint but they differ as regards to the situation they refer to. From the PT viewpoint this raises the following question: what is the reference situation of farmers facing pest risks, the ''protected crop" situation or the ''unprotected crop" situation? Proposing solution concepts for addressing this crucial question is the key feature of the extended version of PT developed by Kőszegi and Rabin (2007). Importantly, the analytical framework proposed by these authors allows farmers' adopting different reference situations, depending on their loss aversion and on their perception of the considered risk.

In the rest of this section, we describe how Kőszegi and Rabin (2007) propose to handle random reference situations. Then, we show that the reference situation plays a crucial role in how farmers use pesticides.

PT utility function, loss aversion and risky reference incomes

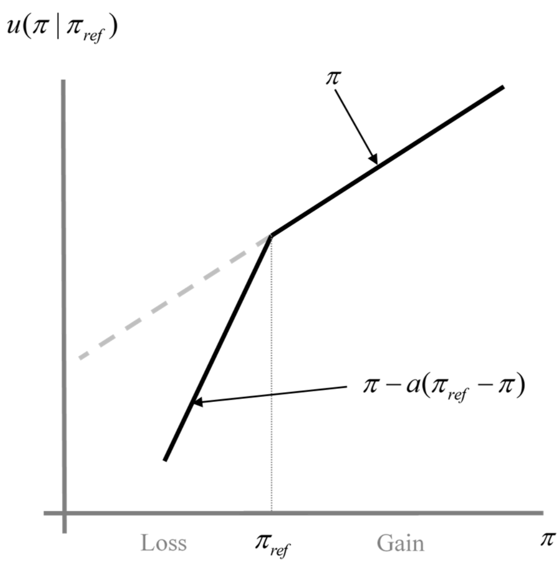
According to the model proposed by Kőszegi and Rabin (2007), individuals rely on the following value function:

(1) $\bar{u}(\pi \mid \tilde{\pi}_r) = \pi - aE[\max\{0, \tilde{\pi}_r - \pi\}]$

when evaluating moderate stake risky prospects at the outcome level π with $\tilde{\pi}_r$ as their possibly random reference outcome. Of course, individuals evaluate a risky prospect $\tilde{\pi}$ according to its expected utility value $E[\overline{u}(\tilde{\pi} \mid \tilde{\pi}_r)]$.

Parameter a measures farmers' loss aversion level. Farmers are strictly loss averse when a is strictly positive. They are loss neutral (as well as risk neutral) when a is null. In empirical and experimental settings the loss parameter a is generally found to lie between 0 and 1.5, indicating that individuals are usually loss averse (see, *e.g.*, Wakker, 2010). Here, we simply assume that a is non-negative. The term $aE[\max\{0, \tilde{\pi}_r - \pi\}]$ accounts for the effects of loss aversion in the valuation function $\overline{u}(\pi \mid \tilde{\pi}_r)$. As shown below, this term induces risk averse attitudes toward risky prospects when these prospects involve gains and losses.

Figure 1. Piecewise linear value function $u(\pi \mid \pi_r)$



In the case where the reference income level is fixed, with $\tilde{\pi}_r = \pi_r$, the valuation of the outcome π is given by the piecewise linear value function $u(\pi \mid \pi_r)$. The term $u(\pi \mid \pi_r)$

simply distinguishes gains with $u(\pi \mid \pi_r) = \pi$ if $\pi \geq \pi_r$ from losses with $u(\pi \mid \pi_r) = \pi - a(\pi_r - \pi)$ when $\pi < \pi_r$. The term $a(\pi_r - \pi)$ can be interpreted as adding the "psychological cost" of losing $\pi_r - \pi > 0$ when $\pi < \pi_r$. The value function $u(\pi \mid \pi_r)$ is depicted in Figure 1. From a technical viewpoint, this piecewise linear PT value function is concave in π since it is kinked at π_r with a slope in π equal to 1 above π_r and equal to $1 + a \geq 1$ below π_r. This kink generates first order risk aversion in $u(\pi \mid \pi_r)$ and can thus induce strongly risk averse choices (Segal and Spivak, 1990).

The randomness of the reference income $\tilde{\pi}_r$ is simply accounted for in Kőszegi and Rabin's (2007) valuation function $\overline{u}(\pi \mid \tilde{\pi}_r)$. The term $\overline{u}(\pi \mid \tilde{\pi}_r)$ is the expectation, with $\overline{u}(\pi \mid \tilde{\pi}_r) = E[u(\pi \mid \tilde{\pi}_r)]$, of the value function $u(\pi \mid \tilde{\pi}_r)$ over the probability distribution of the reference outcome $\tilde{\pi}_r$. Importantly, the loci of the kinks in the value function $\overline{u}(\pi \mid \tilde{\pi}_r)$ determine the shape of this function and, as a result, the risk aversion level that it implies at given levels of loss aversion. As these loci depend on the reference income $\tilde{\pi}_r$, different reference incomes imply different attitude toward pest risks that may in turn imply different pesticide use decisions.

Impact of the reference crop protection level on treatment decisions

Figure 2 depicts $\overline{u}(\pi \mid \tilde{\pi}_{s=0}(p_i))$, the value function obtained when the "unprotected crop" is the reference situation, and $\overline{u}(\pi \mid \pi_{s=1})$, the value function obtained when the "protected crop" is the reference situation. The shape of $\overline{u}(\pi \mid \pi_{s=1})$ is that of the standard (piecewise linear) PT value function with a kink at the sure profit level $y - w$ that is obtained when the crop is treated. This value function displays first-order risk aversion that increases in the loss aversion parameter *a*. The value function $\overline{u}(\pi \mid \tilde{\pi}_{s=0}(p_i))$ has two kinks, at y and $y - \delta$. But, it is linear, and thus doesn't display risk aversion, between these two extreme profit levels.

Figure 2. Impact of the reference situation on the shape of the value function $u(\pi \mid \tilde{\pi}_r)$

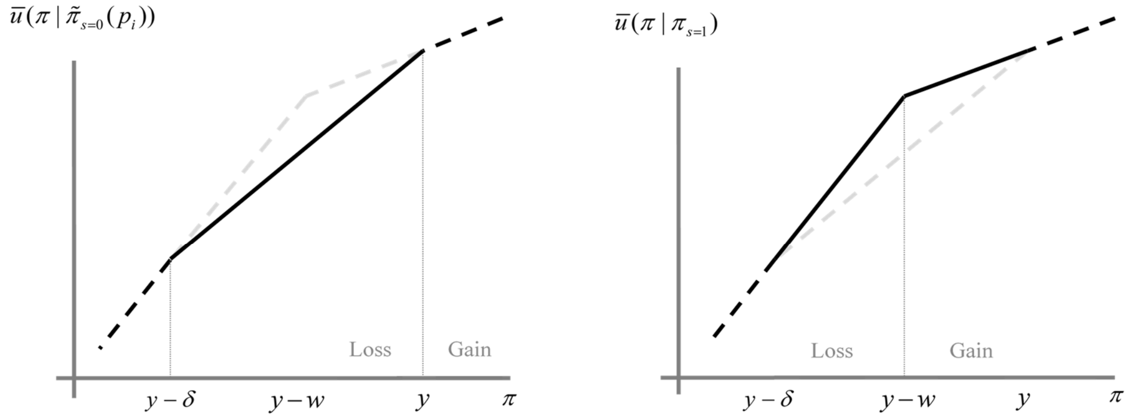


Fig 2a. Value function with the "unprotected crop" as the reference situation

Fig 2b. Value function with the "protected crop" as the reference situation

Of course, the differences in the value functions $\overline{u}(\pi \mid \tilde{\pi}_{s=0}(p_i))$ and $\overline{u}(\pi \mid \pi_{s=1})$ directly affect farmers' pesticide decisions. Let consider farmers define their reference situation with an estimated infestation probability of p_i but face an infestation probability of $p_{i|\hat{e}}$. In this case, the unprotected profit level of the ''unprotected crop", which is denoted by $\tilde{\pi}_{s=0}(p_{i|\hat{e}})$, is equal to y with probability $1-p_{i|\hat{e}}$ and to $y-\delta$ with probability $p_{i|\hat{e}}$. Such choice situations occur when farmers receive information on the pest risk they have to cope with shortly before having to decide whether to spray the relevant pesticide or not. According to Kőszegi and Rabin (2007), in such cases farmers are likely to update their infestation probability estimates without updating their reference situation.

Table 1 reports the expected value of the ''protected crop" return $\pi_{s=1}$ and of the ''unprotected crop" return $\tilde{\pi}_{s=0}(p_{i|\hat{e}})$ when $\pi_{s=1}$ – ''protected crop" situation – or $\tilde{\pi}_{s=0}(p_i)$ – ''unprotected crop" situation – are the reference crop returns. We successively analyze the treatment decision in these two cases for highlighting the impact of the reference situation on how farmers decide their pesticide uses. The uncovered pesticide use patterns directly echoes the shapes of the value functions $\bar{u}(\pi \mid \tilde{\pi}_{s=0}(p_i))$ and $\bar{u}(\pi \mid \pi_{s=1})$.

Table 1. Expected utility levels of the crop returns with and without protection, and with the "protected crop" or the "''unprotected crop" situations as the reference situation

	Reference situation	
	"Protected crop" Reference crop return: $\pi_{s=1}$	***"Unprotected crop"*** Reference crop return: $\tilde{\pi}_{s=0}(p_i)$
	Expected utility level, estimated infestation probability $p_{i\|\hat{e}}$	
Spray	$E[\bar{u}(\pi_{s=1} \mid \pi_{s=1})]$ $= y - w$	$E[\bar{u}(\pi_{s=1} \mid \tilde{\pi}_{s=0}(p_i))]$ $= y - w - a(1-p_i)w$
No spray	$E[\bar{u}(\pi_{s=0}(p_{i\|\hat{e}}) \mid \pi_{s=1})]$ $= y - p_{i\|\hat{e}}\delta - ap_{i\|\hat{e}}(\delta - w)$	$E[\bar{u}(\pi_{s=0}(p_{i\|\hat{e}}) \mid \tilde{\pi}_{s=0}(p_i))]$ $= y - p_{i\|\hat{e}}\delta - a(1-p_i)p_{i\|\hat{e}}\delta$

The "protected crop" is the reference situation. When their reference situation is the ''protected crop", farmers do not incur any psychological cost if they decide to protect their crop. Their crop return, $y-w$, is certain and directly yields their valuation of the ''protected crop" situation, $E[\bar{u}(\pi_{s=1} \mid \pi_{s=1})]$. If they decide not to protect their crop then their crop return is random and entails loss risk. From their viewpoint, farmers lose $\delta - w > 0$ when the infestation actually occurs. This loss risk generates the psychological cost $ap_{i|\hat{e}}(\delta - w)$ in their valuation of the ''unprotected crop" situation, $E[\bar{u}(\tilde{\pi}_{s=0}(p_{i|\hat{e}}) \mid \pi_{s=1})]$.

Comparing $E[\bar{u}(\pi_{s=1} \mid \pi_{s=1})]$ and $E[\bar{u}(\tilde{\pi}_{s=0}(p_{i|\hat{e}}) \mid \pi_{s=1})]$ simply yields that farmers referring to the ‘‘protected crop’’ situation decide to protect their crop if and only if:

(2) $$w \leq \gamma(p_{i|\hat{e}}, \delta; a) = \frac{1+a}{1+ap_{i|\hat{e}}} p_{i|\hat{e}} \delta \; .$$

It is easily shown that the term $\gamma(p_i, \delta; a)$ is increasing in (p_i, δ, a). This implies that farmers referring to the ‘‘protected crop’’ situation treat their crop if they are sufficiently loss averse, if the treatment is sufficiently inexpensive and/or if the infestation is sufficiently likely.

It is also easily shown that $\gamma(p_i, \delta; a) > p_i\delta$ if $a > 0$ with $\gamma(p_i, \delta; 0) = p_i\delta$. Consequently, loss averse farmers referring to the ‘‘protected crop’’ behave as risk averse farmers. If $w \leq p_i\delta$ then the pesticide treatment has a non-negative positive expected return and it is expected to be implemented by any farmer. If $p_i\delta \leq w \leq \gamma(p_i, \delta; a)$ the treatment is justified for loss averse farmers by self-insurance motives (Ehrlich and Becker, 1972). It has a negative expected return but it eliminates the loss risk due to pests, a property valued by such farmers. The term $\gamma(p_i, \delta; a)$ can be interpreted as the (maximum) willingness to pay (WTP) for the treatment of farmers referring to the ‘‘protected crop’’ situation. Similarly, the term

(3) $$\pi(p_i, \delta; a) \equiv \gamma(p_i, \delta; a) - p_i\delta = a\frac{1-p_i}{1+ap_i} p_i\delta$$

can be interpreted as the related loss risk premium. This premium measures the extent to which the reference to the ‘‘protected crop’’ situation and loss aversion combination builds self-insurance motives.

The ‘‘unprotected crop’’ is the reference situation. Farmers incur psychological costs whatever they decide when their reference situation is the ‘‘unprotected crop’’. They take the risk of losing δ if they do not protect their crop. This generates the psychological cost

$a(1-p_i)p_{i|\hat{e}}\delta$ in $E[\bar{u}(\tilde{\pi}_{s=0}(p_{i|\hat{e}})\,|\,\tilde{\pi}_{s=0}(p_i))]$. They take the risk of losing the treatment cost if they protect a healthy crop. This induces the psychological cost $a(1-p_i)w$ in $E[\bar{u}(\pi_{s=1}\,|\,\tilde{\pi}_{s=0}(p_i))]$.

Comparing $E[\bar{u}(\tilde{\pi}_{s=0}(p_{i|\hat{e}})\,|\,\tilde{\pi}_{s=0}(p_i))]$ and $E[\bar{u}(\pi_{s=1}\,|\,\tilde{\pi}_{s=0}(p_i))]$ yields that farmers with the ‘‘unprotected crop” as the reference situation decide to protect their crop if and only if the chemical treatment has a non-negative expected return, namely if and only if $w \leq p_{i|\hat{e}}\delta$. This shows that loss averse farmers behave as risk neutral farmers when they adopt the ‘‘unprotected crop” as their reference situation, whatever their loss aversion level.

Indeed, the risk entailed in random reference situations is accepted, even if only partly, by individuals adopting such reference situations. Risky choices appear to be more acceptable to individuals having adopted the risky prospect implied by this choice as their reference prospect, even when these choices entail significant loss risks.

Taken together these results tend to show that loss aversion – the intrinsic risk preference characteristics considered here – is not sufficient for farmers to exhibit risk aversion toward pest risks. Farmers must be loss averse and must adopt the ‘‘protected crop” as their reference situation for exhibiting risk aversion toward pest risks.

These results also show that the reference situation adopted by farmers has an anchorage effect on their actual decisions. For instance, farmers referring to the ‘‘protected crop” situation are reluctant to skip pesticide treatments when the pest risk they actually face is lower than anticipated at first. Contrary to farmers referring to the ‘‘unprotected crop” situation, farmers referring to the ‘‘protected crop” situation fully accept the risk of losing useless pesticide costs. Indeed, these farmers consider crop protection costs as standard production costs whereas farmers referring to the ‘‘unprotected crop” situation consider pesticide treatments as risky investments. Farmers referring to the ‘‘unprotected crop” situation consider useless pesticide expenditures as losses, not as sunk production costs like farmers referring to the ‘‘protected crop” situation do.

Of course, given the impact of the reference situation on farmers’ decisions, to correctly attribute farmers’ reference situations is necessary for analyzing their pesticide uses. The analytical framework of Kőszegi and Rabin (2007) provides relevant solution concepts.

Farmers’ attitude toward pest risk: determination process and drivers

According to Kőszegi and Rabin (2007) individuals tend to choose their reference situation so that (*a*) the probability distribution of their optimal income conditional on their reference income equals that of their reference income and (*b*) their expected utility level is maximized by their reference situation choice. Condition (*a*) states that individuals choose their reference situation as a *personal equilibrium.*[13] Let consider an individual *i* facing a choice situation *c* where lotteries $\tilde{\pi}$ have to be chosen in the set $\mathcal{L}$. A lottery $\tilde{\pi}^e$ is a personal equilibrium if and only if $\tilde{\pi}^e \in \arg\max_{\tilde{\pi}\in\mathcal{L}} E[u(\tilde{\pi} \mid \tilde{\pi}^e)]$. Condition (*b*) states that if individuals have several personal equilibria for a given choice situation, then they are expected to choose their reference situation among their *preferred personal equilibria*, namely among the personal equilibria maximizing their expected utility level. Let $\mathcal{E}$ define the personal equilibrium set of individual *i* in choice situation *c*. Lottery $\tilde{\pi}^p$ is a preferred personal equilibrium if and only if $\tilde{\pi}^p \in \arg\max_{\tilde{\pi}^e\in\mathcal{E}} E[u(\tilde{\pi}^e \mid \tilde{\pi}^e)]$.

The personal equilibrium notions capture simple intuitions. Individuals facing a risky choice know how their reference situation affects their decisions and choose this reference situation in order to maximize their expected outcome while seeking to minimize the psychological costs induced by loss risk expectations. Reference situations determined as personal equilibria are appealing because the lesser the actual decisions deviate from the ones characterizing the reference situation, the more individuals avoid sensations of loss.

Importantly, this analytical framework implies that attitudes toward risks are context dependent: they depend on intrinsic risk preference parameters but also on the best available risk management tools. These attitudes are also endogenous because they result from an optimization process.

Table 2 summarizes the conditions required for the ‘‘protected crop’’ or ‘‘unprotected crop’’ situations to be personal or/and preferred personal equilibria. Indeed, applying the results reported in Table 1 with $p_{i|\hat{e}} = p_i$ directly yields that protecting the crop leads to a personal equilibrium if and only if $w \leq \gamma(p_i, \delta; a)$, and that not protecting the crop leads to a personal equilibrium if and only if $w \geq p_i\delta$. Provided that $\gamma(p_i, \delta; a) \geq p_i\delta$ for loss averse farmers, the ‘‘protected crop’’ situation is the unique personal equilibrium if $w \leq p_i\delta$ whereas the ‘‘unprotected crop’’ situation the unique personal equilibrium if $w \geq \gamma(p_i, \delta; a)$.

When $\gamma(p_i, \delta; a) \geq w \geq p_i\delta$ both the ‘‘protected crop’’ and ‘‘unprotected crop’’ situations are personal equilibria. But, the ‘‘protected crop’’ situation is farmers’ preferred personal equilibrium in this case. This is a consequence of condition $w \leq \gamma(p_i, \delta; a)$ implying condition $E[\bar{u}(\pi_{s=1} \mid \pi_{s=1})] \geq E[\bar{u}(\tilde{\pi}_{s=0}(p_i) \mid \tilde{\pi}_{s=0}(p_i))]$ to hold.

This finally implies that farmers are expected to adopt the ‘‘protected crop’’ as their reference situation if and only if $w \leq \gamma(p_i, \delta; a)$ or, equivalently, when pesticides are relatively inexpensive, when infestations are perceived as likely and damageable and/or when farmers exhibit sufficient loss aversion.[14] Importantly, the inequality $\gamma(p_i, \delta; a) \geq p_i\delta$ shows that farmers can adopt the ‘‘protected crop’’ as their reference situation even if the expected return of the pesticide treatment is negative. This expected return just needs to be large enough for the self-insurance motivation to justify the treatment.

Table 2. Personal equilibria and reference situations

	Conditions on the choice situation parameters: a, w, δ **and** p_i		
	$w \leq p_i\delta$	$p_i\delta \leq w \leq \gamma(p_i, \delta; a)$	$\gamma(p_i, \delta; a) \leq w$
Personal equilibria	“Protected crop”	‘‘Unprotected crop” ‘‘Protected crop”	‘‘Unprotected crop”
Preferred personal equilibrium	“Protected crop”	“Protected crop”	‘‘Unprotected crop”

This tendency to refer to sure reference situation is due to the fact that sure reference situations are more comfortable than random ones from a psychological viewpoint. For instance, farmers referring to the ‘‘unprotected crop” situation incur psychological costs whatever their spray decision is while farmers referring to the ‘‘protected crop” situation don’t incur any psychological cost when they decide to protect their crop. More generally, loss averse decision makers tend to be averse toward a given risk if they can get full insurance against this risk at reasonable cost. Being appealing, the fully insured situation is then considered and used as a benchmark situation. In the crop protection case, loss averse farmers exhibit strong aversion toward pest risks when they can purchase technically effective pesticides against these risks at reasonable cost.

Reference situation and treatment choice drivers: calibration results

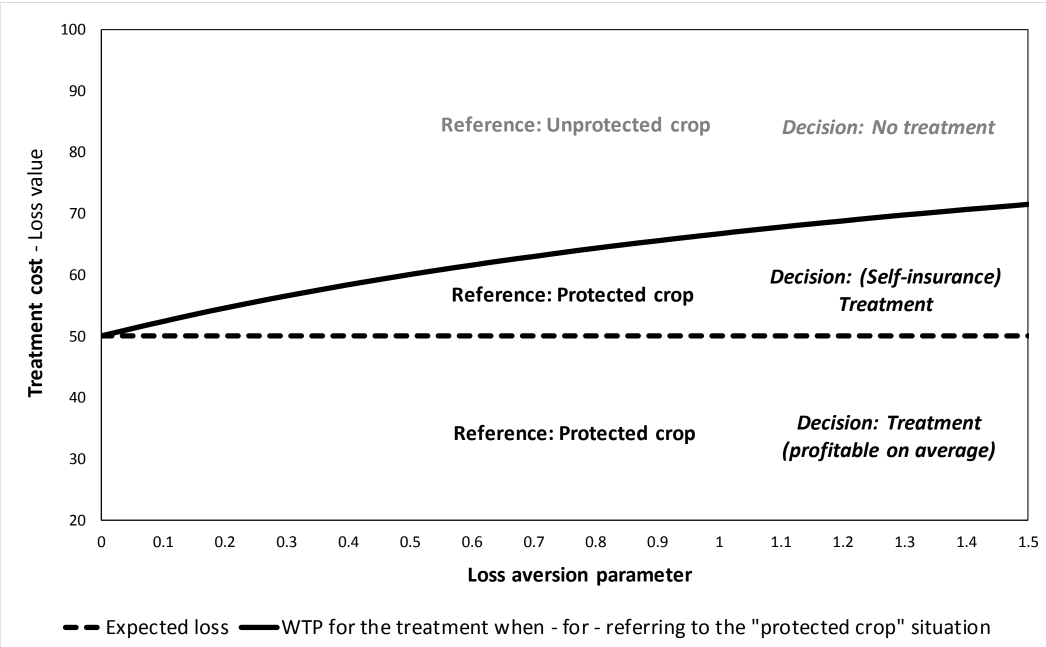
Of course, our results are mainly theoretical. The extent to which farmers actually refer to the 'protect crop' situation or to the 'unprotect crop' situation is an empirical issue. But, the simplicity of our modelling framework allows calibrating numerical results to illustrate the choice mechanisms analyzed above and to provide orders of magnitude of the involved effects for realistic ranges of the considered parameters.

The loss aversion parameter a is often found to lie between 0 (loss/risk neutrality) to 1.5 (strong loss aversion) (see, *e.g.*, Wakker, 2010). Whereas most authors consider 1 as a "normal" value for a (see, *e.g.*, Kőszegi and Rabin, 2007), we use 0.5 as our benchmark value for a for focusing on moderate loss aversion levels. We consider a potential loss δ equal to 100 which can be interpreted as, for instance, a potential loss of 0.5 metric ton per hectare for a crop sold at 200 € per metric ton or a potential loss of 25 bushels per acre for a crop sold at US$4 per bushel.

Figure 3 depicts the expected loss and the WTP for the treatment of farmers referring to the "protected crop" situation as functions of the loss aversion parameter a when the loss probability equals 1/2. This figure can be used for analyzing two decisions; adoption of reference situations by farmers on the one hand, and treatment decisions of farmers referring to the "protected crop" situation on the other hand.

Let assume that 1/2 is the loss probability famers' refer to when choosing their reference situation. Under this assumption the WTP for the treatment curve of Figure 3 depicts $\gamma(p_i,\delta;a)$ while the expected loss curve simply depicts $p_i\delta$ with $p_i = 1/2$. The difference between two curves measures the crop loss premium $\pi(p_i,\delta;a)$. Figure 3 shows that the more farmers are loss averse, the higher is their WTP for the treatment for referring to the "protected crop" situation. For instance, a farmer with a loss aversion parameter equal to 0.5 adopts the "protected crop" as his reference situation if the treatment cost doesn't exceed 60 while facing the risk of losing of 100 with probability 1/2. The maximum treatment cost at which farmers adopt the "protected crop" as their reference situation increases at a decreasing rate in their loss aversion level.

Figure 3. Loss aversion, treatment cost and treatment and reference situation choices ($\delta = 100$, $p_i = 1/2$ or $p_{i|\hat{e}} = 1/2$)



Let now assume that the considered farmer refers to the "protected crop" situation and face a pest risk characterized by a loss probability of 1/2 (*i.e.* $p_{i|\hat{e}} = 1/2$). The WTP curve depicts the maximum WTP of this farmer for the treatment, $\gamma(p_{i|\hat{e}}, \delta; a)$, while the expected loss curve situates the expected loss, $p_{i|\hat{e}}\delta$. Figure 3 then shows that if his loss aversion parameter equals 0.5 then this farmer (a) doesn't implement the treatment if the treatment cost exceeds

60,[15] (*b*) implements a self-insurance treatment if the treatment cost lies between 60 and 50 and (*c*) implements a treatment with positive expected return if the treatment cost doesn't exceed 50. These numerical illustrations tend to show that farmers with realistic loss aversion level would accept to pay significant loss risk premiums – up to 10 when facing a risk of losing 100 with probability 1/2 – for self-insurance motives.

Figure 4. Loss risk premium (in % of the expected loss), loss probability and loss aversion

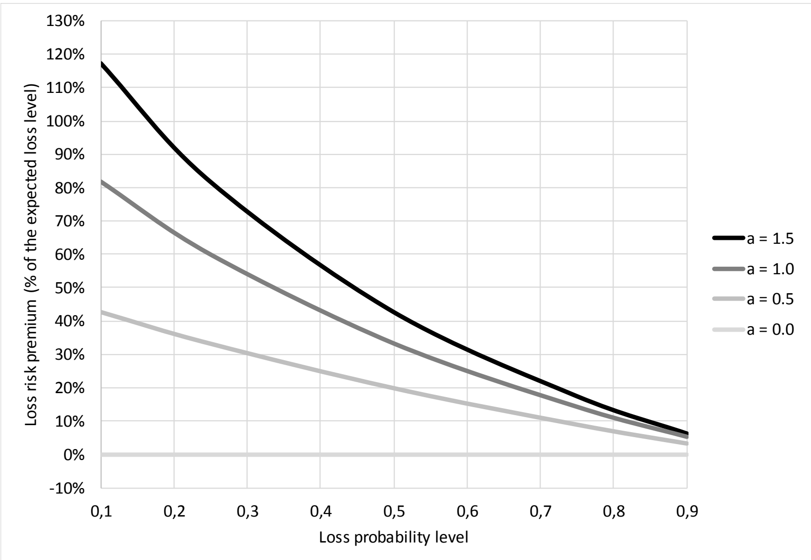


Figure 4 depicts how the loss risk premium $\pi(p_{i|\hat{e}}, \delta; a)$ depends on loss probability $p_{i|\hat{e}}$ for contrasted levels of loss aversion. The lower the loss probability, the higher is the loss risk premium as a share of the expected loss. For instance, at a loss aversion level of 0.5, the loss risk premium amounts to 20% of the expected loss when the loss probability is 1/2. It amounts to 44% of the expected loss when the loss probability is 1/10, meaning that the considered farmer would pay the treatment up to 14.4 – including a loss risk premium of 4.4 – when facing a risk of losing 100 with probability 1/10. The maximum WTP of this farmer for the treatment is 82 – including a loss risk premium of 6.8 (9.1% of the expected loss) – when he faces a risk of losing 100 with probability 3/4.

This suggests that referring to the "protected crop" situation tends to build significantly self-insurance motives for treatments against low probability pest risks. This may explain why extension agents report that it is difficult to convince farmers to skip treatments in low risk situations (see, *e.g.*, Lamine, 2011). Treatments are not called into question in high risk situations, their high expected return pressing down their loss premium.

Figure 5. Loss probability, loss aversion and loss risk premium ($\delta = 100$)

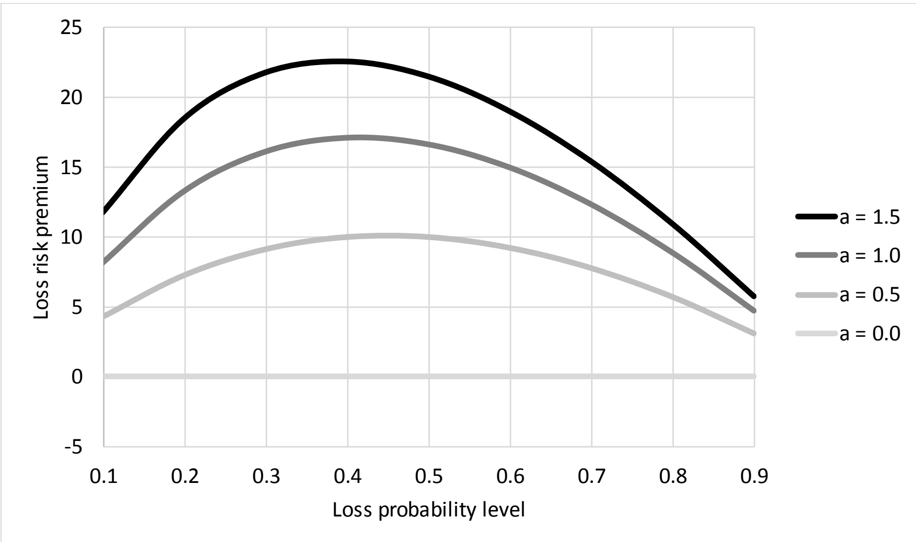


Figure 5 shows that the loss risk premium is much less variable in the loss probability than the corresponding expected loss. For instance, with a loss aversion parameter of 0.5 and considering loss probabilities ranging from 1/10 to 9/10, the loss risk premium ranges from 3 to 10 while the corresponding expected loss range from 10 to 90. Figure 5 also shows that the maximal loss risk premium levels occur at loss probability levels around 4/10 whatever the considered loss aversion parameters. Loss variability is maximal when the loss probability equals 1/2 while loss aversion builds strong self-insurance motives when loss probabilities are low.

On the role of pesticide taxes in pesticide reduction policies

For highlighting important consequences of the results described above let now assume that p_i is the 'true' probability of the crop infestation in the considered choice situation for the considered farmer population. Under this condition, farmers can be sorted into two groups according to their reference crop protection level. Sufficiently loss averse farmers, namely farmers for whom the condition $a \geq \alpha(p_i, w\delta^{-1})$ holds where

(4) $$\alpha(p_i, w\delta^{-1}) = -p_i \frac{p_i - w\delta^{-1}}{1 - w\delta^{-1}},$$

are expected to choose the "protected crop" as their reference situation while the others are expected to refer to the "unprotected crop" situation. Since the loss aversion threshold $\alpha(p_i, w\delta^{-1})$ is negative if $w \leq p_i\delta$, all farmers are expected to choose the "protected crop" as their reference situation when the pesticide treatment has positive expected return. More generally, the term $\alpha(p_i, w\delta^{-1})$ being decreasing in the treatment cost *w*, an increase in the pesticide price is expected to decrease the share of the farmer population choosing the "protected crop" as their reference situation.

Let now assume that farmers receive information (*e.g.*, scout monitoring information, public pest infestation predictions) leading them to believe that the infestation probability equals $p_{i|\hat{e}}$ instead of p_i. Provided that farmers decide to implement the pesticide treatment if $w \leq p_{i|\hat{e}}\delta$ when their reference situation is the "unprotected crop" and if $w \leq \gamma(p_{i|\hat{e}}, \delta; a)$

when their reference situation is the ‘‘protected crop’’, pesticide taxes would unambiguously decrease agricultural pesticide uses through two effects.

First, holding the reference situations constant, such taxes would decrease the expected profitability of the pesticides sprays for all farmers, according to a standard price effect. This expected profitability effect decreases aggregated pesticide uses if the treatment cost w shifts from below to above $\gamma(p_{i|\hat{e}}, \delta; a)$ for farmers' referring to the ‘‘protected crop’’, and from below to above $p_{i|\hat{e}}\delta$ for farmers' referring to the ‘‘unprotected crop’’ situation.

Second, because they shift w from below $\gamma(p_i, \delta; a)$ to above this threshold when a is lower than but sufficiently close to $\alpha(p_i, w\delta^{-1})$, pesticide taxes would encourage farmers to switch from the ‘‘protected crop’’ reference to the ‘‘unprotected crop’’ one. This reference crop protection level effect reduces aggregated pesticide uses if the farmers adopting the ‘‘unprotected crop’’ situation implemented self-insurance treatments when they were referring to the ‘‘protected crop’’ situation.

Pesticide taxes would also reduce farmers' welfare level, by lowering expected profit levels and by increasing psychological costs. Decreases in expected profits can be compensated, at least partly, by direct payments designed so as to preserve the incentive effects of the taxation scheme.[16] Such compensation scheme is likely to be essential for the acceptability of truly incentivizing pesticide taxation schemes (see, *e.g.*, Finger *et al*, 2017).

Farmers shifting their reference situation from the ‘‘protected crop’’ situation to the ‘‘unprotected crop’’ one would suffer additional intangible costs. The ‘‘unprotected crop’’ situation is a random reference situation generating higher psychological costs than those induced by the sure ‘‘protected crop’’ situation. This may explain the very low adoption rates of the agri-environmental contracts aimed to reduce farmers' pesticide use in the European Union Common Agricultural Policy. The specification of these contracts restrict the use of pesticides while compensating farmers for their expected profit losses only.

Of course, our results suggest that pesticide taxes should be the keystone of any agri-environmental policies aimed at reducing agricultural pesticide uses. In particular, pesticide taxes would be complementary to other policy instruments. For instance, pesticide taxes would spur the adoption of pesticide saving production practices, such as integrated crop management (ICM) practices, through two effects. These practices are designed so as to lower pest risks for decreasing crop protection requirements. As a result, pesticide taxes would decrease the expected returns of the conventional production practices more than those of their pesticide saving counterparts. This effect of pesticide taxes is expected to be the main one.

Yet, pesticide taxes may have another effect on the choices of loss averse farmers. Indeed, pesticide saving practices are of little interest when pesticide prices are sufficiently low for loss averse farmers to refer to high crop protection levels whatever their cropping practices. By intensifying the effects of the sensations of loss related to useless treatments pesticide taxes would lead farmers to lower their reference crop protection levels, thereby increasing the valuation of the reduction of pesticide expenditures entailed in the adoption of pesticide saving practices.

Concluding remarks

Using the PT analytical framework with endogenously determined reference situation enables to provide original insights on farmers' pesticide uses. Our most striking results stem from the determination process of farmers' reference situation with respect to pest risks. In the analytical framework proposed by Kőszegi and Rabin (2007), farmers' attitudes toward pest risks depend on farmers' exogenous loss aversion as well as on technical and economic factors. In particular, relatively low pesticide prices tend to induce farmers' aversion toward pest risks because they foster farmers' adoption of the ‘‘protected crop'' as their reference situation.

Farmers referring to the ‘‘protected crop'' situation behave as risk neutral farmers while farmers referring to the ‘‘protected crop'' situation implement chemical pesticide treatments (*a*) when these treatments have positive expected returns or (*b*) for self-insurance motives when the corresponding expected returns are not too negative and farmers are sufficiently loss averse.

Our analysis tends to highlight the role of the economic factors as key factors for explaining the current levels of pesticide uses. Indeed, if farmers seem to be currently ‘dependent' on high pesticide use levels, this seeming dependence is primarily due to economic factors. The behavioral mechanisms considered in this article mostly magnify the effects of low pesticide prices on farmers' pesticide uses. Farmers are reluctant to reduce their use of these efficient and cheap crop protection means because they know that they can use them to achieve profitable and ‘psychologically' comfortable crop protection levels. Yet, farmers would not refer to high crop protection levels if these protection means were too expensive. They would – be forced to – adapt their reference crop protection levels to the protection means available to them at reasonable cost. As a matter of fact, farmers already accept the crop loss risks due to diseases or pests against which no pesticides are available.

Our results have direct implications on the design of pesticide use reduction policies. For instance, pesticide taxes could be more efficient than usually considered. First, they would unambiguously reduce pesticides uses. Second, if farmers' pesticide demand displays limited own-price elasticity at the current levels of pesticide prices, this demand may be more elastic at higher price levels because such price levels may modify farmers' aversion toward pest risks.

Of course, our analytical framework considers a very simple choice situation. However, most of the 'technical' assumptions entailed in our model can be relaxed without affecting our main results. To assume that pesticide treatments eliminate only part of the damage would only slightly modify the conditions and formulas presented above. Results described in the Appendix prove that the main results presented in this article also continue to hold when farmers can choose the pesticide dosage, as in Feder (1979) or Lichtenberg and Zilberman (1986). Farmers' reference and chosen crop protection levels increase in the loss aversion level and in the pest risk level, and decrease in the pesticide price. Non-dichotomous pest risks are technically more challenging and deserves further research efforts.

The dichotomous pest risk and dichotomous decision framework is convenient for obtaining results described by simple conditions and formulas. This is especially useful for further investigating farmers' pesticide uses and the relevance of our modelling framework.

First, results presented in this article can provide a useful analytical framework for addressing difficult issues. For instance, in a companion paper we obtain original results related to farmers' willingness to pay for pest risk information and to the effect of the use of such information on pesticide uses. In particular, it can be shown that farmers' willingness to pay for pest information increases (decreases) in pesticide prices when farmers refer to the '(un)protected crop' situation. It can also be shown that loss averse farmers may prefer to not use (imperfect) costless pest risk information when treatment costs are sufficiently low. Such behavior cannot occur with the EUT framework.

Second, the simple dichotomous pest risk and dichotomous treatment choice situation provides a tractable framework for conducting empirical investigations of the mechanisms underlying farmers' pesticide uses. Data availability and limitations may prevent empirical analyses based on observed choices of farmers but suitably designed experiments may be considered for testing the theoretical results presented in this article. Kőszegi and Rabin (2007) offers guidelines for designing such experiments.

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Appendix. Treatment decisions with adjustable pesticide dosages

The results presented in this Appendix aim to demonstrate that the main results presented in the article also hold when farmers adjust the pesticide dosage of their treatment and under the "imperfect treatment" assumption.

Pesticide treatment with adjustable dosage

We now assume that farmers face a dichotomous pest risk and can choose their pesticide spray dosage *x*. Farmers buy the pesticide at price $w > 0$. If farmers don't protect their crop then their income equals y with probability $p_s = 1 - p_i$ (healthy crop), and $y - \delta$ with probability p_i (damaged crop). If they protect their crop with a pesticide spray at dosage *x* then their income, denoted by $\tilde{\pi}(x, p_i)$, is random. It equals y with probability p_s (healthy crop), and $y - \delta r(x)$ with probability p_i (damaged crop). Function $r(x)$ is a damage reduction function which is assumed to be non-negative, strictly decreasing and strictly convex in $x \geq 0$ with $r(0) = 1$ and $\lim_{x \to +\infty} r(x) = 0$. We also assume that the first derivative in *x* of $r(x)$ is strictly negative at $x = 0$, with $r'_x(0) < 0$, and tends to 0 as *x* grows to infinity.

Feder (1979) considered a similar damage reduction function. Function $r(x)$ differs from the damage abatement functions of Lichtenberg and Zilberman (1986) which are concave at high levels and convex at low levels of *x*. The following analysis also holds with these abatement functions. Note also that we consider that pesticide sprays are imperfectly efficient for controlling the considered plant health risk.

Loss neutral farmers choose the expected return maximizing pesticide dosage defined by $x^n(p_i) \equiv \arg\max_{x \geq 0}\{y - wx - p_i \delta r(x)\}$. $x^n(p_i)$ is null if $-w(p_i \delta)^{-1} \leq r'_x(0)$ and is strictly positive otherwise. Of course, null dosages indicate that farmers don't treat their crop. If

$x^n(p_i)$ is not null then it is characterized by the condition:

(A1) $r'_x(x^n(p_i)) = -w(p_i\delta)^{-1}$.

Given the monotonicity and curvature properties of $r(x)$, $x^n(p_i)$ is always uniquely defined and strictly increasing in p_i when $-w(p_i\delta)^{-1} \geq r'_x(0)$. The expected return maximizing pesticide dosage $x^n(p_i)$ is usefully defined by:

(A2) $x^n(p_i) \equiv \arg\min_{x\geq 0} \eta(x, p_i)$ where $\eta(x, p_i) \equiv wx + p_i\delta r(x)$.

Using standard comparative statics techniques and the monotonicity and curvature properties of $r(x)$ yields that $x^n(p_i)$ increases in the infestation probability p_i, the damage δ and the loss aversion level *a*, and decreases in the pesticide price *w*.

Optimal pesticide treatment decisions of loss averse farmers

Let consider first that farmers use $x_{ref} \geq 0$ as their reference pesticide dosage. Null reference dosage implies that farmers' reference situation is the "unprotected crop" situation. The reference income is random whatever the level of x_{ref}. It equals y with probability p_s (healthy crop), and $y - wx_{ref} - \delta r(x_{ref})$ with probability p_i (damaged crop). The value function based on this reference income in π, $\bar{u}(\pi \mid \tilde{\pi}(x_{ref}, p_i)) = E[u(\pi \mid \tilde{\pi}(x_{ref}, p_i))]$, is given by:

(A3) $$\bar{u}(\pi \mid \tilde{\pi}(x_{ref}, p_i)) = \pi - \begin{cases} \pi \text{ if } y - wx_{ref} < \pi \\ \pi - ap_s(y - wx_{ref} - \pi) \text{ if } y - wx_{ref} - \delta r(x_{ref}) \leq \pi \leq y - wx_{ref} \\ \pi - a(y - wx_{ref} - \pi) + ap_i\delta r(x_{ref}) \text{ if } \pi < y - wx_{ref} - \delta r(x_{ref}). \end{cases}$$

The expected utility of a pesticide spray at dosage *x*, $E[\bar{u}(\tilde{\pi}(x, p_i) \mid \tilde{\pi}(x_{ref}, p_i))]$, is given by:

(A4) $\bar{\bar{u}}^{-}(x, p_i \mid x_{ref}, p_i) = y - (1 + ap_i)\eta(x, p_i) - ap_i p_s \delta r(x) + ap_i\eta(x_{ref}, p_i)$ if $x_{ref} \geq x$

and by:

(A5) $\overline{\overline{u}}^{+}(x, p_i \mid x_{ref}, p_i) = y - (1 + ap_s)\eta(x, p_i) + ap_s w x_{ref}$ if $x \geq x_{ref}$.

Function $\overline{\overline{u}}^{-}(x, p_i \mid x_{ref}, p_i)]$ is usefully rewritten as:

(A6) $\overline{\overline{u}}^{-}(x, p_i \mid x_{ref}, p_i) = y + ap_i\eta(x_{ref}, p_i) - \mu(x, p_i)$

where:

(A7) $\mu(x \mid p_i) \equiv (1 + ap_i)\eta(x, p_i) + ap_i(1 - p_i)\delta r(x)$.

Functions $\overline{\overline{u}}^{-}(x, p_i \mid x_{ref}, p_i)$ and $\overline{\overline{u}}^{+}(x, p_i \mid x_{ref}, p_i)$ are equal at $x = x_{ref}$. Observing that $\arg\min_{x\geq 0} \overline{\overline{u}}^{+}(x, p_i \mid x_{ref}, p_i) = \arg\min_{x\geq 0} \eta(x, p_i)$ yields that $\overline{\overline{u}}^{+}(x, p_i \mid x_{ref}, p_i)$ achieves its unique maximum in $x \geq 0$ at $x = x^{n}(p_i)$. It is easily shown that function $\overline{\overline{u}}^{-}(x, p_i \mid x_{ref}, p_i)$ achieves its unique maximum in $x \geq 0$ at $x = x^{\ell}(p_i)$ where:

(A8) $x = x^{\ell}(p_i) \equiv \arg\min_{x\geq 0} \mu(x, p_i)$.

The term $x^{\ell}(p_i)$ plays an important role below. The monotonicity and curvature properties of $r(x)$ ensure that $\mu(x, p_i)$ has a unique minimum in $x \geq 0$. Given the definition of $\mu(x, p_i)$, $x^{\ell}(p_i)$ is null if $-w(p_i\delta)^{-1}(1 + ap_i)(1 + a)^{-1} \leq r'_x(0)$ and is characterized by the condition:

(A9) $r'_x(x^{\ell}(p_i)) = -w(p_i\delta)^{-1}(1 + ap_i)(1 + a)^{-1}$

otherwise. Obviously, we have $x^{n}(p_i) = x^{\ell}(p_i)$ if $a = 0$, *i.e.* for loss neutral farmers. Let now consider the case of strictly loss averse farmers. Provided that $(1 + ap_i)(1 + a)^{-1} < 1$ if $a > 0$, we have $x^{n}(p_i) < x^{\ell}(p_i)$ if $-w(p_i\delta)^{-1}(1 + ap_i)(1 + a)^{-1} > r'_x(0)$ and $x^{n}(p_i) = x^{\ell}(p_i) = 0$ otherwise. Condition (A9) also implies that $x^{\ell}(p_i)$ is strictly increasing in p_i when $-w(p_i\delta)^{-1}(1 + ap_i)(1 + a)^{-1} \geq r'_x(0)$.

Indeed, we necessarily have $x^n(p_i) \leq x^\ell(p_i)$, implying that $x^\ell(p_i)$ is a dosage exceeding the expected return maximizing dosage $x^n(p_i)$.

Let $x^*(p_i; x_{ref}, p_i)$ define the optimal pesticide spray dosage chosen by farmers facing the pest risk p_i and referring to crop protection level characterized by the pesticide dosage x_{ref} with the pest risk p_i. The expected value function $E[\overline{u}(\tilde{\pi}(x, p_i) \mid \tilde{\pi}(x_{ref}, p_i))]$ being defined by $\overline{\overline{u}}^-(x, p_i \mid x_{ref}, p_i)$ for $x_{ref} \geq x$ and by $\overline{\overline{u}}^+(x, p_i \mid x_{ref}, p_i)$ for $x_{ref} \leq x$, observing that $x^n(p_i) = \arg\max_{x \geq 0} \overline{\overline{u}}^-(x, p_i \mid x_{ref}, p_i) \leq x^\ell(p_i) = \arg\max_{x \geq 0} \overline{\overline{u}}^-(x, p_i \mid x_{ref}, p_i)$ directly yields that:

$$\text{(A10)} \quad x^*(p_i \mid x_{ref}, p_i) = \arg\max_x E[\overline{u}(\tilde{\pi}(x) \mid \tilde{\pi}(x_{ref}, p_i))] = \begin{cases} x^n(p_i) \text{ if } x_{ref} \leq x^n(p_i) \\ x_{ref} \text{ if } x^n(p_i) \leq x_{ref} \leq x^\ell(p_i) \\ x^\ell(p_i) \text{ if } x^\ell(p_i) \leq x_{ref} \end{cases}.$$

This result shows that farmers referring to sufficiently low dosage, *i.e.* with $x_{ref} \leq x^n(p_i)$, behave as risk/loss neutral farmers whatever their loss aversion level. They protect their crop with the expected profit maximizing dosage $x^n(p_i)$. In the other cases, strictly loss averse farmers choose dosages higher than $x^n(p_i)$. They choose $x^\ell(p_i)$ if their reference dosage x_{ref} level exceeds $x^\ell(p_i)$. Farmers choose their reference dosage level x_{ref} if and only if $x^n(p_i) \leq x_{ref} \leq x^\ell(p_i)$, implying that this condition is necessary and sufficient for a reference dosage level x_{ref} to imply a personal equilibrium in the considered pesticide treatment situation.

Optimal reference pesticide dosage

The definition of a preferred personal equilibrium and the results provided above imply that the optimal reference dosage, denoted by $x^o_{ref}(p_i)$, is defined by the following expected utility maximization problem:

(A11) $x^o_{ref}(p_i) \equiv \arg\max_x \left\{ E[\overline{u}(\tilde{\pi}(x,p_i) \mid \tilde{\pi}(x,p_i))] \text{ s.t. } x \in [x^n(p_i), x^\ell(p_i)] \right\}$.

Provided that $E[\overline{u}(\tilde{\pi}(x,p_i) \mid \tilde{\pi}(x,p_i))] = \overline{\overline{u}}^+(x,p_i \mid x,p_i) = \overline{\overline{u}}^-(x,p_i \mid x,p_i)$, we have:

(A12) $E[\overline{u}(\tilde{\pi}(x,p_i) \mid \tilde{\pi}(x,p_i))] = y - wx - (1+ap_s)p_i\delta r(x)$.

The properties of $r(x)$ ensure that $x^o_{ref}(p_i)$ is uniquely defined. Condition $(1+ap_s)^{-1} \le (1+ap_i)(1+a)^{-1} \le 1$ is easily shown to hold, with equalities if and only if $a = 0$. This implies that $x^o_{ref}(p_i) = x^\ell(p_i) = x^n(p_i)$ if farmers are loss neutral. Let now consider the case of strictly loss averse farmers. If $-w(p_i\delta)^{-1}(1+ap_s)^{-1} \le r'_x(0)$ then $x^o_{ref}(p_i) = x^\ell(p_i) = x^n(p_i) = 0$. If $-w(p_i\delta)^{-1}(1+ap_s)^{-1} > r'_x(0)$ then the strict convexity of $r(x)$ in $x \ge 0$ and condition $(1+ap_s)^{-1} < (1+ap_i)(1+a)^{-1}$ imply that $x^o_{ref}(p_i) = x^\ell(p_i)$. The optimal reference dosage $x^o_{ref}(p_i)$ cannot exceed $x^\ell(p_i)$, by definition.

Indeed, among the possible dosages leading to personal equilibria, *i.e.* dosages lying in the interval $[x^n(p_i), x^\ell(p_i)]$, loss averse farmers always choose highest one, $x^\ell(p_i)$. Using standard comparative statics techniques yields that $x^o_{ref}(p_i)$ increases in the reference infestation probability p_i, the damage δ and the loss aversion level *a*, and decreases in the pesticide price *w*. Also, the cheaper the pesticide price, the higher the crop protection level farmers refer to.

Optimal pesticide treatment decisions with endogenous reference pesticide dosages

Let now assume that farmers received information on the pest risk they face shortly before deciding their actual crop protection level. Their updated pest infestation probability is given by $p_{i|\hat{e}}$. In this case, they evaluate their pesticide spray dosages *x* referring to the reference dosage $x^o_{ref}(p_i)$ and the pest risk probability p_i. The expected utility given by a pesticide spray at dosage *x*, $E[\bar{u}(\tilde{\pi}(x, p_{i|\hat{e}}) \,|\, \tilde{\pi}(x^o_{ref}(p_i), p_i))]$, is given by:

(A13) $\bar{\bar{u}}^-(x, p_{i|\hat{e}} \,|\, x^o_{ref}(p_i), p_i) = y + ap_i\eta(x^o_{ref}(p_i), p_i) - \mu(x, p_{i|\hat{e}})$ if $x^o_{ref}(p_i) \geq x$

and by:

(A14) $\bar{\bar{u}}^+(x, p_{i|\hat{e}} \,|\, x^o_{ref}(p_i), p_i) = y + ap_s w x^o_{ref}(p_i) - (1 + ap_s)\eta(x, p_{i|\hat{e}})$ if $x \geq x^o_{ref}(p_i)$.

We also have $\bar{\bar{u}}^-(x^o_{ref}(p_i), p_{i|\hat{e}} \,|\, x^o_{ref}(p_i), p_i) = \bar{\bar{u}}^+(x^o_{ref}(p_i), p_{i|\hat{e}} \,|\, x^o_{ref}(p_i), p_i)$. The results presented above yield that the optimal pesticide spray dosage in this situation, $x^*(p_{i|\hat{e}} \,|\, x^o_{ref}(p_i), p_i) \equiv \arg\max_{x \geq 0} E[\bar{u}(\tilde{\pi}(x, p_{i|\hat{e}}) \,|\, \tilde{\pi}(x^o_{ref}(p_i), p_i))]$, is provided by:

$$\text{(A15)} \quad x^*(p_{i|\hat{e}} \,|\, x^o_{ref}(p_i), p_i) = \begin{cases} x^n(p_{i|\hat{e}}) \text{ if } x^o_{ref}(p_i) \leq x^n(p_{i|\hat{e}}) \\ x^o_{ref}(p_i) \text{ if } x^n(p_{i|\hat{e}}) \leq x^o_{ref}(p_i) \leq x^\ell(p_{i|\hat{e}}) \\ x^\ell(p_{i|\hat{e}}) \text{ if } x^\ell(p_{i|\hat{e}}) \leq x^o_{ref}(p_i) \end{cases}.$$

Given that the functions $x^n(p_{i|\hat{e}})$ and $x^\ell(p_{i|\hat{e}})$ are increasing in $p_{i|\hat{e}}$, two cases can occur when farmers received "good news", *i.e.* when the pest risk is lower than previously anticipated. If $x^o_{ref}(p_i) \leq x^\ell(p_{i|\hat{e}})$ then farmers stick to their reference pesticide dosage $x^o_{ref}(p_i)$, implying that they behave as risk averse farmers. They use dosages exceeding the expected profit maximizing dosage $x^n(p_{i|\hat{e}})$. This sub-case occurs when $p_{i|\hat{e}}$ is lower but close to p_i. If $x^o_{ref}(p_i) \geq x^\ell(p_{i|\hat{e}})$ then farmers reduce their pesticide dosage from the reference one $x^o_{ref}(p_i)$ to $x^\ell(p_{i|\hat{e}})$. Strictly loss averse farmers (deciding to treat) choose "risk averse" pesticide dosage since $x^\ell(p_{i|\hat{e}}) > x^n(p_{i|\hat{e}})$ when $a > 0$ and ($x^\ell(p_{i|\hat{e}}) > 0$). Yet, farmers can decide not to treat their crop when $p_{i|\hat{e}}$ is sufficiently low.

Similarly, two cases can occur when farmers received "bad news", *i.e.* when the pest risk is higher than previously anticipated. If $x^n(p_{i|\hat{e}}) \leq x^o_{ref}(p_i)$ then farmers stick to their reference pesticide dosage $x^o_{ref}(p_i)$. This occurs when $p_{i|\hat{e}}$ is higher but close to p_i. As discussed above, the reference dosage $x^{o}_{ref}(p_i)$ characterizes relatively risk averse crop protection levels when farmers are loss averse. If $x^{n}(p_{i|\hat{e}}) \geq x^{o}_{ref}(p_i)$ then farmers increase their pesticide dosage from the reference one, $x^{o}_{ref}(p_i)$, to the expected profit maximizing one, $x^{n}(p_{i|\hat{e}})$. This occurs when pest risks are significantly higher than previously anticipated. In such cases, the "risk neutral" pesticide dosage $x^{n}(p_{i|\hat{e}})$ is high and, consequently, largely controls the considered severe loss risk.

Concluding remarks

These results are analogous to those obtained in the "fixed dosage" case with perfectly efficient treatment. Loss averse farmers tend to adopt high, relatively risk averse, reference pesticide dosages, especially when pesticide are relatively cheap. These reference dosages tend to anchor the ones actually chosen, implying that loss averse farmers are reluctant to reduce their crop protection level in low pest risk situations. Yet, farmers don't need to be strongly loss averse for considering high pesticide dosages in high pest risk situations. In such cases, the expected profit maximizing dosages controls for most of the loss risk due to pests.

[1] For instance, pesticide taxes were considered by the European Commission (Skevas *et al*, 2013; Finger *et al*, 2017) but have not been implemented. In the few countries where they are, pesticide taxes are generally implemented with low tax rates and mostly for fund raising. The Danish pesticide tax scheme, with tax rates ranging from 25% (fungicides and herbicides) to 35% (insecticides), is a notable exception in this respect. The French and Norwegian taxing schemes are based on the toxic and eco-toxic characteristics of the pesticides but they consider relatively moderate tax rates, not exceeding 8% in the French case and 15% in the Norwegian case.

[2] Econometric analyses often tend to show that farmers' pesticide uses display very limited responsiveness to pesticide price increases (see, *e.g*., Skevas *et al*, 2013).

[3] Alternatives to conventional crop production practices and to chemical crop protection exist but their adoption rate remains low. In particular, non-chemical crop protection practices are often more difficult to master and, in general, only allow achieving lower crop protection levels than the corresponding chemical practices. Pesticide saving cropping management practices generally rely on reduced target yield levels that are costly when crop prices are high. Pesticide saving cropping management systems rely on crop rotations preventing farmers to focus a few crops among the most profitable ones (see, *e.g.*, Aubertot *et al*, 2005).

[4] The economic efficiency of chemical crop protection also explains the focus of plant breeding on productivity rather than on resistances during the past decades (Vanloqueren and Baret, 2009).

[5] These arguments can also include those relating to farmers' risk aversion as it is described by the standard, and economically rational, expected utility framework.

[6] As well the Cumulative Prospect Theory proposed by Tversky and Kahneman (1992).

[7] See also Kőszegi (2010) and Kőszegi and Rabin (2006, 2009) for further insights and, *e.g.*, Heidhues and Kőszegi (2008) or Crawford and Meng (2011) for applications.

[8] Methodological issues also impair empirical analyses of farmers' pesticide uses. For instance, the use of standard farm data only rises serious specification and identification issues. Production technology and preference features of the pesticide use process need to be simultaneously disentangled (see, *e.g.*, Lence, 2009). Farmers' risk perceptions raise additional identification issues (see, *e.g*., Manski, 2004; Just, 2008; Just and Just, 2011).

[9] Pest management must be consistent with the chosen crop production practice and single pesticide use decisions must be consistent with the implemented pest management strategy. But, single pesticide use decisions must primarily provide suitable responses to the pest problem targeted by the considered pesticide treatment.

[10] The assumptions and intuitions underlying our theoretical analysis are grounded on elements gathered upon discussions with farmers and crop protection experts – agricultural scientists and extension experts – as well as on results obtained by sociologists and agronomists analysing farmers' pesticide uses from their own disciplinary perspectives (see, *e.g.*, Jorgensen *et al*, 2008; Lamine, 2011; Bürger *et al*, 2012). According to our experience, the results presented in this article are more easily understood by non-economists than the results obtained from EUT analyses.

[11] The efficiency of pesticide treatment is only ensured at specific stages of the pest and crop biological cycles and under specific climatic conditions.

[12] *I.e.*, we ignore three phenomena accounted for by in PT: probability weighting, risk aversion in the gain domain and risk loving in the loss domain. According to Wakker (2010: 292), '… more than half of the risk aversion empirically observed has nothing to do with utility curvature or probability weighting, but is generated by loss aversion, the main empirical phenomenon regarding preference dependence.' Indeed, risk aversion in the gain domain and risk loving in the loss domain do not matter much when considering moderate stake risky decisions (Kőszegi and Rabin, 2007). Also, whether or not probability weighting impacts farmers' crop health risk perceptions doesn't affect our main results.

[13] The term 'personal equilibrium' is used here as a shorthand for the term 'unacclimating personal equilibrium' used by Kőszegi and Rabin (2007).

[14] Of course, farmers can adopt different references depending on the risks they face.

[15] Note however, farmers may not refer to the ''protected crop'' situation if the treatment cost is too high.

[16] Such a compensation scheme could be designed as per hectare payments defined per crop in a given region, for accounting for differences in pesticide uses across crops and pedo-climatic conditions. If the total tax revenue were to be redistributed for compensation purpose, farmers would be rewarded or penalized depending on their pesticide expenditures relative to the regional crop average expenditures.