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WORKING PAPER

Land allocation and the adoption of innovative practices in agriculture: a real option modelling of the underlying hidden costs

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The agricultural sector is faced with barriers to the adoption and dissemination of innovative practices that cannot be properly captured by the standard financial analysis of their profitability. These barriers can be particularly detrimental to the shift towards practices favourable to environmental protection and mitigation or adaptation to climate change. This article focuses on how irreversibility premium and risk premium can combine to refrain adoption. It emphasizes the particular context of agriculture, in particular the role of land allocation choices which make it possible to modulate the uncertain and potentially irreversible consequences of adoption by a particular type of hedging. It is highlighted from a numerical simulation on the case of Miscanthus in France that irreversibility and risk premiums of prima facie low magnitude can strongly curb the adoption and diffusion of an innovative practice.

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1 Introduction

Economic analysis of new technologies or practices adoption and diffusion has often used the agricultural sector as a case study. One of the reasons is that the agricultural sector is characterized by multiple decision-makers who are heterogeneous and between whom information is transmitted progressively. David Davis (1966) followed by Davies (1979) for instance highlight the role of the heterogeneity of the surfaces cultivated by each farmer to explain the mechanisation of reaping in the United States during the 19th century. Their work is considered as one of the first discrete choice modelling of new technologies adoption and diffusion. Griliches (1957), for his part, proposed one of the first econometric applications of epidemiological models by analysing the diffusion of hybrid maize. A renewed interest in these questions of adoption and diffusion of new agricultural practices took place when it appeared that no-cost options, as identified for instance with the highly mediated McKinsey curve (Enkvist et al. 2007), for the mitigation of greenhouse gas (GHG) emissions in agriculture were not meeting with success. An OECD paper (Wreford et al. 2017) devoted to barriers to the adoption of climate-friendly practices in agriculture stressed that *governments should identify and tackle the existing barriers before designing and implementing new policy measures*. This paper highlights the specifics of irreversibility combined with risk aversion as a key barrier to adoption in the agricultural sector. It puts the emphasis on the role of information as a public good, and on the need to address informational externalities.

No-cost options for the mitigation of GHG are notably defined by Jaffe et al. (2017) as *investments, technologies or practices whose adoption (1) reduces the environmental impact of a farm, and (2) does not reduce the profitability of the farm, measured in conventional financial terms. This means that any benefits (e.g. aesthetic) or costs (e.g. psychological) that are associated with adoption but which are not typically included in financial analyses are not considered in determining whether an option is "no-cost" in this context.* Jaffe et al. (2017) moreover propose a typology of barriers to adoption as a guideline to understand the gap between observed adoption decisions and those predicted on the basis of the no-cost criteria. Subsequently, Fleming et al. (2019) surveyed New Zealand farmers to assess the respective importance of the different barriers listed in this typology. Alongside behavioural factors, a more in-depth analysis of which can be found in Streletskaya et al. (2020), their survey highlights two main factors. First, the adoption in question is arguably efficient in the sense that it seems no-cost at first sight but is no longer so when a more complete and more adequate analytical framework than a simple costs benefits analysis is implemented. Disregarding the sunk cost nature of the required investment may be misleading, for instance. Next, there is imperfect information on the outcomes to be expected from the adoption. These two factors put the emphasis on an irreversibility premium on the one hand, and on a risk premium on the other hand, to explain the existence of "hidden" costs, in the sense that these premiums are not considered in standard financial analysis.

Irreversibility is significant for a number of practices aimed at improving the environmental and ecological quality of agricultural activity. This is the case, for instance, of the abandonment or reduction of tillage or the implementation of perennial energy crops. Once these practices implemented, it is technically complex and economically costly to return to the previous situation in the short term. Real options theory (Dixit and Pindyck 1994) has shown that, combined with uncertainty about gains, irreversibility leads to a form of rational wait-and-see attitude. Köppl et al. (2013) propose a survey of real option problems applied to the agricultural sector. Applications include, among others, the decision to switch from conventional to organic farming (Kuminoff and Wossink 2005), the decision to adopt site-specific crop management (Isik et al. 2000) or the decision to develop perennial crops (Price and Wetzstein 1999). We can add applications where irreversibility is contractual. More precisely, legal irreversibility is introduced by policy makers in order to avoid time inconsistency in the decision to adopt the targeted practice. Tegene et al. (1999) study for instance conservation easements and Isik and Yang (2004) analyze the case of the US Conservation Reserve Program. Beyond the agricultural sector, Ginbo et al. (2022) present a recent meta-analysis of the application of real options to issues of adaptation to, and mitigation of, climate change. They note that very few works simultaneously take into account risk aversion and irreversibility. Yet, risk aversion plays an important role in the agricultural sector because, unlike in the industrial sector, decisions are generally made by individual entrepreneurs. These entrepreneurs are often constrained in the use of hedging instruments against risk which requires a good command of finance, or face idiosyncratic risks which do not lend themselves well to hedging. This article proposes to go further than the few previous works mentioned by Ginbo et al. (2022) by not limiting itself to a *stricto sensu* application of the theory of real options in the presence of risk aversion to investment decisions in agriculture, but rather by proposing an in-depth consideration of agricultural sector specifics.

Isik (2005) is one of the very first to apply real options theory in the presence of risk aversion to the agricultural sector. The decision analysed is that of farmers who can switch from farming stochastic revenues to a risk free retribution by integrating the US Conservation Reserve Program. Narita and Quaas (2014) extend this type of analysis to the choice between two climate sensitive productions, while Ihli et al. (2013) conduct an experimental study on farmers in order to investigate the combined effect of irreversibility and risk aversion. They obtain two interesting results for our purposes. The first result is that the Real Option Value (ROV) criterion better fits the experimental data than the Net Present Value (NPV) criterion. The second result is that risk aversion tends to significantly reduce the effect of irreversibility in the sense that more risk-averse farmers invest earlier and disinvest earlier. These results contrast with those of Chronopoulos et al. (2011) or Hugonnier and Morellec (2013) who were among the first to introduce the expected utility criterion into the canonical real option model to address risk aversion in a context where contingent claims analysis is not implementable due to incomplete financial markets. Indeed, in these two studies it is shown that, at least theoretically, the incentive to delay investment is magnified by risk aversion. However, these theoretical models completely rule out the possibility of hedging against risk. With a related model, but assuming that partial hedging is possible thanks to the existence of an asset that is imperfectly correlated with the risk of the investment project, Henderson (2007) obtains an opposite result where the wait-and-see attitude is reduced by risk aversion. This raises the question of the degree of hedging against risk that farmers can resort to. Applications of options theory usually assume that each farmer faces a binary choice between fully adopting a new technology or practice or not adopting it at all. However, through her choice of allocation of the total area of land at her disposal, each farmer actually benefits from divisibility of the adoption project, and consequently from an opportunity of risk diversification. This room for maneuver is taken into account, in a different context of irreversible land use decision on a larger geographical scale and without risk aversion, by Capozza and Helsley (1990). The first major contribution of this article is to examine the consequences of combining risk aversion and divisibility as a hedging instrument at the farm level.

Divisibility refers to the fact that farmers can choose to devote only a fraction of their total acreage rather than the whole of it to a new culture or a new practice. It is key in land allocation models under risk which assume, following Chambers and Just (1989) that land is a fixed but allocatable factor. When risk affects yields, authors have either adopted the mean-variance portfolio choice proposed by Markowitz (1952) (see e.g. Aradhyula and Holt 1989; Sckokai and Moro 2006) or its more general version based on expected utility and developed by Levy and Markowitz (1979) and Kroll et al. (1984) (see e.g. Chavas and Holt 1990). In these models, risk-averse farmers choose to allocate their land to different crops in order to balance expected returns on the one hand and risk on the other hand but the modelling is static and irreversibility in land allocation decisions is totally disregarded. This approach follows on from the literature dealing with profit maximization under price risk, initiated by Sandmo (1971) and Pope and Kramer (1979) and further applied to farmers by Moschini and Hennessy (2001) and Ramaswami (1992), but it puts the emphasis on the case of land as a quasi-fixed input. In most theoretical studies, results show that the adoption of innovations, as well as the proportion of land allocated to innovative practices, tends to increase with the farm size, due to a decrease of the impact of risk on choices (the DARA assumption prevails). These results have been empirically confirmed by Saha (1997), Chavas and Holt (1996) and Feder and O'Mara (1981) for instance. Following the portfolio risk diversification principle, negative (resp. positive) correlations between yields from conventional *versus* innovative productions increases (resp. decreases) the likelihood of adoption by risk-averse farmers. This is confirmed by a large strand of articles (Feder 1980; Feder 1982; Just and Zilberman 1983; Just and Zilberman 1988). Nevertheless, when the exact correlation structure is uncertain, adoption is partially deterred (Ghadim and Pannell 1999). This highlights the importance of distinguishing between risk and uncertainty following the terminology introduced by Knight Frank (1921). The second major contribution of this article is precisely to focus on the fact that decisions related to innovation and its diffusion are made under uncertainty rather than risk.

Profit uncertainty, information and potential irreversibility of adoption of new practices or land-uses are considered as playing an important role in agriculture (see e.g. Sunding and Zilberman 2001, Ghadim and Pannell 1999, Knowler and Bradshaw 2007). Uncertainties affecting profits are already known as barriers to adoption in the literature dealing with innovation. Concerning specifically the agricultural sector, the capacity of a risk-averse farmer to adopt innovations on the one hand, and the global management of her production on the other hand, are the two main areas of research in the field of uncertainty and risk (Isik and Khanna 2003).

The perspective of receiving more information as time goes makes decisions under uncertainty tightly linked to dynamic analysis. Some authors have more specifically analyzed irreversible decisions in this context. Their work departs from the standard real option theory because the stochastic dynamics they consider does not rely on Markovian processes but explicitly refers to Bayesian learning. For instance, Jensen (1982) analyses the impact of initial beliefs, and their Bayesian updating as information arrives, on the diffusion of an innovation with uncertain outcomes.

As outlined by Sunding and Zilberman (2001), the option value rationale can be an interesting tool to analyze adoption of new technologies in agriculture if it is able to grasp the dynamics of beliefs and their updating with the arrival of information. Feder and Slade (1984) introduce information as a cost supported by farmers who have a willingness to pay for it in order to better assess the level of profits that accrue from the use of a new input. The level of adoption is shown to depend on the level of knowledge of farmers, among which the most educated and those with the better access to information seem to adopt more easily. Farmers operating larger farms are also more willing to pay to access to this information. In another vein, Leathers and Smale (1991) showed that when an uncertain innovation is proposed to farmers in the form of different complementary packages, some risk-neutral farmers who do not trust the information providers tend to adopt specific part of the innovation (package) in order to learn on their own the potential results. This leads to a sequential and reversible diffusion of the innovation where late adopters tend to delay adoption in order to observe what is the outcome for early adopters in the neighborhood. By contrast, our paper focuses on the role of irreversibility in the adoption of mitigation practices by farmers in the presence of uncertainty and learning and combines it with divisibility. Whereas the two features, irreversibility and divisibility, have been disconnected in the literature, the paper highlights how they are intertwined and how their simultaneous analysis can help designing policies to circumvent informational barriers to the diffusion of profitable mitigation practices by farmers.

The paper is organized as follows. Section 2 introduces the modelling of Bayesian learning. Section 3 applies this modelling to risk-neutral farmers facing the decision to convert part or all of their land to a new, innovative, practice in the case of an exogenous arrival of information. The concept of irreversibility premium, or quasi option value, is discussed as a hidden cost in this context. Section 4 extends the model to the case of risk-averse farmers. It is shown that the risk premium also acts as a hidden cost but interacts in a non additive way with the irreversibility premium. Section 5 then discusses the case of an endogenous arrival of information and focuses on the informational externality between farmers when they have to allocate some land to the new practice to experience it. The absence of proper internalization of the informational externality is a third type of hidden cost. In this section the different types of hidden costs are compared on the basis of a calibration of the model for adoption of Myscanthus in France. The last section concludes with policy implications.

2 Modelling assumptions

We consider farmers individually facing the choice to switch some acreage of land from a proven conventional practice to a new innovative practice. Such a switch is irreversible because it requires for instance a soil work or an input use that drastically alter the ability to turn back to the proven practice. Moreover, the turn back to the proven practice takes time (rehabilitation, soil nutriment updating). In this sense, there is physical irreversibility between two agricultural campaigns. Typical examples of such switches from proven practices to alternative "innovative" practices are tillage reduction or fertilizer burying, or long-run land use changes such as bio-fuel crops (miscanthus for instance), agroforestry development or forest, development and further adoption of durable grasslands in herb systems. Conservation practices aiming at keeping a parcel in a carbon-storage intensive activity constitutes another example. In the model developed thereafter, we assume the time path between two choices periods to be sufficiently short for ruling out a turn back in case of adoption of the new practice. Let L_i be the total available land for a farmer i. We assume a continuum of farmers with $L_i \in [L_{min}, L_{max}]$. There are two agricultural practices or activities, respectively p for "proven" (currently widely spread among farmers) and n for "new" (innovative practice or activity). l_i^p and l_i^n denote the acreage of land a farmer i allocates respectively to the proven and to the new practice. In order to analyse the decision problem at stake, we have to further discuss the economic parameters that drive farmers' choices.

We consider two time periods, denoted $t = 0$ (present) and $t = 1$ (future), in order to account for the effect of irreversibility and information arrival. In $t = 0$ as in $t = 1$ the gross margin (profit per unit of area, thus revenues net from input costs that are not explicitly modeled) from the proven practice is certain and denoted r^p. The gross margin from the new practice is uncertain. There are two scenarii as regards the true state-of-the-nature. The first scenario $S = sup$ is "optimistic" and associated to a high level of gross margin r_{sup}^n. The second scenario $S = inf$ is "pessimistic" and associated to a low gross margin $r_{inf}^n < r_{sup}^n$. The prior belief, in $t = 0$, in favor of the "optimistic" scenario is represented by a probability $X_0 = Pr[S = sup]$ (thus $1 - X_0$ is the subjective probability $Pr[S = inf]$ associated to the "pessimistic" scenario). Both r^p and r_s^n (with $s = inf$ or sup) may account for environmental negative and/or positive externalities, but we do not focus on the exact policy implemented and treat it as exogenous.

For the time being we consider the simple case where the information arrival is totally exogenous. We will relax this assumption later on. Between $t = 0$ and $t = 1$ two types of message M can be received and their probability of reception depends on the true state-of-the-nature. If the true state-of-the-nature matches the "optimistic" scenario, a positive message $M = pos$ is received with probability $\theta_{sup} > 1/2$ (and a negative message $M = neg$ is received with probability $1 - \theta_{sup} < 1/2$). If the true state-of-the-nature matches the "pessimistic" scenario, a negative message $M = neg$ is received with probability $\theta_{inf} > 1/2$ (and a positive message $M = pos$ is received with probability $1 - \theta_{inf} < 1/2$). The reception of a positive message $M = pos$ corresponds to the fact that the new practice has performed well as it was implemented by some farmers or by an agricultural research center, and conversely for the reception of a negative message $M = neg$. The two probabilities θ_{sup} and θ_{inf} capture noise surrounding the reception of a message. For instance, an intrinsically efficient practice, for which the "optimistic" scenario matches with the true state-of-the-nature, may perform bad due to exceptionally unfavourable weather conditions. We do not impose symmetry between θ_{sup} and θ_{inf}, so that our modelling approach admits special cases where one type of message is perfectly informative (i.e. the corresponding θ amounts to 1) whereas the other type is noisy.

The reception of a message affects the beliefs in a Bayesian updating process, as in Jensen (1982) or **?**. Accordingly, the posterior belief may be computed by using Bayes' theorem. In case of a positive message received between dates $t = 0$ and $t = 1$, the posterior beliefs are given by:

$$\begin{cases} X_1^{pos} = \frac{\theta_{sup} X_0}{P^{pos}} \\ 1 - X_1^{pos} = \frac{(1-\theta_{inf})(1-X_0)}{P^{pos}} \end{cases} \tag{1}$$

where X_1^{pos} is used as a shortcut for $Pr[S = sup|M = pos]$ at date $t = 1$. Similarly, noting X_1^{neg} for $Pr[S = sup|M = neg]$, we obtain

$$\begin{cases} X_1^{neg} = \frac{(1-\theta_{sup}) X_0}{P^{neg}} \\ 1 - X_1^{neg} = \frac{\theta_{inf}(1-X_0)}{P^{neg}} \end{cases} \tag{2}$$

Beliefs thus follow a stochastic process driven by the type of message received between the two consecutive dates $t = 0$ and $t = 1$. The term $P^{pos} = X_0\theta_{sup} + (1 - X_0)(1-\theta_{inf})$ (resp. $P^{neg} = X_0(1-\theta_{sup}) + (1-X_0)\theta_{inf}$) is the subjective probability of receiving a positive (resp. negative) message whatever the true state-of-the-nature. Given that $\theta_{sup} > 1 - \theta_{sup}$ and $\theta_{inf} > 1 - \theta_{inf}$, a comparison of the likelihood of the two scenarii shows that the belief in favour of the optimistic scenario increases from $t = 0$ to $t = 1$ if a positive message is received whereas it decreases if a negative message is received. A positive (resp. negative) message thus unambiguously increases (resp. decreases) the expected gross margin from adopting the new practice. The effect on the variance of the gross margin is more ambiguous and crucially depends on the prior beliefs and/or on the noise parameters θ_{sup} and θ_{inf}. This point will be further commented latter on.

3 The risk-neutral farmer

Because of irreversibility in the adoption of the new practice, the farmer's problem has to be solved backwards. Accordingly, we first examine the optimal allocation of her land by a farmer i at the second period $t = 1$ given the acreage l_i^n already devoted to the new practice at the first period $t = 0$ and conditionally on the type of message m received between the two dates. Due to irreversibility, we express this problem as the choice of the increment $\Delta l_i^n \in [0, L_i - l_i^n]$ of land eventually added to l_i^n at date $t = 1$ at the expense of less land devoted to the proven practice. The corresponding program for profit maximization is given by:

$$\begin{cases} \max_{\Delta l_i^n \in [0, L_i - l_i^n]} X_1^m (r^p l_i^p + r_{sup}^n (l_i^n + \Delta l_i^n)) + (1 - X_1^m)(r^p l_i^p + r_{inf}^n (l_i^n + \Delta l_i^n)) \\ \text{with } l_i^p = L_i - (l_i^n + \Delta l_i^n) \end{cases} \tag{3}$$

where X_1^m takes the value X_1^{pos} if a favourable message has been received and X_1^{neg} if a unfavourable message has been received. This constrained optimization program is easily solved by substituting the land availability constraint $l_i^p = L_i - (l_i^n + \Delta l_i^n)$ in the expected profit. The linearity of the expected profit in $t = 1$ then implies that the outcome of its maximization is a corner solution:

$$\begin{cases} \Delta l_i^n = 0 & \text{if } \mathbf{E}_{X_1^m}(r^n) < r^p \\ \Delta l_i^n = L_i - l_i^n & \text{if } \mathbf{E}_{X_1^m}(r^n) >= r^p \end{cases} \tag{4}$$

where $\mathbf{E}_{X_1^m}$ (with $m = neg$ or $m = pos$) stands for mathematical expectation $X_1^m r_{sup}^n + (1 - X_1^m) r_{inf}^n$ of margins computed on the basis of posterior beliefs. If the farmer believes in $t = 1$ that the expected margin generated by the new practice exceeds the margin from the proven practice, then the irreversibility constraint (i.e. $\Delta l_i^n >= 0$) is not binding and the risk-neutral farmer allocates all her available land to the new practice. The higher X_1^m, the more likely this choice is. Therefore, for the problem to make sense we focus on the case where full adoption is optimal if and only if a positive message has been received. The resulting maximum expected profit level is

$$\pi_1^{pos} = L_i \mathbf{E}_{X_1^{pos}}(r^n) \tag{5}$$

If a negative message is received the irreversibility constraint is binding. The risk-neutral farmer would ideally reallocate all her land to the proven practice but is constrained to keep the amount of land l_i^n already devoted at $t = 0$ to the new practice and can just choose not to further adopt the new practice in $t = 1$. The resulting maximum expected profit level depends on the acreage already allocated to the new practice at $t = 0$ and reads

$$\pi_1^{neg} = r^p(L_i - l_i^n) + l_i^n \mathbf{E}_{X_1^{neg}}(r^n) \tag{6}$$

A direct consequence of our assumption that the irreversibility constraint is binding in the case a negative message is received is that the land allocation problem is dynamic.

More precisely, in $t = 0$ the farmer chooses the acreage l_i^n she will devote to the new practice, taking into account the impact of her choice in the second period according to the type of message she will get. Indeed, if and only if a negative message is received the choice of l_i^n at the first period will affect the profit flow at the second period. Formally, the problem can be written as:

$$\max_{l_i^n \in [0, L_i]} \left\{ \begin{array}{l} X_0(r^p(L_i - l_i^n) + r_{sup}^n l_i^n) \\ +(1 - X_0)(r^p(L_i - l_i^n) + r_{inf}^n l_i^n) \\ +\beta(P^{pos}\pi_1^{pos} + P^{neg}\pi_1^{neg}) \end{array} \right\} \tag{7}$$

where $\beta = \frac{1}{1+\rho}$ and ρ stands for the discount rate. Again, the optimization problem (7) admits a corner solution characterized by the following choice:

$$\begin{cases} l_i^n = 0 & \text{if } \mathbf{E}_{X_0}(r^n) < r^p + \beta P^{neg}(r^p - \mathbf{E}_{X_1^{neg}}(r^n)) \\ l_i^n = L_i & \text{if } \mathbf{E}_{X_0}(r^n) >= r^p + \beta P^{neg}(r^p - \mathbf{E}_{X_1^{neg}}(r^n)) \end{cases} \tag{8}$$

where $\mathbf{E}_{X_0}$ stands for mathematical expectation computed on the basis of prior beliefs. Note that (8) does not depend on the total land L_i farmed. The decision to adopt the new practice does not rely on the size of the farm as long as farmers are risk-neutral. The last term in the right hand side of (8) follows on from our assumption that the irreversibility constraint is binding when a negative message is received. If the irreversibility constraint was never binding, this term would vanish and full adoption in $t = 0$ would be decided on the basis of the sole comparison of the expected margin from the new practice in $t = 0$ and that of the proven practice. Going back to (4), we know that the additional term induced by the biding irreversibility constraint when $m = neg$ is positive. In the terminology used by Arrow and Fisher (1974) this term is the quasi option value.

In our context, the quasi option value as defined by Arrow and Fisher (1974) is the excess of expected margin compared to the proven practice required for full adoption of the new practice in the presence of a binding irreversibility constraint. It may thus be thought of as an irreversibility premium. Actually, the corner solutions (4) and (8) make the adoption problem similar to a two periods real option problem where the farmer decides to convert all her land to the new practice if and only if the expected margin associated with the new practice according to her current beliefs exceeds an optimal threshold. At the first period, the threshold is given by the right hand side of inequalities in (8). The fact that the threshold for expected margins from the new practice above which its development is decided exceeds the margin r^p of the proven (or *status quo*) practice is referred to by Arrow and Fisher (1974) and Henry (1974) as the irreversibility effect. At the second period, the optimal threshold of expected margins above which the new practice is adopted is directly given by r^p. It may be the case that the farmer decides not to develop in $t = 0$ and changes her mind in $t = 1$ if a positive message is received whereas she gives up if a negative message is received.

4 The risk-averse farmer

We now assume that farmers are risk-averse and that their aversion is correctly captured by an expected utility decision criteria where u is the von Neumann and Morgenstern utility function, increasing continuous and twice differentiable with respect to the profit level (See Neumann and Morgenstern 2007). Moreover, the flow of utility is assumed to be time additive. As in the risk-neutral case, the intertemporal problem of land allocation has to be solved backwards.

At the second period, due to the irreversibility constraint, the farmer chooses whether to further adopt the new practice and add Δl_i^n acres more of land to the l_i^n acres already devoted to the new practice at the first period or to stay with l_i^n. Substituting the land availability constraint directly in the expression of the profit flow, the problem faced by the farmer may be written as

$$\max_{\Delta l_i^n \in [0, L_i - l_i^n]} X_1^m u(r^p L_i + (r_{sup}^n - r^p)(l_i^n + \Delta l_i^n)) + (1 - X_1^m) u(r^p L_i + (r_{inf}^n - r^p)(l_i^n + \Delta l_i^n)) \tag{9}$$

It is shown in Appendix A that if the allocation choice at the first period was not irreversible (i.e. if Δl_i^n was chosen in $[-l_i^n, L_i - l_i^n]$ rather than in $[0, L_i - l_i^n]$) the optimal choice for Δl_i^n would satisfy the following first order condition

$$\frac{\mathbf{E}_{X_1^m}(r^n) - r^p}{\sigma^2_{\mathbf{X_1^m}}(r^n)} = (l_i^n + \Delta l_i^n) A_{X_1^m}(\Delta l_i^n) \tag{10}$$

with

$$A_{X_1^m}(\Delta l_i^n) = -\frac{u''(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))}{u'(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))} \tag{11}$$

the absolute index of risk aversion, and

$$\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}) = r^p L_i + (\mathbf{E}_{X_1^m}(r^n) - r^p)(l_i^n + \Delta l_i^n) \tag{12}$$

the expected profit based on posterior beliefs conditionally on the reception of a message of type m from $t = 0$ to $t = 1$. The right hand side of (10) is thus the product of the absolute index of risk aversion and the total acreage devoted to the new practice. The left hand side of (10) is similar to the Sharpe ratio except that its denominator is the variance, instead of the standard deviation, of the margin from the new practice. This variance is computed on the basis of posterior beliefs if a message of type m ($m = pos$ or $m = neg$) has been received between the first and the second period. An alternative way to write the first order condition (10) is

$$\mathbf{E}_{X_1^m}(r^n) = r^p + \mathbf{R}_{X_1^m} \tag{13}$$

with

$$\mathbf{R}_{X_1^m} = A_{X_1^m}(\Delta l_i^n)\sigma^2_{X_1^m}(r^n)(l_i^n + \Delta l_i^n) \tag{14}$$

the risk premium applied by the farmer. For risk-averse farmers $\mathbf{R}_{X_1^m}$ is positive. As long as $\mathbf{E}_{X_1^m}(r^n)$ is superior (resp. inferior) to r^p plus this risk premium, the expected utility increases (resp. decreases) with Δl_i^n. Note that for a CARA utility function (10) and equivalently (13) are linear equations to be solved with respect to Δl_i^n. Whereas for the left hand side of (13) we systematically have $\mathbf{E}_{X_1^{pos}}(r^n) > \mathbf{E}_{X_0}(r^n)$ and $\mathbf{E}_{X_1^{neg}}(r^n) < \mathbf{E}_{X_0}(r^n)$, it is unclear how the right hand side, more precisely the risk premium, evolves from $t = 0$ to $t = 1$ conditionally on the type of message received. We can distinguish three cases.

A first case with little interest occurs when the irreversibility constraint is not binding whatever the type of message received. It implies that the total land allocated at the second period systematically increases compared to that of the first period. This surface is either obtained as the solution to the first order condition (10) if this solution is lower than the total surface L_i available or set equal to this total surface if the solution to (10) is higher than L_i. As a result, the optimal profit at the second period does not depend on the land l_i^n allocated to the new practice at the first period and the inter-temporal expected profit maximization resumes to a succession of two static equilibria. More specifically, the optimal land allocated to the new practice at the first period solves the optimization program

$$\max_{l_i^n \in [0, L_i]} \mathbf{E}_{\mathbf{X_0}}(u(r^p L_i + (r^n - r^p) l_i^n)) \tag{15}$$

where the land availability constraint has been directly substituted in the expression of the profit flow. The corresponding first order condition may be written as[1]

$$\mathbf{E}_{\mathbf{X_0}}(r^n) = r^p + \mathbf{R}_{\mathbf{X_0}} \tag{16}$$

[1] We focus on the case of an interior solution. This first order condition is obtained following the same lines that the proof developed in Appendix A.

with

$$\mathbf{R}_{\mathbf{X_0}} = -\frac{u''(r^p L_i + (\mathbf{E}_{\mathbf{X_0}}(r^n) - r^p)l_i^n)}{u'(r^p L_i + (\mathbf{E}_{\mathbf{X_0}}(r^n) - r^p)l_i^n))}\sigma^{\mathbf{2}}_{\mathbf{X_0}}(r^n)l_i^n \tag{17}$$

the absolute index of risk aversion at the first period. Equation (16) just states that the farmer applies a risk premium when comparing the uncertain margin from the new practice and the margin of the proven practice. In the peculiar case of a CARA utility function, (16) is linear in l_i^n so that the optimal acreage devoted to the new practice is easily obtained. The presence of the risk premium in the right hand side of (16) implies that the expected margin from the innovation practice that triggers adoption is strictly higher than the margin from the proven practice. Hence, the farmer may still refrain from converting land to the new practice even if the expected gap of margins is positive. Indeed the decision involves uncertainty at the farmer level so that the farmer will require the expected margin from the new practice to exceed that of the proven practice plus the risk premium before converting part of her land.

The second case corresponds to a binding irreversibility constraint at the second period whatever the type of message is received. It only occurs if the farmer has a high preference for the present that makes her devote a large surface of land to the new practice in the first period at the cost of systematically considering it is too large at the second period. Although this case is theoretically possible, it is not consistent with the observation that farmers rather refrain from adopting new practices.

The third case is more interesting. It corresponds to a situation where the irreversibility constraint is binding for one type of message and is not binding for the other type. The more realistic configuration, although not necessarily the only one, is when the reception of a negative message leads to a binding irreversibility constraint. It means that the farmer regrets having allocated too much land to the new practice at the first period if a negative message is received whereas she is willing to allocate more at the second period if a positive message is received. It implies that the acreage of land allocated at the first period to the new practice impacts the expected profit at the second period so that the land allocation problem is intrinsically a dynamic problem. More precisely, the optimal profit at the second period associated with the reception of a positive message is given by

$$\tilde{\pi}_1^{pos} = r^p L_i + (r^n - r^p) Min\left\{\hat{l}_i^n, L_i\right\} \tag{18}$$

with $\hat{l}_i^n > l_i^n$ the solution to (13) for $m = pos$ that makes $\tilde{\pi}_1^{pos}$ independent of l_i^n. Conversely, the optimal profit at the second period associated with the reception of a negative message is given by

$$\tilde{\pi}_1^{neg} = r^p L_i + (r^n - r^p)l_i^n \tag{19}$$

and depends on l_i^n. The dynamic land allocation problem that the farmer is facing is then

$$\max_{l_i^n \in [0, L_i]} \left\{ \begin{array}{l} \mathbf{E}_{\mathbf{X_0}} u(r^p L_i + (r^n - r^p)l_i^n) \\ +\beta[P^{pos}\mathbf{E}_{\mathbf{X_1^{pos}}} u(\tilde{\pi}_1^{pos}) + P^{neg}\mathbf{E}_{\mathbf{X_1^{neg}}} u(\tilde{\pi}_1^{neg})] \end{array} \right. \tag{20}$$

where the land availability constraint has been directly substituted in the expression of the profit flow of the first period. It is shown in Appendix B that the first order condition associated to this program is[2]

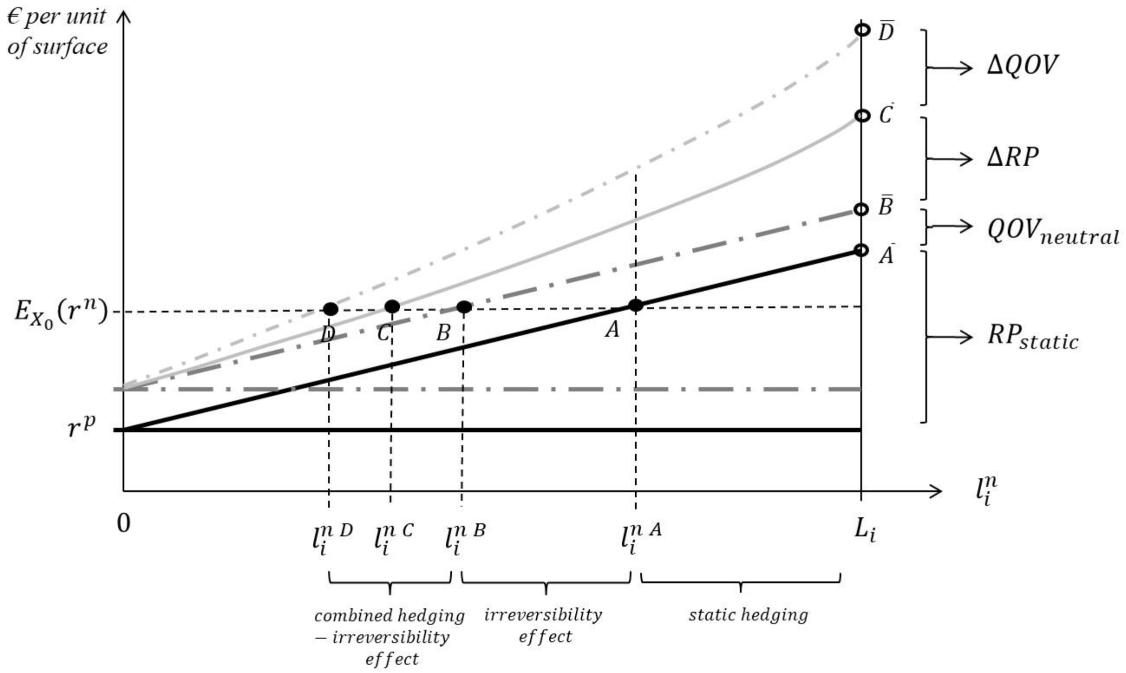
$$\mathbf{E}_{\mathbf{X_0}}(r^n) = r^p + \mathbf{R}_{\mathbf{X_0}} + \beta P^{neg} \frac{u'(r^p L_i + (\mathbf{E}_{\mathbf{X_1^{neg}}}(r^n) - r^p) l_i^n)}{u'(r^p L_i + (\mathbf{E}_{\mathbf{X_0}}(r^n) - r^p) l_i^n)} [(r^p + \mathbf{R}_{\mathbf{X_1^{neg}}}) - \mathbf{E}_{\mathbf{X_1^{neg}}}(r^n)] \tag{21}$$

with $\mathbf{R}_{\mathbf{X_0}}$ the absolute index of risk aversion at the first period, defined in (17), whereas $\mathbf{R}_{\mathbf{X_1^{neg}}}$ is the risk premium, defined in (14) at the second period when a negative message has been received. (21) may be rearranged as follows to better highlight how the irreversibility premium and the risk premium are combined in a non additive way.

$$\mathbf{E}_{\mathbf{X_0}}(r^n) = \begin{cases} r^p \\ + \underbrace{\mathbf{R}_{\mathbf{X_0}}}_{RP_{static}} \\ + \underbrace{\beta P^{neg}[(r^p - \mathbf{E}_{\mathbf{X_1^{neg}}}(r^n)]}_{QOV_{neutral}} \\ + \underbrace{\beta P^{neg} \frac{u'(r^p L_i + (\mathbf{E}_{\mathbf{X_1^{neg}}}(r^n) - r^p) l_i^n)}{u'(r^p L_i + (\mathbf{E}_{\mathbf{X_0}}(r^n) - r^p) l_i^n)} \mathbf{R}_{\mathbf{X_1^{neg}}}}_{\Delta RP} \\ + \underbrace{\beta P^{neg} (\frac{u'(r^p L_i + (\mathbf{E}_{\mathbf{X_1^{neg}}}(r^n) - r^p) l_i^n)}{u'(r^p L_i + (\mathbf{E}_{\mathbf{X_0}}(r^n) - r^p) l_i^n)} - 1)[(r^p - \mathbf{E}_{\mathbf{X_1^{neg}}}(r^n)]}_{\Delta QOV} \end{cases} \tag{22}$$

[2]We focus on the case of an interior solution for l_i^n.

Figure 1: Effects of risk aversion, irreversibility, and farmer's hedging behavior



The different components of (22) and their impact on the farmer's choice are illustrated by Figure 1 (for ease of representation, we assume the attitude towards risk is consistent with a CARA utility function). The first component is the usual risk premium RP_{static} characterising the optimal choice in a static framework with the information available at the first period. Whereas a risk-neutral farmer would either fully adopt (i.e. choose $l_i^n = L_i$) or not adopt at all (i.e. choose $l_i^n = 0$) the new practice, a risk-averse farmer optimally hedges against the risk surrounding the return on this new practice by allocating only part of her total surface to this new practice. We assume that $\mathbf{E}_{\mathbf{X_0}}(r^n)$ is higher than r^p so that full adoption would be optimal for a risk-neutral farmer in a static framework. The risk premium associated with CARA preferences is linear increasing in l_i^n. In Figure 1, it is measured by the height between the horizontal thick and dark line corresponding to r^p and the thick and dark line increasing in l_i^n. If the risk-averse farmer was stick to the total surface L_i allocated to the new practice, the trigger level of $\mathbf{E}_{\mathbf{X_0}}(r^n)$ would increase from r^p to the ordinate of point $\bar{A}$ due to the static risk premium. Nevertheless, optimal hedging in this static framework leads to allocate a surface l_i^{nA} to the new practice that equalizes the expected return $\mathbf{E}_{\mathbf{X_0}}(r^n)$ with $r^p + RP_{static}$ (point A).

The second term in (22) is the quasi option value $QOV_{neutral}$ obtained in a dynamic framework with irreversibility but no risk aversion. This quasi option value is independent of l_i^n and thus induces an upward translation of the previous lines (thick lines in dashed dark grey in Figure 1). If the farmer was stick to L_i (full adoption), accounting for this quasi option value would induce a switch to point $\bar{B}$ corresponding to exact additivity of RP_{static} and $QOV_{neutral}$. However, faced with $QOV_{neutral}$ the farmer optimally adapt by reducing the surface allocated to the new practice at the first period, from l_i^{nA} to l_i^{nB}. Such an adjustment corresponds to point B in Figure 1 and implies that the sum of RP_{static} and $QOV_{neutral}$ is equalized to $\mathbf{E}_{\mathbf{X_0}}(r^n)$. The additivity of RP_{static} and $QOV_{neutral}$ thus no longer holds because the farmer adjusts her hedging level and the resulting risk premium.

The third component in (22) is the adjustment ΔRP in the risk premium that results from the irreversibility effect. Indeed this component only appears when the irreversibility constraint is binding at the second period if a negative message is received between the two periods, which leads the farmer to take into account the discounted sum of risk premiums at the two periods to decide how much surface should be allocated to the new practice at the first period. One easily check that, because $\mathbf{E}_{\mathbf{X_1^{neg}}}(r^n) < \mathbf{E}_{\mathbf{X_0}}(r^n)$ and the utility function is increasing and convex, the ratio of the two marginal utility levels in ΔRP is greater than 1. Moreover, with a CARA utility function it is the exponential of a linear increasing function of l_i^n (and amounts to zero if $l_i^n = 0$) illustrated by the continuous curve in light grey in Figure 1 Again, if the farmer was stick to L_i, this third component would induce a switch from point $\bar{B}$ to point $\bar{C}$ and there would be overadditivity compared to the sum of the risk premium in a static framework and the quasi option value under risk-neutrality. However, the farmer is able to adapt her hedging level by decreasing the surface of land allocated to the new practice from l_i^{nB} to l_i^{nC} so that the sum of RP_{static}, $QOV_{neutral}$, and ΔRP remains equal to $\mathbf{E}_{\mathbf{X_0}}(r^n)$ and there is finally an apparent subadditivity (point C).

The fourth and last component in (22) is the adjustment ΔQOV in the quasi option value that results from risk aversion. Indeed, it is an additional term compared to the quasi option value obtained in (8) under risk-neutrality. This component is positive because, as explained when detailing the previous component, the ratio of marginal utility levels is higher than 1. Like ΔRP, with a CARA utility function ΔQOV is the exponential of a linear increasing function of l_i^n that amounts to zero if $l_i^n = 0$). It is illustrated by the dashed curve in light grey in Figure 1. Once again, if the farmer was stick to L_i, this fourth component would induce a switch from point $\bar{C}$ to point $\bar{D}$ and there would be an additional overadditivity compared to the sum of the risk premium in a static framework and the quasi option value under risk-neutrality. However, the farmer is able to further adapt her hedging level by decreasing the surface of land allocated to the new practice from l_i^{nC} to l_i^{nD} so that the sum of RP_{static}, $QOV_{neutral}$, ΔRP, and ΔQOV remains equal to $\mathbf{E}_{\mathbf{X_0}}(r^n)$ (point D in Figure 1).

We can summarize all the effects illustrated in Figure 1 by stating that, with an unchanged surface allocated to the new practice, there is overadditivity of the effects of risk aversion and irreversibility. Nevertheless, this overadditivity is more than offset by the risk hedging strategy which consists of reducing the area allocated to the new practice so as to align the total premium combining risk aversion and the irreversibility effect on the expected return on the new practice given the information available in the first period.

5 Endogenous learning process

So far, information has been treated as exogenous in the sense that farmers were benefiting from messages whatever the surface of land they were collectively devoting to the new practice. Such a context matches with the information provided by an agricultural research center but disregards all information produced by farmers themselves. This section thus turns to the case of farmers who self-produce information. It addresses the question of how to extend the model to this case of endogenous learning and the subsequent question of how to determine from this adapted model the subsidy required to internalize the inherent informational externality. A numerical illustration to the case of miscanthus in the French departement of Eure-et-Loire is also provided.

5.1 Information as a Public Good

The two key parameters influencing the learning process in the case of exogenous information examined *supra* are the probabilities θ_{sup} and θ_{inf} that capture the noise surrounding the reception of messages. A high value of θ_{sup} (resp. θ_{inf}) means that there is a low degree of noise surrounding the reception of a message when the correct scenario is the optimistic (resp. pessimistic) scenario. Going back to equations (1) and (2), one easily checks that higher values of both θ_{sup} and θ_{inf} imply a more drastic change in the subjective likelihood ratio $\frac{X_1^m}{1-X_1^m}$ ($m \in \{pos, neg\}$) in $t = 1$ between the two scenarios compared to $t = 0$, whatever the type of message received (with an upward change if a positive message is received and a downward change if a negative message is received). With endogenous learning, we assume that the degree of noise depends on the scale of experiments of the new practice which is directly related to the total surface allocated to it at period $t = 0$ over all farmers. As a consequence, each farmer contributes to the production of information through the land she allocates to the new practice, even if farmers are atomistic in the sense that they are too small to consider that the land they will allocate individually to the new practice influences the learning process. Said another way, information is a public good that is involuntarily produced by atomistic farmers. The "production" of information is assumed to satisfy the law of positive but decreasing marginal returns in the sense that the θs are increasing and concave with respect to the total land allocated by farmers to the new practice. Formally, we capture this idea by setting

$$\begin{cases} \theta_{sup}(\bar{L}^n) = 1 - e^{ln(\frac{1}{2}) - \lambda_{sup}\bar{L}^n} \\ \theta_{inf}(\bar{L}^n) = 1 - e^{ln(\frac{1}{2}) - \lambda_{inf}\bar{L}^n} \end{cases} \tag{23}$$

with

$$\bar{L}^n = \int_i l_i^n di \tag{24}$$

As farmers are assumed to be identical in our model, this last term is equivalent to $\bar{L}^n = I * l_i^n$ where I denotes the (high) number of farmers. According to (22), if no land is allocated to the new practice at period $t = 0$ then $\theta_{sup} = 1/2$ and $\theta_{inf} = 1/2$, which in turn implies according to (1) and (2) that the beliefs remain unchanged. This is consistent with the fact that there is no information if no land is allocated to the new practice. At least a small surface dedicated over all farmers to the new practice is required to experience it and learn from that experience. It also means that endogeneous learning is incompatible with risk-neutrality. Indeed it has been shown *supra* that risk-neutral farmers individually opt for a all or nothing adoption strategy. Given that all farmers are identical according to the assumption of symmetry, only two cases occur: either all risk-neutral farmers totally allocate their land to the new practice at the first period and the information produced is worthless because of the irreversibility of adoption; or all farmers do not allocate any acreage of land to the new practice at the first period so that no information is produced, beliefs remain unchanged and farmers have no new element to make them revised their decision at the second period. By contrast, in the presence of risk aversion, farmers may choose to allocate part of their land to the new practice, the exact surface involved being dependent of the amount of information anticipated and thus of the total amount of land that switches to the new practice at the first period. For I symmetric farmers, the amount of land individually allocated to the new practice is determined as a fixed point of the system formed by i) the solution in l_i^n to program (20) for given parameters θ_{sup} and θ_{inf} and ii) the value of parameters θ_{sup} and θ_{inf} resulting from the acreage l_i^n individually allocated by farmers to the new practice at the first period, as defined in (23) and (24). Prior detailing the numerical solution obtained for this fixed point in the case of miscanthus for the French department Eure-et-Loire in the next subsection, the internalization of the informational externality characterizing the case of endogenous learning deserves some discussion.

With endogenous learning, each farmer contributes to the production of information as a public good. This contribution is unintentional because farmers do not internalized the effects of this production on other farmers, besides the fact that there are atomistic and do not even consider that their decision will affect the degree of information they will collectively benefit from at the second period. The surface of land they individually decide to allocate to the new practice is thus socially suboptimal. A social planner would actually determine the individual surface l_i^n by solving

$$\max_{l_i^n \in [0, L_i]} \left\{ \begin{array}{l} \mathbf{E}_{\mathbf{X_0}} u(r^p L_i + (r^n - r^p) l_i^n) \\ +\beta [P^{pos} \mathbf{E}_{\mathbf{X_1^{pos}}(\mathbf{l_i^n})} u(\tilde{\pi}_1^{pos}) + P^{neg} \mathbf{E}_{\mathbf{X_1^{neg}}(\mathbf{l_i^n})} u(\tilde{\pi}_1^{neg})] \end{array} \right. \tag{25}$$

subject to the following constraints

$$\left\{ \begin{array}{l} P^{pos}(l_i^n) = X_0 \theta_{sup}(l_i^n) + (1 - X_0)(1 - \theta_{inf}(l_i^n)) \\ P^{neg}(l_i^n) = X_0(1 - \theta_{sup}(l_i^n)) + (1 - X_0)\theta_{inf}(l_i^n) \\ X_1^{pos}(l_i^n) = \frac{\theta_{sup}(l_i^n) X_0}{P^{pos}(l_i^n)} \\ X_1^{neg}(l_i^n) = \frac{(1-\theta_{sup}(l_i^n)) X_0}{P^{neg}(l_i^n)} \\ \theta_{sup}(l_i^n) = 1 - e^{ln(\frac{1}{2}) - \lambda_{sup} I * l_i^n} \\ \theta_{inf}(l_i^n) = 1 - e^{ln(\frac{1}{2}) - \lambda_{inf} I * l_i^n} \end{array} \right. \tag{26}$$

A subsidy to allocate more land to the practice is thus required to make individual decisions match with the collective interest of farmers. The optimal subsidy per unit of land devoted to the new practice has to be fixed in a standard way for internalizing an positive externality: consider that the total land surface dedicated to the new practice is fixed at its social optimum as defined in (25) and (26), the optimal subsidy then amounts to the sum over all farmers of the marginal increase of the expected discounted sum of profits of each farmer at the first and second periods that results from a marginal increase of unit of the land devoted to the new practice. However, due to the intricate impact of the total surface devoted to the new practice on the optimal allocation choice of a farmer, we are not able to obtain an analytical solution and thus have to rely on numerical computations to assess the amount of subsidy required.

5.2 Numerical illustration

Equation (22) and Figure 1 provide qualitative results as regards how risk aversion and the irreversibility effect have intertwined effects. One can however wonder about the importance of these effects, in particular the magnitude of the different hedging steps highlighted by Figure 1, in real cases faced by farmers. In parallel, the comparison between, on the one hand, the decentralized equilibrium where the farmers do not take into account the informational externality that they generate and, on the other hand, the social optimum which integrates this externality can only be made on concrete cases. Indeed, as was highlighted just above, there is no simple analytical solution for determining the social optimum. This is why a simulation calibrated on realistic data is proposed in what follows. It does not aim to give an exact forecast of behaviors, but rather seeks to give an idea of the order of magnitude of the various effects. The proposed simulation focuses on the case of Miscanthus, a perennial energy crop cultivable in Europe and North America. The case of Miscanthus fits particularly well with the model developed in this article. As Witzel and Finger (2016) point out in their review of economic evaluations of Miscanthus production, uncertainty about the agronomic and economic performance seems to play a critical role in the uptake of Miscanthus by farmers. It takes several years to reach a standard yield, so that there is physical irreversibility when deciding to cultivate Miscanthus. Witzel and Finger (2016) also stress that cultivation and harvest of Miscanthus can be carried out with conventional farm equipment so that, as assumed in our theoretical model, there is no sunk cost of investment to be incurred[3].

We calibrate our model with data from Bocqueho and Jacquet (2010) about Miscanthus and switchgrass adoption decisions by farmers in the French Eure-et-Loire *département* (see Table 1). These authors provide observed data about yields, output prices, subsidies and variables costs for Miscanthus, switchgrass and conventional crops, namely rape, winter barley and soft wheat. We use these data for the margins from the cultivation of Miscanthus as the innovative practice and wheat as the proven conventional crop, wheat being the most cultivated crop in the studied *département* according to the last public agricultural census (Agreste, 2010). The same authors choose a discount rate of 5% and an absolute risk aversion coefficient of $1,4.10^{-5}$. The utility function is thus assumed to be of the CARA form, $u = 1 - e^{-A\Pi}$.

We consider a population of 1000 farmers having each 100 hectares of land to allocate to Miscanthus and/or wheat. The initial value of the beliefs X_0 on the

[3]For many other examples of innovative practices, no or reduced tillage for instance, farmers have to incur a sunk cost of investment in new machinery. In that case, irreversibility is not only physical but also economic, i.e. due in part to this sunk cost of investment.

Table 1: Simulation parameters

Yields	$r^p = 198$€/ha	$r^{sup} = 500$€/ha	$r^{inf} = 130$€/ha
Learning process	$X_0 = 0.25$	$\theta_{sup} = 0.6$	$\theta_{inf} = 0.85$
Preferences	$\rho = 0.05$	$A = 1, 4.10^{-5}$€$^{-1}$	
Others	$L_i = 100ha$	$I = 1000$	

optimistic scenario has been chosen to reflect a significant reluctance of farmers to uptake Miscanthus cultivation. Indeed, one of the main results in the review conducted by Witzel and Finger (2016) is that hidden costs generate barriers to adoption and that the observed uptake is significantly less than forecasted with standard cost benefit analysis tools. In the case of exogenous information, the values of θ_{sup} and θ_{inf} are chosen so as to introduce a significant amount of noise in the messages. Table 2 synthesizes simulation results. The first column displays the value of the different components of the total premium, as introduced in equation (22), if the typical farmer was allocating all her land to Miscanthus. 85% of the total premium then corresponds to the static risk premium (233.93€/ha), whereas the quasi option value represents 12.63% (i.e. 34.39€/ha). The additional components due to the interplay between risk aversion and irreversibility thus amounts to only a small share of the total premium. The next four columns display similar results when switching to respectively points A B C and D on Figure 1. The first row reports the optimal land allocated by the representative farmer at these different points. Its decrease indicates to what extent the farmer hedges. A striking result is that, in spite of the relatively small shares of the quasi option value and interaction components of risk aversion and irreversibility in the total premium whatever the point considered, hedging increases substantially. The total surface optimally allocated to Miscanthus when switching to point A (considering static risk aversion only) to point D (corresponding to the individual optimal choice in the model) is more than halved. One third of the decrease is generated when switching from point B to C, i.e. when considering the joint effect of risk aversion and irreversibility. Our simulations thus typically highlight how relatively small hidden costs can substantially refrain from adopting an innovative practice.

The last column in Table 2 displays the socially optimal surface to be allocated by each farmer to Miscanthus cultivation when taking account of the endogeneity of information, and the values of the different components of the resulting total premium. The values of parameters λ_{sup} and λ_{inf} are set in such a way that the decentralised equilibrium where farmers do not take account of the informational externality is exactly the same than the equilibrium obtained with an exogenous arrival of information. There are obtained by plugging the values of θ_{sup} and θ_{inf} in the case of exogenous information in the left hand sides of equation (23) and then solving for λ_{sup} and λ_{inf}. Internalizing the informational externality significantly mitigate the hedging strategy of farmers and results in a surface dedicated to the innovative practice that ranges between the ones obtained in point A and point B. In this respect, we can say that the internalization of the informational externality compensates not only for the cross-effects of risk aversion and irreversibility, but also part of the irreversibility effect taken in isolation. On the one hand, the effect (compared to the case with exogenous information) on the static risk premium is limited to a proportional effect with the surface because this risk premium only depends on initial beliefs, not on the learning process. The effect on the other three components of the total premium is, on the other hand, affected by the endogenous arrival of information. The quasi option value $QOV_{neutral}$ is systematically higher compared to all the other cases considered in Table 2 but its crossed effect with risk aversion, ΔQOV, is systematically much lower. The impact on ΔRP is less significant, its value ranging between that obtained in points A and B. It is noticeable that the social optimal is reached with a low (compared with yields values reported in Table 1) subsidy of 0.0274372€/ha per unit of land allocated to the innovative practice in the first period. This low level is explained by the leverage effect exercised at the level of the whole population of farmers.

Table 2: Simulations of premiums and hedging

	No hedging	A	B	C	D	Social optimum with endogenous information
reference surface	l_{tot}	l_i^{nA}	l_i^{nB}	l_i^{nC}	l_i^{nD}	$l_i^{nsocial}$
surface value (ha)	100	68.17	40.08	27.79	27.49	46.24
$RP_{static}(€/ha)$	233.93	222.5	212.40	207.98	207.88	214.62
$QOV_{neutral}(€/ha)$	34.39	34.39	34.39	34.39	34.39	36.95
$\Delta RP(€/ha)$	6.02	3.97	2.26	1.55	1.53	2.82
$\Delta QOV(€/ha)$	3.86569	2.59	1.50	1.03	1.02	0.000026

6 Conclusion

In this paper, we address the question of adoption and diffusion of innovative practices in the agricultural sector by associating the portfolio risk management model (CAPM) to the classic option value theory with Bayesian learning, in a dynamic land allocation model. We show that, whereas risk aversion and the irreversibility effect have over-additive effects for an exogenous land allocation, they have sub-additive effects when land allocation decisions are endogenized. It results from two important factors. Firstly, land allocation, and more specifically limitation of the surface allocated to an innovative practice with uncertain and irreversible effects, plays the role of hedging against potentially negative effects of the innovative practice. Secondly, informational feedbacks inherent to the learning by doing process generate a free riding attitude that refrains farmers from being early adopters. As a consequence, the "hidden" costs associated with risk aversion combined with irreversibility may induce much lower rates of adoption and diffusion than predicted by a standard financial evaluation of the profitability of the innovative practice. This is confirmed by simulations conducted on the basis of data for the case of Myscanthus in France. "Hidden" costs that seem *prima facie* of low magnitude reveal to have a large negative impact on the surface allocated to the cultivation of Myscanthus and its dynamics.

This paper raises an important question in terms of accurate public policies. Information generated by early adopters plays a key role in the early stages of the diffusion of a new practice. Yet, this role is not internalized in farmers decisions as information is a public good. A subsidy aiming at paying the first adopters for the informational feedbacks they generate may be crucial in triggering and sustaining the adoption process. Our simulations show a significant cost-efficient potential of subsidizing information production, which must be further investigated. Indeed the amount of subsidy which is required per unit of land allocated to the innovative practice in the first period to trigger a socially optimal adoption and learning process is quite small compared to yields. Unlike environmental externalities which produce a constant flow of damages that must be limited through permanent taxation, positive informational externalities decrease over time, thus justifying one shot subsidies and then letting subsequent adoptions produce endogenous information, leading to further adoptions without subsidies.

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Appendices

Appendix A

This appendix presents the optimal choice of a farmer at the second period given that l_i^n acres of land have been allocated to the new practice at the first period but there is no irreversibility. Let first define

$$\epsilon = r^n - \mathbf{E}_{X_1^m}(r^n) \tag{27}$$

the difference between the realization of the margin of the new practice and its expected value with posterior beliefs when a message of type m is received. Let also define

$$\tilde{\pi} = r^p L_i + (r^n - r^p)(l_i^n + \Delta l_i^n) \tag{28}$$

the associated random profit at the second period.

We consider the following expected profit maximization problem:

$$\max_{\Delta l_i^n \in [-l_i^n, L_i - l_i^n]} \mathbf{E}_{X_1^m}(u(\tilde{\pi})) \tag{29}$$

The associated first order condition for an interior solution writes

$$\mathbf{E}_{X_1^m}(u'(\tilde{\pi})r^n) - \mathbf{E}_{X_1^m}(u'(\tilde{\pi}))r^p = 0 \tag{30}$$

This first order condition is transformed in two steps. In a first step, the property $\mathbf{Cov}(x,y) = \mathbf{E}(xy) - \mathbf{E}(x)\mathbf{E}(y)$ (and thus $\mathbf{E}(xy) = \mathbf{Cov}(x,y) + \mathbf{E}(x)\mathbf{E}(y)$ is applied to (30). This yields

$$\mathbf{Cov}_{\mathbf{X_1^m}}(u'(\tilde{\pi}), r^n) + \mathbf{E}_{\mathbf{X_1^m}}(\mathbf{u}'(\tilde{\pi}))(\mathbf{E}_{\mathbf{X_1^m}}(r^n) - r^p) = 0 \tag{31}$$

In a second step, it is assumed that ϵ is sufficiently small to enable the use of a linear approximation of the marginal utility in the vicinity of zero :

$$u'(\tilde{\pi}) \approx u'(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi})) + u''(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))(\tilde{\pi} - \mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi})) \tag{32}$$

It follows on that we may write

$$\mathbf{E}_{\mathbf{X_1^m}}(\mathbf{u}'(\tilde{\pi})) \approx u'(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi})) \tag{33}$$

and, combining with the properties of the covariance

$$\mathbf{Cov}_{\mathbf{X_1^m}}(u'(\tilde{\pi}), r^n) \approx u''(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))\mathbf{Cov}_{\mathbf{X_1^m}}(\tilde{\pi}, r^n) \tag{34}$$

Substituting the expression of $\tilde{\pi}$ and using the notation $\sigma^2_{\mathbf{X_1^m}}(r^n) = \mathbf{Cov}_{\mathbf{X_1^m}}(r^n, r^n)$ we can also write

$$\mathbf{Cov}_{\mathbf{X_1^m}}(u'(\tilde{\pi}), r^n) \approx u''(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))(l_i^n + \Delta l_i^n)\sigma^2_{\mathbf{X_1^m}}(r^n) \tag{35}$$

Accordingly, the first order condition (31) becomes

$$u''(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))(l_i^n + \Delta l_i^n)\sigma^{\mathbf{2}}_{\mathbf{X_1^m}}(r^n) + u'(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))(\mathbf{E}_{\mathbf{X_1^m}}(r^n) - r^p) = 0 \tag{36}$$

or equivalently

$$\mathbf{E}_{\mathbf{X_1^m}}(r^n) = r^p - \frac{u''(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))}{u'(\mathbf{E}_{\mathbf{X_1^m}}(\tilde{\pi}))}\sigma^{\mathbf{2}}_{\mathbf{X_1^m}}(r^n)(l_i^n + \Delta l_i^n) \tag{37}$$

Appendix B

This appendix presents the optimal choice of a farmer at the first period given that l_i^n acres of land can be allocated to the new practice and there is irreversibility (program 20). Irreversibility is binding only in the case of the reception of a negative message. In this case, the acreage of land allocated at the first period is such that it impacts negatively the expected profits at the second period and the farmer would regret her allocation choice.

We consider the following expected profit maximization problem:

$$\max_{l_i^n \in [0,L_i]} \mathbf{E}_{X_0}(u(\tilde{\pi})) + \beta[P^{pos}\mathbf{E}_{X_1^{pos}}(u(\pi_1^{\tilde{pos}})) + P^{neg}\mathbf{E}_{X_1^{neg}}(u(\pi_1^{\tilde{neg}}))] \tag{38}$$

The associated first order condition for an interior solution can be written

$$\mathbf{Cov}_{\mathbf{X_0}}(u'(\tilde{\pi}), r^n) + \mathbf{E}_{X_0}(u'(\tilde{\pi}))(\mathbf{E}_{\mathbf{X_0}}(r^n) - r^p) + \beta P^{neg}[\mathbf{Cov}_{\mathbf{X_1^{neg}}}(u'(\tilde{\pi}), r^n) + \mathbf{E}_{X_1^m}(u'(\tilde{\pi}))(\mathbf{E}_{\mathbf{X_1^{neg}}}(r^n) - r^p)] \tag{39}$$

The first order condition becomes

$$\begin{aligned} u''(\mathbf{E}_{\mathbf{X_0}}(\tilde{\pi}))l_i^n \sigma^{\mathbf{2}}_{\mathbf{X_0}}(r^n) + \mathbf{E}_{X_0}(u'(\tilde{\pi}))(\mathbf{E}_{\mathbf{X_0}}(r^n) - r^p) + \\ \beta P^{neg}[u''(\mathbf{E}_{\mathbf{X_1^{neg}}}(\tilde{\pi}))l_i^n \sigma^{\mathbf{2}}_{\mathbf{X_1^{neg}}}(r^n) + \mathbf{E}_{X_1^m}(u'(\tilde{\pi}))(\mathbf{E}_{\mathbf{X_1^{neg}}}(r^n) - r^p)] = 0 \end{aligned} \tag{40}$$

or equivalently

$$\mathbf{E}_{\mathbf{X_0}}(r^n) = r^p - \frac{u''(\mathbf{E}_{\mathbf{X_0}}(\tilde{\pi}))}{u'(\mathbf{E}_{\mathbf{X_0}}(\tilde{\pi}))}\sigma^{\mathbf{2}}_{\mathbf{X_0}}(r^n)l_i^n + \beta P^{neg}\frac{u'(\mathbf{E}_{\mathbf{X_1^{neg}}}(\tilde{\pi}))}{u'(\mathbf{E}_{\mathbf{X_0}}(\tilde{\pi}))}[r^p - \frac{u''(\mathbf{E}_{\mathbf{X_1^{neg}}}(\tilde{\pi}))}{u'(\mathbf{E}_{\mathbf{X_1^{neg}}}(\tilde{\pi}))}\sigma^{\mathbf{2}}_{\mathbf{X_1^{neg}}}(r^n)l_i^n - \mathbf{E}_{\mathbf{X_1^{neg}}}(r^n)] \tag{41}$$

WORKING PAPER

PREVIOUS ISSUES