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How to achieve significant reduction in pesticide use? An empirical evaluation of the impacts of pesticide taxation associated to a change in cropping practice

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Abstract

In this paper, we use an econometric approach to investigate the impacts of potential changes in cropping practices on the reduction in pesticide use implied by a taxation policy. We combine economic data, reflecting the relatively intensive cropping practices currently used in France, and experimental agronomic data on a low-input technology to estimate micro-econometric models of farmers' production and acreage choices. In a second step, these estimated models are used to conduct policy simulations. Our results show that a small tax on pesticide use could provide agricultural producers sufficient economic incentive to adopt low-input cropping practices and thereby lead to significant reductions in pesticide use, close to public short-term objectives. However, given the limited impacts of taxation once these practices have been adopted, other public instruments or further improvement of low-input cropping systems should be considered to achieve more ambitious longer term public objectives.

Keywords: econometric model, field trial data, pesticide taxation, low-input technology

JEL classifications: Q12, Q18, Q55, C54

Comment atteindre une réduction significative de l'utilisation de pesticides ? une évaluation empirique des impacts d'une taxation des pesticides associée à un changement de pratiques culturales

Résumé

Nous utilisons dans ce papier une approche économétrique pour analyser les impacts de changements éventuels de pratiques culturales sur la réduction de l'utilisation de pesticides induite par une politique de taxation. Nous combinons des données économiques, reflétant les pratiques relativement intensives actuellement utilisées en France, et des données agronomiques expérimentales sur une pratique à bas niveau d'intrants pour estimer des modèles micro-économétriques de choix de production et d'assolement d'agriculteurs. Ces modèles estimés sont utilisés dans une seconde étape pour conduire des simulations de politiques. Nos résultats montrent que qu'une faible taxe sur l'utilisation de pesticide pourrait suffisamment d'incitation économique aux producteurs pour adopter des pratiques à bas intrants et ainsi conduire à des réduction de l'utilisation de pesticides proches des objectifs politiques fixés à court terme. Toutefois, étant donné le faible impact d'une taxation une fois ces pratiques adoptées, d'autres instruments de politique publique devront être envisagés pour atteindre des objectifs de long terme plus ambitieux.

Mots-clés : modèle économétrique, données agronomiques expérimentales, taxation des pesticides, pratiques à bas intrants

Classifications JEL : Q12, Q18, Q55, C54

How to achieve significant reduction in pesticide use? An empirical evaluation of the impacts of pesticide taxation associated to a change in cropping practice

1. Introduction

Traditional intensive cropping systems involve heavy use of pesticides, plant growth regulators and chemical fertilizers to achieve high crop yields. However, the intensive use of chemical inputs, notably pesticides, is associated with numerous health and environmental risks. Increasing attention is being paid to this issue, and governments in developed countries are setting objectives to control the use of pesticides. This is the case in the European Union (European Commission, 2006), at the global level as well as at country levels. In France, for instance, one of the objectives of the *"Grenelle de l'Environnement"* is a 25% reduction in pesticides use by 2020 and a 50% reduction by 2025. There is thus a need for new policy instruments to reach these goals. In this respect, the taxation of pesticide use has often been advocated in the economic literature (Lichtenberg, 2004; Sexton *et al.*, 2007). This policy instrument actually exhibits several advantages: it is sufficiently flexible, can be progressively implemented, allowing farmers time to adjust their production decisions, does not impose any particular practice and involves fewer management costs than other instruments such as contracts (Aubertot *et al.*, 2005). However, as mentioned by Skevas *et al.* (2013) in their literature review on the design of an optimal European policy, the pesticides demand elasticity is very low (literature estimates range between -0.7 and -0.02). There is thus a risk that limited tax rates have very minor impacts on farmers' consumption of pesticides, implying that very high tax levels would be needed to achieve significant reduction. This raises the question of the political acceptance of this instrument (Falconer and Hodge, 2000). However, this assertion holds under the assumption of a constant production technology and does not account for a potential change in cropping practices induced by the taxation. Indeed, another way to lower the use of pesticides would be to provide incentives to agricultural producers to adopt new production technologies that involve less use of pesticides. Over the last few years, several agronomic studies have focused on low-input crop management systems that allow a significant reduction in pesticide and excess fertilizer use (Bouchard *et al.*, 2008; Félix *et al.*, 2002, 2003; Loyce *et al.*, 2012; Meynard *et al.*, 2009; Rolland *et al.*, 2003, 2006). To avoid the risk of diseases linked to pesticide reduction, these cropping systems are usually associated with specific cultivars, which are more resistant to diseases, and to lower seeding rates. The yields obtained with the combination of resistant cultivars and low-input crop management are slightly lower than those obtained with conventional cropping systems. However, the reduction in input expenditures induced by the adoption of such innovative systems can compensate for the yield losses and lead to gross margins comparable to those of intensive cropping systems, depending on output prices (Bouchard *et al.*, 2008; Loyce *et al.*, 2001; Loyce *et al.*, 2012; Meynard *et al.*, 2009; Rolland *et al.*, 2003). Despite this apparent attractiveness, low-input farming systems are still rarely used in Europe. A number of reasons can explain this low adoption rate, among which are the role played by seed companies (Vanloqueren and Baret, 2008), the information provided to farmers and their perceptions regarding the production risk associated with the new technology (Roussy *et al.*, 2015). These are subjective criteria that might vary between farmers (Blazy *et al.*, 2011). The present study focuses on one objective aspect related to the decision made by farmers to adopt new technologies: their economic profitability. Indeed, regardless of whether individual characteristics and subjective factors influence farmers' decisions on whether adopt a new practice, the technology will not be adopted if it is not profitable. However, the "objective" economic profitability might be questioned in the current context of relatively high crop prices, which raises the question of the need for a public intervention to incent farmers to adopt these practices.

Several studies have in fact focused on innovative technology adoption but few have attempted to analyze the impacts of public interventions on the adoption of low-input farming systems using econometric models based on agricultural producers' optimization behaviors. The results of the above-mentioned agronomic studies rely on gross margins computation based on experimental data: there is no representation of farmers' economic decisions. The lack of econometric studies dealing with the adoption of these innovative cropping practices can certainly be explained by a lack of observed economic data on these practices. Indeed, because this new technology is rarely adopted, no data are available to conduct econometric estimations. Neither is it possible to conduct ex post surveys on farmers using these practices, as has been done by, *e.g.*, Fernandez-Cornejo (1996) and Foltz and Chang (2002) for practices that were already fairly widespread. A solution to overcome the data issue is to use expert judgment to calibrate the parameters of the production function or input demand equations corresponding to the new technology, as in Mathematical Programming (MP) models. This approach was used by Jacquet *et al.* (2011) and Falconer and Hodge (2000) to study the issue of economic incentives related to the adoption of new crop management techniques. However, because MP models are generally derived from optimization problems that do not admit analytical closed form solutions, their parameters are calibrated at one point and are not estimated on a range of data as in econometric models, which does allow any statistical inference for model validation (Carpentier *et al.*, 2015). Another solution to address the lack of data issue would be to use experimental agronomic data collected from field trials to characterize the low-input production technology in econometric models. However, following the seminal work of Chambers and Just (1989), most applied econometric models used to represent farmers' production decisions are based on dual approaches using reduced form functions and implicit production technology (see, *e.g.*, Carpentier *et al.*, 2015 and Just and Pope, 2001 for a discussion on this issue). There is thus a need to rely on another type of approach, allowing for an explicit representation of the production technology, if one wants to account for the information contained in experimental data.

Our objectives in this article are first to analyze *ex ante* the effects of the adoption of a low-input practice on farmers' production decisions (input uses, acreage choices, *etc*.), and then to study the impacts of pesticide taxation on their choice to adopt the innovative practice, and on their use of pesticides given that the innovative practice is available. We focus on the case of low-input wheat cropping on which agronomic experiments have been conducted in France since 1999. To conduct our study, we rely on the econometric model originally proposed by Carpentier and Letort (2012, 2013), which was also used by Kamininski *et al.* (2013) in a study on the adaptation of agricultural technology to climate change. This multi-crop economic model, including yield supply, input demand and acreage choice equations, is particularly well suited for our purpose because it offers an explicit representation of the agricultural production technology. This model is based on a standard quadratic production function, similar to the ones considered by agricultural scientists, in which yields depend on variable inputs and mostly represent the biological crop production process. The input demands and acreage choices equations are derived from the maximization of farmers' profit, subject to constraints on acreage choices represented by a cost function that define the motives for crop diversification. The complete economic model is estimated using economic data from a French territorial division, *la Meuse*, where traditional, relatively intensive cropping practices are prevalent. In a second step, we use the agronomic data on both conventional and low-input cropping practices to statistically estimate the changes in the yield function parameters induced by the adoption of the new cultivar. This allows us to define a new economic model, corresponding to the low-input technology, and to run our simulations on the two types of cropping practices. We first simulate the impact of a change in cropping practice on famers' production decisions and wheat production outcomes and then rely on the simulated effects of pesticide taxation.

The first part of the paper is devoted to the presentation of the economic model and the results of the econometric estimations conducted on data representing the behaviors of farmers using conventional cropping practices. In the second part, we present the agronomic data and the estimated changes in the model parameters induced by a switch from conventional to low-input cropping practices. The third part is devoted to the presentation of the simulations results, followed by a conclusion.

2. Economic modeling of agricultural production decisions

In this first step, we rely on the multicrop econometric model proposed by Carpentier and Letort (2012) to represent farmers' yield and acreage decisions. This model is indeed particularly well suited to achieve the objectives of the present study because its parameters are easily interpretable in agronomic terms and allow a change in cropping practice to be implemented quite easily. This economic model is presented in the first subsection; the second subsection is devoted to the results of its econometric estimation.

1.1. The economic model

We consider K crops and a quadratic production technology, the yield $y_{k,it}$ of crop $k \in \{1, \dots, K\}$ for farmer i at period t being a function of a set of J variable input quantities $\mathrm{x}_{k,it} \equiv (x_{1k,it}, \dots, x_{Jk,it})$, such that:

$$y_{k,it} = \alpha_{k,it} - 0.5(\boldsymbol{\upbeta}_{k,it} - \mathrm{x}_{k,it})' \boldsymbol{\Gamma}_k{}^{-1} (\boldsymbol{\upbeta}_{k,it} - \mathrm{x}_{k,it}) \qquad (1)$$

The $\alpha_{k,it}$ parameter in Eq. 1 can be interpreted as the highest potential achievable yield by farmer i for crop k at time t. The $\boldsymbol{\upbeta}_{k,it} \equiv (\beta_{k1,it}, \dots, \beta_{kJ,it})$ parameters correspond to the quantities of inputs necessary to reach this potential yield. $\boldsymbol{\Gamma}_k$ is a matrix of parameters determining the curvature of the yield function and is positive definite, which guarantees the concavity of the yield function. The $\alpha_{k,it}$, $\boldsymbol{\upbeta}_{k,it}$ and $\boldsymbol{\Gamma}_k$ parameters thus characterize the production technology and will be impacted by a change in cropping practices.

Let us consider a farmer i who, at each time period, chooses yields, input use levels and acreages that maximize his expected profit Π_{it} subject to the production technology constraint; the expected profit being equal to the sum of the expected gross margins of each crop $\bar{\pi}_{k,it}$ multiplied by its acreage $s_{ki,t}$, minus the acreage management costs. We can reasonably consider that input prices are observed by the farmer at the time production decisions are taken; on the other hand, output prices are determined after harvest and are thus unknown to the farmer at that time. Farmers' decisions are thus based on observed input prices and expected output prices.

The farmer's economic optimization program is defined as:

$$\max_{\mathbf{y},\mathbf{x},\mathbf{s}>\mathbf{0}} \Pi_{it}(\mathbf{s}_{it}, \bar{\mathbf{p}}_{\mathbf{it}}, \mathbf{w}_{it}) = \sum_k s_{k,it}\bar{\pi}_{k,it}(\bar{p}_{k,it}, \mathbf{w}_{it}) - \mathrm{C}_{it}(\mathbf{s}) \quad (2)$$

$$\text{s. t. } y_{k,it} = \alpha_{k,it} - 0.5(\beta_{k,it} - \mathrm{x}_{k,it})'\boldsymbol{\Gamma}_k{}^{-1}(\beta_{k,it} - \mathrm{x}_{k,it})$$

$$\text{s. t. } \sum_k s_{k,it} = S_i$$

where $\mathbf{s}_{it}$ is a dimension *K* vector of acreages $s_{ki,t}$, $\bar{\mathbf{p}}_{\mathbf{it}}$ is a dimension *K* vector of expected selling prices $\bar{p}_{k,it}$ (we assume here that farmers' expectations are naive: the expected price is equal to the previous year's price), and $\mathbf{w}_{it}$ is a dimension *J* vector of input prices. The expected gross margins $\bar{\pi}_{k,it}$ are defined as $\bar{\pi}_{k,it} = \bar{p}_{k,it}y_{k,it} - \mathbf{w}_{it}{}'\mathrm{x}_{ki,t}$. .

Acreage management costs $\mathrm{C}_{it}(\mathbf{s})$ are introduced to account for constraints associated with acreage management and for diversification motives, implying that the farmers only partly adjust their acreage at each cropping season. These costs correspond to quasi-fixed costs associated with labor or machinery, for instance. A quadratic specification was chosen for the acreage management cost function[1]:

$$\mathrm{C}_{it}(\mathbf{s}) = 0.5(\mathbf{r}_i - \mathbf{s}_{it})'\mathbf{M}^{-1}(\mathbf{r}_i - \mathbf{s}_{it}) \quad (3)$$

$\mathbf{M}$ is a symmetric matrix and $\mathbf{r}_i$ is a dimension *K* vector composed of elements $r_{k,i}$ that sum to the total land available to farmer *i:* $\sum_k r_{k,i} = S_i$.

This function can be interpreted as a distance, measured by a metric $\mathbf{M}^{-1}$, between the acreage chosen at period *t*, $\mathbf{s}_{it}$, and an acreage $\mathbf{r}_{it}$ that would minimize management costs. Acreage management costs depend on farm characteristics, such as their capital, machinery and labor endowment. Because the innovative cropping practice on which we focus in this study requires the use of standard materials for wheat cropping and has been developed to minimize the number of farmers' interventions, we consider that the structure of the acreage management costs does not change with the adoption of the new cropping system: the parameters of this cost function will thus not be impacted by the change in cropping practice.

Solving the farmer's optimization program leads to the econometric model defined by Eq. 4 to Eq. 8[2].

$$y_{k,it} = \alpha_{k,it} - 0.5\bar{p}_{k,it}{}^{-2}\mathbf{w}_{it}{}'\boldsymbol{\Gamma}_k\mathbf{w}_{it} + u^{y}_{k,it} \quad (4)$$

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[1] This quadratic specification is the same as that proposed by Carpentier and Letort (2012). Carpentier and Letort (2014) propose an alternative entropic specification that leads to a multinomial logit model of acreage choices.

[2] The derivation of the model is presented in the Appendix

$$\mathbf{x}_{k,it} = \boldsymbol{\beta}_{k,it} - \bar{p}_{k,it}{}^{-1}\boldsymbol{\Gamma}_k \mathbf{w}_{it} + u^{x}_{k,it} \tag{5}$$

$$\bar{\pi}_{k,it} = \bar{p}_{k,it}\alpha_{k,it} - \mathbf{w}_{it}{}'\boldsymbol{\beta}_{k,it} + 0.5\bar{p}_{k,it}{}^{-2}\mathbf{w}_{it}{}'\boldsymbol{\Gamma}_k \mathbf{w}_{it} \tag{6}$$

$$s_{k,it} = g_{k,i} + S_i\rho_k + S_i \sum\nolimits_{l=1,\dots,K-1} \delta_{kl}\left(\bar{\pi}_{l,it} - \bar{\pi}_{K,it}\right) + u^{s}_{k,it}, \forall k \in \{1,\dots,K-1\} \tag{7}$$

$$s_{K,it} = S_i - \sum\nolimits_{k=1}^{K-1} s_{k,it} \tag{8}$$

The $g_{k,i}$ and δ_{kl} parameters are functions of the elements of $\mathbf{r}_i$ and $\mathbf{M}$, respectively, and thus depend on the cost structure of the farm; they represent the flexibility of the acreage adjustments. Crop K is a crop chosen as the "reference crop" to account for the land use constraint and its implied constraints on parameters[3]. $u^{y}_{k,t}, u^{x}_{k,t}$ and $u^{s}_{k,t}$ are random terms accounting for unobservable heterogeneity among farmers and stochastic events that can impact production once the decisions are taken. This economic model allows a full representation of farmers' production decisions based on market conditions, which is not the case in agronomic studies (*e.g.*, Loyce *et al.*, 2012). Based on Eq. 4 to Eq. 7, we notice that yields, input demands and acreage choices essentially depend on netput prices.

1.2. Data and estimation strategy

Inputs for the econometric model presented above were based on a sample of farms located in the French territorial division, *La Meuse,* for which acreages, yields, output prices and input quantities have been observed from 2007 to 2012. This dataset is based on analytical accounting data and includes a detailed decomposition of input uses per crop, which makes it particularly well suited for our estimation purpose. The three main crops in the region, which represent more than 50% of total acreage, are considered: wheat (24% of total acreage), barley (13% of total acreage) and rapeseed (17% of total acreage); the latter was chosen as the reference crop in the estimation process. To avoid corner solutions in the model, we focus on farmers producing these three crops simultaneously, resulting in a total of 1089 observations. We focus on two inputs: pesticides and fertilizers. In the agronomic experimental data, on which the impact of a change in cropping practice was subsequently estimated, the fertilizer use is represented by nitrogen quantities. Consequently, because this information is available in our economic dataset, we also use nitrogen as a proxy for fertilizer use in the econometric estimation. The input price indexes were provided by the French Department of Agriculture. The descriptive statistics of the data are provided in Table 1 below.

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[3] See the Appendix for more detail.

Table 1: Descriptive statistics of the economic data

	Wheat		Barley		Rapeseed	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
Acreage (ha)	51.24	27.58	27.02	15.80	35.55	22.19
Yield (q/ha)	70.95	10.45	64.34	11.08	33.61	6.59
Output price (€/ton)	159.04	34.10	142.63	34.97	332.14	54.45
Fertilizer use (€/ha)	123.09	28.14	106.96	24.98	122.32	29.87
Pesticide use ((€/ha)	160.64	44.18	153.18	45.45	221.60	52.18
Fertilizer price index	1.17	0.21	1.17	0.21	1.17	0.21
Pesticide price index	0.98	0.03	0.98	0.03	0.98	0.03

Despite the fact that we work with a relatively small region, several heterogeneous factors, such as climate and soil or capital endowment, are likely to have an impact on farmers' production decisions. To control for this potential heterogeneity in farmers' behaviors, different linear combinations of exogenous variables are introduced in the constant terms of the model. Climatic and soil variables are selected[4] to be introduced in the constant terms of the yield supply (Eq. 4) and input demand equations (Eq. 5), and a linear combination of the farm characteristics is introduced in the acreage equation (Eq. 7). The $\alpha_{k,it}$ and $\beta_{k,it}$ parameters, which represent the respective potential crop yields and input levels needed to achieve these yields, thus decompose into two parts: a constant term common to all farms and a term depending on climatic conditions (which vary across farms and time) and soil conditions (which vary across farms). The climatic data were provided by *Météo France*, the French national meteorological service. The soil condition index was obtained from the *Chambre d'Agriculture de Lorraine* (Hance, 2007). In Eq. 7, the $g_{k,it}$ term decomposes into a constant term and a linear combination of the effects of farms'

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[4] Climatic variables include monthly average rainfall, temperature, solar radiation and number of frost days at the municipality level and have been selected so as to obtain significant parameter estimates. In the yield equation, we focused on variables corresponding to the growing seasons of the crops, from February to July. In the input demand equations, we focused on the periods where most input applications take place*, i.e.* the regrowth of vegetation, from April to June.

labor endowment and fodder acreage, which was introduced to control for the impact of livestock production[5] on acreage choices.

The model was estimated using an iterative Seemingly Unrelated Regression (SUR) method implemented in SAS software.

1.3. Estimation results

The main parameter estimates are reported in Table 2. Due to space limitation, the estimates of the coefficients associated with the control variables are not reported here but are available from the authors upon request. Almost all parameters of the production and acreage management cost functions are significantly estimated and lie in their expected ranges, with respect to the empirical distributions of yields and input uses (provided in Table 1). It should be noticed that the average potential yield values ($\alpha_{k,it}$), expressed in quintals per hectare, correspond to the average values observed in the region. The estimated values of $\beta_{kP,it}$ reflect the fact that cropping rapeseed requires greater use of pesticide compared with wheat and barley. The estimated parameters also guarantee the concavity of the production function ($\mathbf{\Gamma}$ is positive definite) and the convexity of the cost function ($\delta_{kk} > 0$ for $k \in \{1, \dots K-1\}$ and the matrix of δ_{kl} for $k, l \in \{1, \dots K-1\}$ is positive definite). The R² criteria are, however, rather low for the yields and input demands equations. This issue has already been raised by Carpentier and Letort (2012) and is probably largely due to sources of heterogeneity among famers that are not observed in economic or climatic and soil data. The recent work conducted by Koutchade *et al.* (2015) proposed relying on a random parameter approach using statistical methods to overcome this issue but this is out of the scope of the present study.

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[5] Our data show that fodder acreage includes 81% permanent grassland and 19% corn; this corn is used for on-farm livestock feeding and not for market sales. This explains why fodder is not considered here as competing with cash crops (wheat, barley and rapeseed) in farmer's acreage decisions but as a proxy for livestock production.

Table 2: Parameter estimates of the economic model – conventional cropping practices

	Wheat	Barley	Rapeseed
Yield supply			
Average potential yield $\alpha_{k,it}$	71.37	64.86	33.84
	(0.35)	(0.42)	(0.25)
Curvature parameters $\boldsymbol{\Gamma}$			
γ_{FF}	746.03	669.09	586.38
	(65.46)	(105.30)	(123.90)
γ_{PP}	679.05	562.40	844.74
	(100.30)	(176.00)	(164.00)
γ_{PF}	-642.11	-558.79	-523.18
	(64.58)	(127.30)	(164.00)
R^2	*0.26*	*0.21*	*0.23*
Fertilizer demand			
Average required use $\beta_{kF,it}$	137.53	123.19	127.42
	(2.74)	(2.46)	(3.55)
R^2	*0.53*	*0.38*	*0.47*
Pesticide demand			
Average required use $\beta_{kP,it}$	156.28	146.59	228.42
	(6.19)	(7.04)	(10.63)
R^2	*0.05*	*0.02*	*0.04*
Acreage shares			
$g_{k,i}$	1.45	1.61	-
	(0.96)	(0.90)	
ρ_k	0.43	0.23	-
	(0.01)	(0.01)	
δ_{kk}	0.005	0.003	-
	(0.002)	(0.001)	
δ_{kl}	-0.001	-0.001	-
	(0.001)	(0.001)	
R^2	*0.86*	*0.63*	-

Standard deviations are in parentheses

3. Estimation of the low-input production function

In the previous section, we estimated an economic model representing the production decisions of farmers using conventional cropping practices. Our objective here is to estimate another model representing the new behaviors that would arise if low-input practices were adopted by farmers for wheat cropping. Because no observed economic data are available for these practices, this new model cannot be estimated directly. Experimental agronomic data are thus used to estimate the changes in production technology, hence in the model parameters, induced by a change in cropping practices. These estimates allow the re-parameterization of the economic model to represent production decisions of farmers using low-input practices.

0.1. Description of the experimental agronomic data

The experimental agronomic data used in this section were collected from 2007 to 2012 by a French trial network. The main objective of this network was to compare the performance of wheat cultivars for different cropping practices ranging from a highly intensive system to an extensive system involving important reductions in input uses. The database thus contains information on pesticides, fertilizer (nitrogen) uses and wheat yields associated with different practices and cultivars. We focus here on two practices: the first is intended to replicate the conventional practices used in France; the second is a low-input practice that involves less use of pesticides and fertilizers. To avoid the development of diseases resulting from the reduction in pesticides, the low-input practice is associated with less productive but more resistant wheat cultivars, lower seeding rates, and late planting. Finally, as opposed to the conventional practice, no plant growth regulators are used in the low-input practice (this is made possible by the reduction in fertilizer use).

The initial database included 5289 observations collected from 191 trials[6]. For each trial, between 4 and 90 combinations of cropping practices and wheat cultivars were tested. We selected the trials for which both the conventional and low-input practices were tested and combined for at least three types of wheat cultivars to avoid potential biases due to tests implemented on one particular and highly experimental cultivar only. For certain reasons, almost no differences in input uses between the conventional and low-input practices were reported for some of the trials. This seems to be related to unusually low-input uses reported for the conventional practice. These trials were removed from the data. The final database contains 759 observations collected from 35 trials.

As previously mentioned, the data on which the economic model was estimated were collected in one particular French region, *La Meuse*. This is not the case for the agronomic data because the trials took place in different locations in France, none of which were located in *La Meuse*. We

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[6] One trial includes data collected for different practices and wheat cultivars in one location and one year.

assume here that the cropping practice qualified as "conventional" in the agronomic dataset actually corresponds to farmers' behaviours as they were estimated based on the economic dataset. This assumption is supported by the comparison of input use levels in the two datasets. Indeed, as reported in Table 3 below, the average levels of pesticide and fertilizer uses in the economic data are very close to those corresponding to the conventional cropping practice in the agronomic data. In fact, Student's t-tests performed on the data did not lead to a rejection of the assumption of an equality of average input uses between the conventional practice agronomic data and the *Meuse* data, whereas the assumption was rejected when comparing the conventional and low-input practice agronomic data. On the other hand, wheat yields appear to be significantly lower in the economic data than in the agronomic data for both practices. This might be because the *Meuse* region does not benefit from the good cropping conditions such as those in other French regions where agronomic trials have been conducted, *e.g.*, in the Paris basin. Furthermore, soil heterogeneity, which increases with land area, can result in farmers cultivating less productive plots of land, which may not have been taken into account in the experimental trials.

However, this heterogeneity in natural endowment has, at least partly, been controlled for in the estimation of the economic model, and will be controlled for in the subsequent estimation conducted using the agronomic data, through the introduction of climatic variables.

Table 3: Input use and yield levels of the two datasets – Summary statistics

		Pesticide uses		Fertilizer uses		Yields	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
Economic data (*La Meuse*)		160.64	44.18	123.10	28.14	70.95	10.45
Agronomic data	Conventional practice	159.70	60.82	120.00	37.15	91.82	16.05
	Low-input practice	78.84	33.69	94.40	30.14	80.79	16.04

Another interesting feature that appears in Table 3 concerns the variability of the wheat yields observed in the agronomic data: the yield standard deviations for the low-input practice are very close to those of the conventional practice. In fact, the equality of the yield variances of the two subsets was not rejected by Student's t-test. In other words, moving from the conventional to the low-input practice does not appear to increase the variability of the yields. This is not surprising from an agronomic point of view because potential yield losses resulting from a reduction in pesticide use are mitigated by the use of multi-resistant varieties and an improvement in lodging and disease management, which are systematically associated with low-input practices (Meynard and Savini, 2003). The low-input practice thus does not appear to be more risky in terms of yield losses. Therefore, even if we acknowledge the absence of risk aversion as a potential limitation of our economic model, yield risk considerations might in fact not intervene in the choice of farmers of whether or not to adopt the low-input technology.

0.2. Estimation results

To estimate the impacts of a change in cropping practice on the parameters representing the production technology in our economic model ($\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ and $\boldsymbol{\Gamma}$), we consider a quadratic production technology, similar to the one used to derive the economic model (Eq. 1), and introduce a "cropping practice effect" for each of its parameters. We use *p* to denote the cropping practice implemented: $p \in \{0,1\}$; 0 and 1 correspond to the conventional and low-input practices, respectively. The yield of wheat for practice *p*, in location *l* at period *t* is thus equal to

$$y_{p,lt} = \alpha_{p,lt} - 0.5\left(\boldsymbol{\beta}_p - \mathbf{x}_{p,lt}\right)' \boldsymbol{\Gamma}_p{}^{-1}\left(\boldsymbol{\beta}_p - \mathbf{x}_{p,lt}\right) \tag{9}$$

with

$$\alpha_{1,lt} = (1 + \lambda_\alpha)\alpha_{0,lt} \tag{10}$$

$$\beta_{j1} = \left(1 + \lambda_{\beta j}\right)\beta_{j0} \tag{11}$$

$$\Gamma_{jj'1} = \left(1 + \lambda_{\Gamma jj'}\right)\Gamma_{jj'0} \tag{12}$$

The λ_α, $\lambda_{\beta j}$ and $\lambda_{\Gamma jj}$ parameters are thus the parameters of interest here: they will be used to re-parameterize the economic model to represent the low-input technology.

In the economic model estimation, a linear combination of climatic variables is introduced in the constant term of the model to control for the impact of climate on yields[7]. The model is estimated using an iterative Ordinary Least Square (OLS) regression implemented in SAS software.

The estimation results are presented in Table 4. We first notice that all of the model parameters are significantly estimated and the model fits the data relatively well because it explains 73% of the yield variability as shown by the R^2 criterion. The fitting criterion is thus higher than that obtained for the economic model. This certainly relates to the fact that here, the heterogeneous aspects of the farmers' behavior do not intervene: the main source of heterogeneity is geographic and we control for a large part of it using climatic variables.

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[7] The soil condition index used in the economic model estimation is available for the *Meuse* region only; consequently, we were not able to use it here. However, we can expect a strong correlation between soil and climate in France at the national level. Climatic variables should thus be able to control for a large part of the heterogeneity in cropping conditions between different locations in France. The good fitting criteria of the model are an additional argument in this respect.

Table 4: Parameter estimates of the production function – conventional and low-input practices

	Conventional practice	Variation induced by the change in practice (%)
Average potential yield $\alpha_{k,it}$	100.90	-0.12
	(50.20)	(0.01)
Required fertilizer use $\beta_{kF,it}$	140.25	-0.30
	(15.61)	(0.09)
Required pesticide use $\beta_{kP,it}$	231.76	-0.50
	(28.45)	(0.08)
Curvature parameters $\mathbf{\Gamma}$		
γ_{FF}	252.28	-0.31
	(53.94)	(0.14)
γ_{PP}	598.07	-0.69
	(182.00)	(0.07)
γ_{PF}	185.06	-0.87
	(93.28)	(0.18)
R^2	*0.73*	

Standard deviations are in parentheses

The relevant information pertains to the variations in the model parameters induced by the switch in cropping practice. All of these variations are significantly estimated and, as could be expected, the potential wheat yield (α) decreases by 12% and the quantities of fertilizers and pesticides needed to achieve this yield (β) decrease by 30% and 50%, respectively, when the low-input practice is used in place of the conventional intensive practice. These results are in accordance with those of previous studies relying on field trial data and expert judgment (Jacquet *et al.*, 2011). The estimated changes in the parameters were applied to the coefficient of the economic model previously estimated using data corresponding to conventional practices (Table 2) to obtain a new economic model corresponding to the low-input cropping practice.

4. Simulation results

4.1 Impacts of the adoption of the low-input cropping practice

Two economic models representing farmers' behaviors were estimated in the previous sections; the first model corresponded to the use of conventional practices, and the second to the use of low-input practices. These two models are now used to simulate the impacts of a change in cropping practice on farmers' production decisions. The simulations are conducted on our sample of farms. These data cover a period where several factors – *e.g.,* agricultural policy reforms, the emergence of biofuels and the economic development of emerging countries – have had strong impacts on crop prices, leading notably to huge price increases in 2008 followed by sharp decreases in 2009, with the global trend being an upward shift in prices. For this reason, we do not rely on average prices observed during this specific period to conduct our simulations; instead, we use average levels observed over the past five years in France because crop prices are less volatile during this period. The output prices are thus set to 171€/ton for wheat (instead of 160€/ton on average in our sample), 148€/ton for barley (instead of 142€/ton on average in our sample) and 357€/ton for rapeseed (instead of 332€/ton on average in our sample).

The simulated impacts, based on wheat production decisions induced by a change in cropping practices for all farms in our sample, are reported in Table 5. The figures reported in this table correspond to the average values computed over the full sample. The adoption of low-input technology by all farmers would lead to an average decrease in wheat yields of 14.1%, and to decreases of 46.7% and 55.8% in fertilizer and pesticide use, respectively, at the intensive margin. This is in accordance with the conclusion of the agronomic studies: the use of the low-input technology allows a significant reduction in input use for a moderate yield decrease.

The first thing to note here is that the decreases in input expenditures are not sufficient to compensate for the loss of income induced by the yield decrease: the wheat gross margin decreases by 0.8% on average, which implies that in the absence of other economic incentives, the low-input technology would not be adopted by the farmers in our sample. A lack of economic incentive could thus in itself explain the non-adoption of low-input practices today, independent of other factors advocated in the economic literature, such as a lack of information provided to farmers, and their perceptions and attitudes toward risk (Falconer and Hodge, 2000; Jacquet *et al.*, 2011).

Table 5: Impacts of a change from conventional to low-input practice in the wheat sector (sample averages)

	Conventional Practice	Low-input practice	Variation (in %)
Yield (ton/ha)	7.1	6.1	-13.5
Fertilizer expenditures (€/ha)	123.4	66.1	-46.7
Pesticide expenditures (€/ha)	161.3	71.2	-55.8
Gross margin (€/ha)	962.4	952.8	-0.8
Production (tons)	366.0	316.0	-13.7
Acreage (ha)	51.4	51.3	-0.1

We can also notice that the decrease in wheat production is slightly higher than the yield decrease (13.7% compared with 13.5%) because part of the land devoted to wheat cropping with conventional practice (approximately 0.1 ha) is reallocated to other crops. This change in acreage is due to the decrease in wheat profitably compared with other crops and implies that barley and rapeseed production decisions will also be impacted by the adoption of low-input technology for wheat. Some impacts on input uses are thus to be expected at the extensive margin as well. They are presented in Table 6, which reports annual averages of the total effects of a change in wheat cropping practice on global crop production.

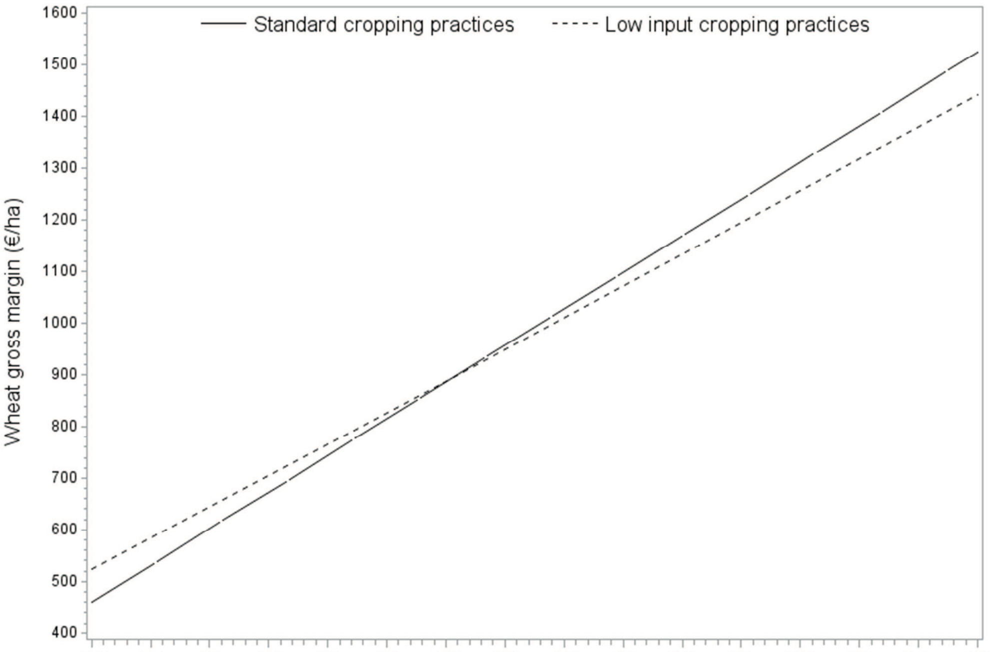
Table 6: Impacts of a change from conventional to low-input practice on crop production (annual averages)

	Conventional Practice	Low-input practice	Variation (in %)
Wheat acreage (ha)	7,997	7,988	-0.1
Barley acreage (ha)	4,184	4,187	+0.1
Rapeseed acreage (ha)	5,524	5,529	+0.1
Wheat production (tons)	56,933	49,168	-13.7
Barley production (tons)	27,022	27,040	+0.1
Rapeseed production (tons)	18,346	18,365	+0.1
Total fertilizer expenditures (€)	2,125,905	1,666,274	-21.9
Total pesticide expenditures (€)	3,161,497	2,439,021	-22.9

Following the 0.8% decrease in the wheat gross margin, 0.1% of the wheat acreage is reallocated to the other crops, primarily to rapeseed, which requires more pesticide use than wheat and barley. However, the share of land involved in these reallocations is quite limited, which is not surprising given the limited impact on the wheat gross margin, and the total pesticide expenditures eventually decrease by 22.9%.

The adoption of the low-input practice for wheat cropping could thus lead to a significant decrease in pesticide use. However, the main conclusion remains, *i.e.*, in the current context of relatively high crop prices – notably wheat – this new technology is not profitable for farmers and will thus not be adopted. To study the effect of the wheat price on farmers' economic incentives to adopt the low-input technology, we report the evolution of the wheat gross margins (Figure 1), with respect to price, for the two cropping practices: the conventional practice is shown using a dashed line and the low-input practice is shown using a dotted line.

Figure 1: Evolution of the wheat gross margin with respect to the price of wheat – sample average



The average gross margins equalize at 161€/ton of wheat, which is in the range of the results found in previous studies on the economic profitability of low-input practices that have been conducted by agronomists (Bouchard *et al.*, 2008). This price level would actually lead to 43% of the farmers in our sample adopting the low-input practice. Indeed, if input prices remain unchanged, lower wheat prices would translate into a higher profitability of the low-input cropping practice compared with the conventional practice and thus encourage farmers to adopt the new technology. Here, a 6% decrease in the wheat price compared with the recently observed averages would thus be sufficient to favor the adoption of the new technology. However, given the past upward trend in crop prices, there is no guarantee that any decrease will arise in the near future. A public intervention thus seems necessary to provide farmers sufficient economic incentives to adopt low-input practices. In the next part, we focus on one specific instrument: the taxation of pesticides, and study its impacts on the adoption of the low-input farming practices and on the use of inputs.

4.2. Impacts of a pesticide taxation

Pesticide taxation has often been advocated in the economic literature as one of the most cost effective policy instruments to reduce the use of pesticide (Aubertot *et al.*, 2005). One can also expect here that following the increase in pesticide price induced by the taxation, the low-input practice will become more profitable compared with the conventional practice, and that some farmers will adopt this new technology. In this case, the taxation could lead to a greater decrease in pesticide use than if only the conventional practice was available to farmers.

To study this issue, we simulate the impacts of pesticide taxation on the decisions of farmers to adopt low-input cropping practices and on their use of pesticide given that this new technology is available. This last subsection decomposes into four parts: after a brief presentation of the simulated taxation policy, we study the potential impacts of different taxation rates combined with the adoption of low-input practices on the levels of pesticide use, and we then focus on one particular taxation rate to study the impacts of the policy on all farmers' production decisions. Finally, our results are placed in the current context of crop price uncertainty.

The simulated taxation policy

We focus here on the impacts of an *ad valorem* tax on pesticide expenditure. Most studies dealing with pesticide policy argue for the establishment of differentiated taxes based on the toxicity of the products because this allows more reduction in harmful pesticides and is thus more effective from an environmental point of view (Hoevenagel *et al.*, 1999; Oskam *et al.*, 1998; Skevas *et al.*, 2012). This type of policy has already been implemented in some European countries such as Denmark and Norway (Bragadóttir *et al.*, 2014) and is currently under discussion in France. We thus acknowledge that considering an *ad valorem* tax is a potential limitation of our work. We could in fact expect a more significant reduction in (harmful) pesticide use to be achieved with this type of instrument, both with standard and low-input practices, with the difference in impacts between the two practices depending on the difference in the types of pesticides used. Unfortunately, the information required to simulate these impacts, such as differentiated pesticide expenditures and toxicity indexes, is not available in our dataset.

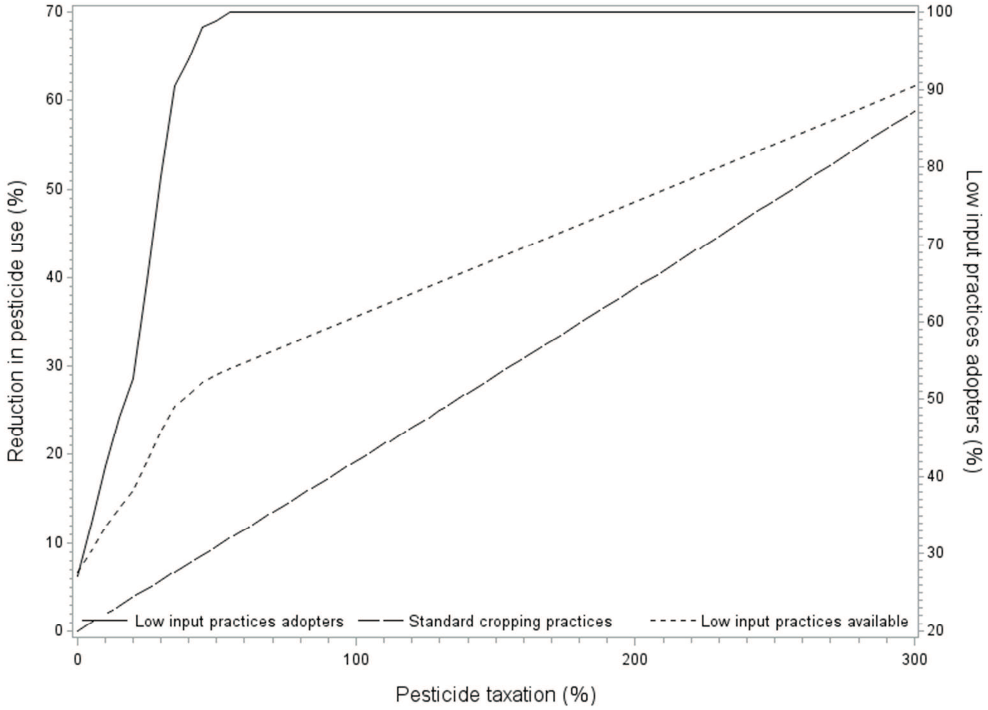
Furthermore, taxing pesticide use implies that farmers bear most of the costs of the pesticide reduction policy, which is in accordance with the polluter-pays principle. However, governments may wish to compensate them for these losses, and the best way to compensate farmers without cancelling the incentive effects of the tax is to pay them a direct compensation (Carpentier, 2010; Jacquet *et al.*, 2011). Here, we consider that the revenue raised from the tax is uniformly redistributed to the farmers in the form of a payment per hectare.

Impacts of the taxation on pesticide use

A first set of simulations was run to determine the reduction in pesticide use induced by different taxation rates. The outcomes of these simulations are represented in Figure 2, which indicates decreases in pesticide use (left hand axis) with respect to the taxation rates for two scenarios: a first scenario in which all farmers in our sample continue using conventional cropping practices and a scenario in which the low-input cropping practice is available and is adopted by the farmers for whom it becomes more profitable. The adoption rates of the low-input practice in the second scenario are also reported on this graph (right hand axis). It appears that when the new technology is available, a 35% taxation rate provides farmers sufficient economic incentive to achieve the 25% reduction in pesticide use targeted by the French *Grenelle de l'Environnement*. In this case, 90% of the farmers adopt the low-input cropping practice. By contrast, the same reduction would not possible without a change in cropping practices unless a 130% tax is implemented, which is less acceptable from a political point of view.

It also apparent in Figure 2 that a 50% decrease in pesticide use by 2025, which is the second objective of the *Grenelle de l'Environnement*, would not be achievable unless an extremely high tax rate (at least 200%) was implemented, regardless of whether or not the low-input practice is available. The higher the tax, the lower the differences in pesticide reduction between the two practices. This result implies that if a moderate pesticide taxation seems to be a good policy instrument to achieve a significant reduction in pesticide use in the presence of low-input cropping practices, the picture is different for higher targeted reduction: the possible adoption of low-input technologies has almost no impact on the effects of taxation with respect to achieving more than 40% decreases in pesticide use. This last result is illustrated by the slopes of the two curves representing the pesticide reduction in Figure 2 (the curve corresponding to the conventional practice is steeper), and is actually related to a decrease in the price elasticity of the pesticide demand induced by the adoption of the low-input technology.

Figure 2: Impacts of pesticide taxation on pesticide use and the adoption of low-input practices



The own- and cross-price elasticity estimates of the input demands derived from our economic models are reported in Table 7. We can first notice that the elasticity estimates are in accordance with the values commonly found in the literature, with the own-price elasticities of pesticide demand ranging from -0.10 for rapeseed to -0.24 for wheat under conventional cropping practice (Skevas et al., 2013 reported estimates ranging from -0.02 to -0.7 in their literature review). We also can notice from Table 7 that switching from the conventional to the low-input technology leads to a decrease (in absolute terms) in the pesticide demand elasticity, from -0.24 to -0.16. The use of pesticides is thus less sensitive to price changes under low-input cropping practices. This reflects the fact that when the low-input technology is adopted, pesticide uses are limited to minimum needed levels of fungicides, herbicides and insecticides (Roland et al., 2003). Farmers can thus less easily adjust their consumption when prices increase. Regarding the impacts of pesticide taxation, this lower elasticity implies that all else being equal, a tax has smaller impacts on pesticide use under low-input compared with conventional practice. A change in cropping practice following the establishment of a tax on pesticide use thus has ambiguous effects: on the one hand, one can expect the tax to lead to a significant number of farmers adopting the low-input practices, leading to a decrease in pesticide use; on the other hand, the tax will have less impact on pesticide use once the new technology is adopted.

Table 7: Estimated elasticities of input uses with respect to input prices (sample averages)

	Elasticities of pesticide use with respect to the price of		Elasticities of fertilizer use with respect to the price of	
	Pesticide	Fertilizer	Pesticide	Fertilizer
Wheat – Conventional practice	-0.24	0.27	0.30	-0.42
Wheat – Low-input practice	-0.16	0.08	0.07	-0.47
Barley	-0.24	0.29	0.35	-0.50
Rapeseed	-0.10	0.08	0.12	-0.16

Impacts of a 35% pesticide taxation on farmers' production decisions

We now further explore the impacts of a pesticide taxation combined with the adoption of low-input practices on all farmers' decisions related to crop production. We focus our discussion on the 35% taxation rate that can be considered as politically acceptable and which allows, when the new technology is available, achievement of the 25% reduction in pesticide use targeted by the French government for crop prices comparable to recently observed levels. The simulated impacts of this tax on farmers' production decisions are reported in Tables 8a and 8b. As shown in the first column of Table 8a, following the implementation of the tax and the adoption of the low-input technology by a large share of farmers, the wheat yield decreases by 13%, and the quantities of fertilizers and pesticides used per hectare of wheat decrease by 40% and 54%, respectively. These impacts on input uses are driven by two elements: first, the adoption of the low-input practice results in decreases in both fertilizer and pesticide uses; second, the taxation of pesticides induces a decrease in pesticide use and a slight increase in fertilizer use. Indeed, as shown by the input price elasticities in Table 7, pesticides and fertilizers appear to be substitute in our data. The increase in fertilizer use induced by the taxation policy could be considered as a negative side-effect of the policy; it is, however, more limited when the low-input technology is adopted – the elasticity of fertilizer demand with respect to pesticide price is equal to 0.07 compared with 0.30 for the conventional practice.

The results reported in the second column of Table 8a confirm this point. They correspond to the impacts of the tax simulated without considering the possibility of farmers changing their cropping practices, *i.e.*, with the conventional technology available only. In this case, the establishment of pesticide taxation results in an increase in fertilizer expenditure and a moderate decrease in pesticide use compared with the case where producers switch to the new technology. This increase in fertilizer use almost compensates for the decrease in pesticide use, resulting in a small decrease in wheat yield. Before the tax redistribution, the wheat gross margin decreases by 3.36% on average when the low-input practice is available compared with 5.59% when all farmers continue using the conventional practice. These decreases can essentially be attributed to the yield decrease in the "low-input practice case" and to the increase in fertilizer expenditures in the "conventional practice" case. However, in both cases, these decreases are almost compensated for by the uniform redistribution of the tax.

Table 8a: Simulated impacts of a 35% tax on pesticides – Average impacts at the intensive margin in the wheat sector (% age change compared with the initial situation)

	Low-input practice not available (conventional practice only)	Low-input practice available
Yield	-0.04	-12.54
Fertilizer expenditures	+10.59	-39.90
Pesticide expenditures	-8.48	-53.86
Gross margin before tax redistribution	-5.59	-3.26
Gross margin after tax redistribution	-0.24	-0.60

Turning now to the impacts at the extensive margin for the three crops reported in Table 8b, we observe that following the taxation, part of the land is reallocated from rapeseed to wheat and barley cropping. This is due to greater decreases in the gross margins of rapeseed, which is the most pesticide-demanding crop. Gross margin variations and thus land reallocation are, however, limited by the tax redistribution[8]. Because the decrease in the wheat gross margin is even smaller when the low-input practice is available, the land reallocation is more important with the new technology. The impacts of the taxation on barley and rapeseed productions are actually comparable to those obtained for wheat without a change in the cropping practice: the policy induces decreases in pesticide use and increases in fertilizer use, implying small yield increases for

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[8] Simulations were also conducted without the tax redistribution, and effectively show more land reallocation: +0.48% for wheat, +0.16% for barley and -0.83% for rapeseed. However, because the main impacts of the taxation arise at the intensive margins, the outcomes in terms of crop production and input uses were not significantly different. The results of these simulations are available upon request.

the two crops. The reallocation of land to wheat cropping is not sufficient to compensate for the yield decrease induced by the adoption of the low-input practice, and wheat production significantly decreases in that case whereas it slightly increases with the conventional practice. Overall, pesticide expenditures decrease by 25% when farmers adopt the low-input practice, compared with 7% when only the conventional practice is available.

Table 8b: Simulated impacts of a 35% tax on pesticides – Impacts at the extensive margin in the three crop sectors (% age change compared with the initial situation)

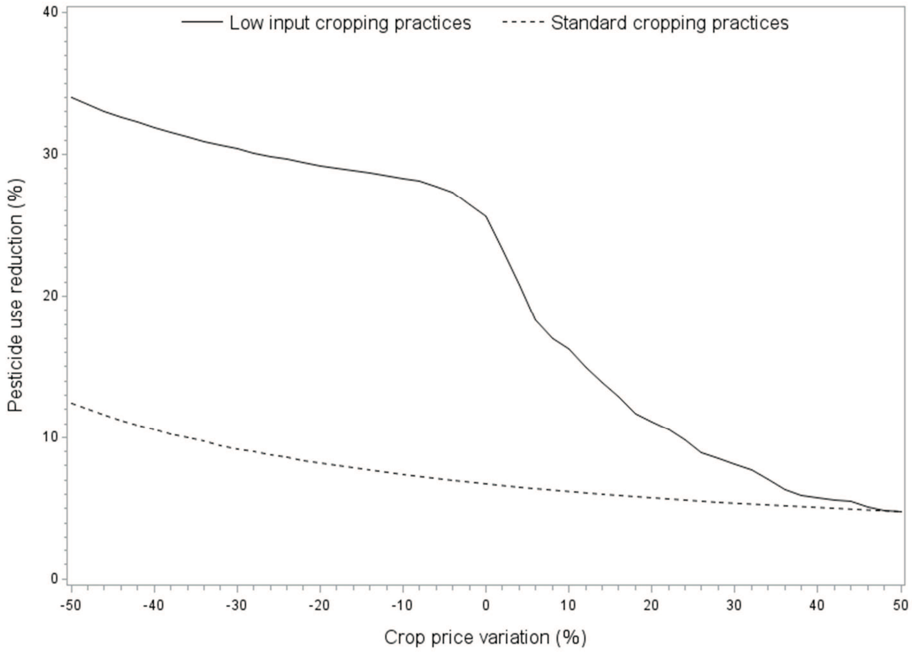
	Low-input practice not available (conventional practice only)	Low-input practice available
Wheat acreage	+0.08	+0.05
Barley acreage	+0.09	+0.11
Rapeseed acreage	-0.18	-0.16
Wheat production	+0.05	-12.35
Barley production	+0.11	+0.13
Rapeseed production	-1.46	-1.44
Fertilizer expenditures	+9.01	-14.50
Pesticide expenditures	-6.65	-25.00
Farmers’ incomes	-0.62	-0.64

The adoption of the new technology by a large share of farmers thus has a significant impact on the reduction in pesticide use induced by the taxation. Interestingly, the decrease in fertilizer expenditures implied by the technological change largely compensate for the small increases due to the substitution between the two inputs, and total fertilizer expenditures decrease by 15%, whereas they increase by 9% with the conventional practice, which can be considered (as previously mentioned) as a negative side effect of the pesticide taxation. As could be expected given the tax redistribution, the farmers’ income does not significantly decrease under either scenario.

Impacts of a change in crop prices on the effect of the tax

Pesticide taxation appears to be a good instrument to incent farmers to adopt low-input practice and thereby generate significant reductions in pesticide use. These results should, however, be placed in the prevailing context of price uncertainty in crop markets. Indeed, as illustrated in section 3.1, output prices play an important role in farmers' incentive to adopt the low-input technology. One can thus wonder what would be the impact of a change in crop prices on the reduction in pesticide use induced by the taxation. To answer this question, we report the reduction in pesticide use induced by the 35% taxation rate (Figure 3) with respect to changes in crop prices[9] compared with the average levels considered thus far, *i.e.*, 171€/ton for wheat, 148€/ton for barley and 357€/ton for rapeseed. We observe a decrease in the impact of the taxation on pesticide use as the crop prices increase. This is an expected result: the increase in prices leads to farmers seeking to increase their yield and thereby increasing their use of inputs, including pesticides. We also notice that at a price increase of up to 50%, the policy generates stronger impacts when the low-input technology is available for wheat cropping. Using pesticide taxation to reach a particular objective of pesticide reduction would, however, be challenging in the current context of price volatility. In fact, at a price decrease of more than 5%, the taxation induces all farmers in our sample to adopt the low-input practice, which generates decreases in pesticide use that are approximately 3 times higher than those under the conventional practice. Then, as crop prices increase, increasingly fewer farmers are incited to adopt the new technology, leading to a sharp decrease in the "low-input" curve.

Figure 3: Impacts of a 35% tax on pesticides with respect to crops prices



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[9] Given the high correlation in crop prices, we assume that they all vary in the same proportions.

Finally, at a crop price increase of more than 50%, *i.e.*, for price levels comparable to those observed during the price spike in 2008[10], the 35% taxation rate simulated here is not sufficient to induce a change in cropping practice, and the "low-input" and "conventional" curves overlap. Higher pesticide taxation rates would thus be needed to incent farmers to use the low-input technology in the case of a huge price increase.

5. Conclusion

By relying on an economic model of acreage and crop production decisions derived from a primal approach, we have been able to combine economic data on conventional cropping practices and experimental agronomic data on low-input practices for wheat to estimate econometric models of farmers' choice with respect to the two technologies.

Our results show that in spite of some land reallocation that would arise between wheat and other higher pesticide consuming crops, the adoption of low-input practices for wheat cropping would induce a significant decrease in input, notably pesticide use. However, adopting low-input cropping practices would not be profitable for farmers in the current context of relatively high crop prices. A lack of economic incentives can thus primarily explain the low adoption rate of this type of technology. In this respect, a tax on pesticide appears to be a useful policy instrument to incent agricultural producers to adopt low-input practices. We found that a relatively limited tax would provide sufficient economic incentives for farmers to adopt these practices. This could lead to a significant decrease in pesticide use, corresponding to the French *"Grenelle de l'Environnement*" short-term objective of a 25% decrease, even if defining a taxation rate that leads to this precise objective is a challenging task in the context of crop price volatility. Conversely, a change in cropping practice appears absolutely necessary for a pesticide taxation policy to succeed: the huge tax rates needed to achieve comparable levels of pesticide decrease without technological change would not be acceptable from a political point of view. On the other hand, because farmers are less responsive to input price changes once they have adopted low-input practices, achieving a higher reduction in pesticide use such as a 50% decrease, which is a medium-term target in France, would not be possible through pesticide taxation even if farmers adopt this new technology. We would, however, like to stress two elements that mitigate these results. First, the pesticide reductions reported in this paper are based on expenditures related to

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[10] In 2008, price levels reached 254€/ton for wheat, 204€/ton for barley and 416€/ton for rapeseed (source: French Ministry of Agriculture)

pesticide inputs, whereas the objectives targeted by public policies generally refer to reductions in terms of Treatment Frequency Index (TFI). The TFI includes the use of plant growth regulators, which are avoided in low-input cropping practices. Because this element is not accounted for in our estimations, we are probably underestimating the potential decreases in the TFI induced by a switch in cropping practice. Second, two inputs, *i.e.*, pesticide and fertilizer, have been introduced in our economic model. However, low-input cropping systems also allow a lower dependency on fossil energy, which further increases their profitability compared with the conventional system. As noted by Loyce *et al.* (2012), oil prices, which are highly volatile, can thus have some impact on the price of wheat, for which low-input practices become less profitable than conventional practices. By not considering the decrease in oil expenditure implied by the change in cropping practice, we are thus also possibly overestimating the level of pesticide taxation needed to incent farmers to adopt the low-input technology. Our framework could be adapted to study this issue by introducing a third input, *i.e.*, oil, in the economic model. This would, however, significantly increase the number of parameters to estimate and complicate the estimation procedure, eventually leading to fairly similar conclusions: pesticide taxation appears to be a good instrument to incent farmers to change their cropping practice and can therefore induce significant reductions in pesticide use, but other policy reforms should be considered to achieve a more ambitious decrease in pesticide usage. Public policies could notably be oriented toward research and development to favor technical progress and further improve low-input cropping practices. In France, for instance, agronomists are currently working on wheat cultivars and are seeking to improve their performance under low-input practices; similar studies are currently underway on other crops, notably barley.

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Appendix: Derivation of the economic model

The farmer chooses acreages, yields and input quantities that maximize his expected profit, subject to production technology and land use constraints:

$$\max_{\mathbf{y},\mathbf{x},\mathbf{s}>\mathbf{0}} \Pi_{it}(\mathbf{s}, \bar{\mathbf{p}}, \mathbf{w}) = \sum_k s_{k,it}\bar{\pi}_{k,it}\left(\bar{p}_{k,it}, \mathbf{w}_{it}\right) - \mathrm{C}_{it}(\mathbf{s})$$

$$\text{s. t. } y_{k,it} = \alpha_{k,it} - 0.5\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right)\mathbf{T}_k{}^{-1}\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right)$$

$$\text{s. t. } S_i = \sum_k s_{k,it}$$

with

$$\bar{\pi}_{k,it} = \bar{p}_{k,it}y_{k,it} - \mathbf{w}_{it}{}'\mathbf{x}_{k,it}$$

and $\mathrm{C}_{it}(\mathbf{s}) = 0.5(\mathbf{r}_{it} - \mathbf{s}_{it})'\mathbf{M}^{-1}(\mathbf{r}_{\boldsymbol{it}} - \mathbf{s}_{it})$.

Following the approach proposed by Chambers and Just (1989), we decompose this optimization problem into two steps. In the first step, the farmer chooses optimal yields and input levels that maximize the expected gross margins for each crop. These optimal gross margins are then used in a second step to determine the optimal acreages that maximize the expected profit.

A.1 Optimal yields and input levels

Yields and input quantities are chosen to maximize the expected gross margins of each crop k, subject to a quadratic production technology constraint:

$$\max_{y_{k,it},\mathbf{x}_{k,it}} \bar{\pi}_{k,it}\left(\bar{p}_{k,it}, \mathbf{w}_{it}\right) = \bar{p}_{k,it}y_{k,it} - \mathbf{w}_{it}{}'\mathbf{x}_{k,it} \tag{A.1}$$

$$\text{s. t. } y_{k,it} = \alpha_{k,it} - 0.5\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right)'\boldsymbol{\Gamma}_k{}^{-1}\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right)$$

The Lagrangian function of this optimization program is defined by:

$$L\left(y_{k,it}, \mathbf{x}_{kit}, \lambda_{k,it}\right) = \bar{p}_{k,it}y_{k,it} - \mathbf{w}'_{it}\mathbf{x}_{k,it} + \lambda_{k,it}\left(y_{k,it} - \alpha_{k,it} + 0.5\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right)'\boldsymbol{\Gamma}_k{}^{-1}\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right)\right) \tag{A.2}$$

This leads to the following first-order conditions:

$$\frac{\partial L}{\partial y_{k,it}} = \bar{p}_{k,it} + \lambda_{k,it} = 0 \tag{A.3}$$

$$\frac{\partial L}{\partial \mathbf{x}_{k,it}} = -\mathbf{w}_{it} - \lambda_k\boldsymbol{\Gamma}_k{}^{-1}\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right) = \mathbf{0} \tag{A.4}$$

$$\frac{\partial L}{\partial \lambda_k} = y_{k,it} - \alpha_{k,it} + 0.5\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right)'\boldsymbol{\Gamma}_k{}^{-1}\left(\boldsymbol{\beta}_{k,it} - \mathbf{x}_{k,it}\right) = 0 \tag{A.5}$$

with $\mathbf{0}$ as the dimension J null vector.

From (A.3), we have:

$$\lambda_k = -\bar{p}_{k,it} \tag{A.6}$$

Replacing λ_k by its value in (A.4) provides the input demand function (Eq. 5 in the paper):

$$\mathbf{x}_{k,it} = \boldsymbol{\beta}_{k,it} - \bar{p}_{k,it}{}^{-1}\boldsymbol{\Gamma}_k\mathbf{w}_{it} \tag{A.7}$$

Combining (A.5) and (A.7) leads to the yield supply equation (Eq. 4. in the paper):

$$y_{k,it} = \alpha_{k,it} - 0.5\bar{p}_{k,it}{}^{-2}\mathbf{w}_{it}{}'\boldsymbol{\Gamma}_k\mathbf{w}_{it} \tag{A.8}$$

Optimal gross margins are thus given by (Eq. 6. in the paper):

$$\bar{\pi}_{k,it} = \alpha_{k,it}\bar{p}_{k,it} + \mathbf{w}_{it}{}'\boldsymbol{\beta}_{k,it} + 0.5\bar{p}_{k,it}{}^{-1}\mathbf{w}_{it}{}'\boldsymbol{\Gamma}_k\mathbf{w}_{it} \tag{A.9}$$

A.2 Optimal acreage

Based on the optimal gross margins, the farmer seeks the optimal acreage that maximizes his profit, subject to the land use constraint:

$$\max_{\mathbf{s}>\mathbf{0}} \Pi_{it}(\mathbf{s}, \bar{\mathbf{p}}, \mathbf{w}) = \mathbf{s}_{it}{}'\bar{\boldsymbol{\pi}}_{it} - 0.5(\mathbf{r}_i - \mathbf{s}_{it})'\mathbf{M}^{-\mathbf{1}}(\mathbf{r}_i - \mathbf{s}_{it}) \tag{A.10}$$

$$\text{s. t. } S_i = \mathbf{s}_{it}{}'\mathrm{I}$$

The Lagrangian function of this optimization program is defined by:

$$L(\mathbf{s}_{it}, \lambda_{it}) = \mathbf{s}_{it}{}'\bar{\boldsymbol{\pi}}_{it} - 0.5(\mathbf{r}_i - \mathbf{s}_{it})'\mathbf{M}^{-\mathbf{1}}(\mathbf{r}_i - \mathbf{s}_{it}) + \lambda_{it}(\,S_i - \mathbf{s}_{it}{}'\mathrm{I}) \tag{A.11}$$

This leads to the first-order conditions:

$$\frac{\partial L}{\partial \mathbf{s}_{it}} = \bar{\boldsymbol{\pi}}_{it} + \mathbf{M}^{-\mathbf{1}}(\mathbf{r}_i - \mathbf{s}_{it}) - \lambda_{it}\mathrm{I} = 0 \tag{A.12}$$

$$\frac{\partial L}{\partial \lambda_{it}} = \; S_i - \mathbf{s}_{it}{}'\mathrm{I} = 0 \tag{A.13}$$

From (A.12), we have

$$\mathbf{s}_{it} = \mathbf{M}\bar{\boldsymbol{\pi}}_{it} + \mathbf{r}_i - \mathbf{M}\mathrm{I}\lambda_{it} \tag{A.14}$$

Replacing $\mathbf{s}_{it}$ in (A.13) by its expression (A.14) leads to:

$$\lambda_{it} = (\mathrm{I}'\mathbf{M}\mathrm{I})^{-1}\mathrm{I}'\mathbf{M}\bar{\boldsymbol{\pi}}_{it} + (\mathrm{I}'\mathbf{M}\mathrm{I})^{-1}\mathrm{I}'\mathbf{r}_i - (\mathrm{I}'\mathbf{M}\mathrm{I})^{-1}\,S_i \tag{A.15}$$

Given the constraint on $\mathbf{r}_{it}$: $\mathrm{I}'\mathbf{r}_{it} = \;S_i$, we have the value of the Lagrange multiplier associated with the binding land use constraint:

$$\lambda_{it} = (\mathrm{I}'\mathbf{M}\mathrm{I})^{-1}\mathrm{I}'\mathbf{M}\bar{\boldsymbol{\pi}}_{it} \tag{A.16}$$

Replacing λ_{it} in (A.14):

$$\mathbf{s}_{it} = \mathbf{r}_i + (\mathbf{M} - (\mathrm{I}'\mathbf{M}\mathrm{I})^{-1}\mathbf{M}\mathrm{I}\mathrm{I}'\mathbf{M})\bar{\boldsymbol{\pi}}_{it} \tag{A.17}$$

By denoting $\mathbf{Q} = \mathbf{M} - (\mathrm{I}'\mathbf{M}\mathrm{I})^{-\mathbf{1}}\mathbf{M}\mathrm{I}\mathrm{I}'\mathbf{M}$, we can easily check that $\mathbf{Q}$ is a symmetric matrix and that the elements of its rows or columns sum to 0. Indeed, because $\mathbf{M}$ is a symmetric matrix, we have $\mathbf{Q}' = \mathbf{M} - (\mathrm{I}'\mathbf{M}\mathrm{I})^{-\mathbf{1}}\mathbf{M}\mathrm{I}\mathrm{I}'\mathbf{M} = \mathbf{Q}$ and $\mathrm{I}'\mathbf{Q} = \mathbf{Q}'\mathrm{I} = \mathbf{M}\mathrm{I} - (\mathrm{I}'\mathbf{M}\mathrm{I})^{-\mathbf{1}}\mathbf{M}\mathrm{I}(\mathrm{I}'\mathbf{M}\mathrm{I}) = \mathbf{M}\mathrm{I} - \mathbf{M}\mathrm{I} = \mathbf{0}$.

Here, it must be noted that $\mathbf{Q}$, which is positive definite, is a sufficient condition for the acreage management cost function to be convex. Indeed, if $\mathbf{Q}$ is positive definite, then for any vector v, $\mathbf{v}'\mathbf{Q}\mathbf{v} > 0$, which implies that $\mathbf{v}'\mathbf{M}\mathbf{v} > (\mathrm{I}'\mathbf{M}\mathrm{I})^{-\mathbf{1}}\mathbf{M}\mathrm{I}\mathrm{I}'\mathbf{M}$. Because $\mathbf{M}\mathrm{I}\mathrm{I}'\mathbf{M} > 0$, a sufficient condition for $\mathbf{M}$ to be positive definite (*i.e.*, to have $\mathbf{v}'\mathbf{M}\mathbf{v} > \mathbf{0}$) is that the sum of all elements of $\mathrm{I}'\mathbf{M}\mathrm{I}$ must be positive. However, knowing $\mathbf{Q}$ allows the identification of only part of the elements of $\mathbf{M}$; it thus always possible to find a matrix $\mathbf{M}$ satisfying $\mathbf{Q} = \mathbf{M} - (\mathrm{I}'\mathbf{M}\mathrm{I})^{-1}\mathbf{M}\mathrm{I}\mathrm{I}'\mathbf{M}$ and $\mathrm{I}'\mathbf{M}\mathrm{I} > 0$ simultaneously. This matrix will be positive definite if $\mathbf{Q}$ is positive definite, which ensures the convexity of the cost function.

We can now rewrite the acreage equation as

$$\mathbf{s}_{it} = \mathbf{r}_i + \mathbf{Q}\bar{\boldsymbol{\pi}}_{it} \tag{A.18}$$

Then, following Carpentier and Letort (2012), we define the parameters in (A.18) as affine functions of total land available to each farmer to account for the scale effect of S_i: $\mathbf{r}_i = \mathbf{g}_i + \boldsymbol{\rho}\, S_i$ and $\mathbf{Q} = S_i\boldsymbol{\Delta}$, with $\mathrm{I}'\mathbf{g}_i = 0$, $\mathrm{I}'\boldsymbol{\rho} = 1$, and $\boldsymbol{\Delta}$ a symmetric matrix $\mathrm{I}'\boldsymbol{\Delta} = \mathbf{0}$.

Replacing $\mathbf{r}_{it}$ and $\mathbf{Q}$ in (A.18) by their expressions gives

$$\mathbf{s}_{it} = \mathbf{g}_i + S_i\boldsymbol{\rho} + S_i\boldsymbol{\Delta}\bar{\boldsymbol{\pi}}_{it} \tag{A.19}$$

It is important here to note that the above-mentioned constraints on $\mathbf{g}_i$, $\boldsymbol{\rho}$ and $\boldsymbol{\Delta}$ parameters ensure that the land constraint $\mathrm{I}'\mathbf{s}_{it} = S_i$ is satisfied. This allows the acreage model to be simply defined as follows.

Choosing crop K as a “reference crop” and developing (A.19), we have

$$s_{k,it} = g_{k,i} + S_i\rho_k + S_i\left(\sum_{l\neq K}\delta_{kl}\bar{\pi}_{l,it} + \delta_{Kl}\bar{\pi}_{K,it}\right) \tag{A.20}$$

where δ_{kl} are the elements of $\boldsymbol{\Delta}$.

Given that $\mathrm{I}'\boldsymbol{\Delta} = \mathbf{0}$, we know that $\delta_{Kl} = -\sum_{l\neq K}\delta_{kl}$, which leads to the acreage equation (Eq. 7 in the paper):

$$s_{k,it} = g_{k,i} + S_i\rho_k + S_i\sum_{l\neq K}\delta_{kl}\left(\bar{\pi}_{l,it} - \bar{\pi}_{K,it}\right), \quad \text{for all } k \in \{1, \dots, K-1\} \tag{A.21}$$

The acreage of crop K is then determined by the land use constraint (Eq. 8 in the paper):

$$s_{K,it} = S_i - \sum_{k=1}^{K-1} s_{k,it} \tag{A.22}$$

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