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On the induced impacts of French pesticide policies: some macroeconomic assessments

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On the induced impacts of French pesticide policies: some macroeconomic assessments

Abstract

The applications of synthetic pesticides by farmers generate fierce debates in France. This paper offers an original macroeconomic quantification of their economic and environmental impacts. We first reveal the statistically significant influence of the prices of crops and pesticides on these application. This influence is lower for cereals than other crops. We then simulate some economic and environmental impacts of future potential French policies. We find, as expected, that a simple tax policy reduces pesticide use and hurts the economic situation of French farmers and food processors. The French livestock sectors are also negatively impacted. We also find that such a simple policy will increase nitrogen pollution and greenhouse gas emissions due to global land use changes. Finally, policy insights regarding these macroeconomic results are discussed.

Keywords: agriculture, pesticide taxation scheme, land-use change, carbon emissions

JEL classifications: Q11, Q18

Impacts induits de la politique française sur les pesticides : quelques évaluations macroéconomiques

Résumé

Les applications de pesticides de synthèse par les agriculteurs suscitent de vifs débats en France. Cet article propose une quantification macroéconomique originale de leurs impacts économiques et environnementaux. Nous révélons d'abord l'influence statistiquement significative des prix des cultures et des pesticides sur ces applications. Cette influence est plus faible pour les céréales que pour les autres cultures. Nous simulons ensuite certains impacts économiques et environnementaux des futures politiques françaises potentielles. Nous constatons, comme prévu, qu'une taxe sur les pesticides réduit l'utilisation des pesticides mais nuit à la situation économique des agriculteurs et des transformateurs alimentaires français. Les filières d'élevage françaises sont également impactées négativement. Nous constatons qu'une telle politique augmenterait les fuites d'azote en France et engendrerait aussi des émissions de gaz à effet de serre plus élevées en raison des changements d'usage des terres à l'échelle mondiale induits par les marchés. Les perspectives politiques concernant ces résultats macroéconomiques sont discutées en fin de travail.

Mots-clés : agriculture, taxe sur les pesticides, changement d'usage des sols, émissions de carbone

Classification JEL : Q11, Q18

On the induced impacts of French pesticide policies: some macroeconomic assessments

1. Introduction

Over the last century, global food production has increased faster than the wealthier population, improving global food security. Enhanced crop protection has led to a massive increase in realized crop yields, limiting the expansion of arable lands and deforestation. Before, protecting crops against pests and weeds mostly involved the management of their natural enemies, a technique known as biological control, and some labour-intensive techniques such as weeding and tilling. The application of chemical products started in the 19th century with the utilization of copper on vineyards and potatoes to protect the crops from fungi damage. The utilization of synthetic products appeared at the beginning of the 20th century, starting with the commercialization of dichlorodiphenyltrichloroethane (better known as "DDT"). In the last century, increasingly complex synthetic pesticides were introduced. At the same time, new agronomic techniques and farm machines enhanced the application of these new products and saved professional farmers, as well as leisure gardeners, from painful labour.

However, societal concerns regarding the health and environmental impacts of pesticides have increased in recent decades, particularly for synthetic pesticides. Scientific evidence has accumulated indicating that significant exposure to these pesticides directly influences farmers' health and can cause cancer or chronic diseases such as Parkinson's disease (Alavanja et *al*., 2003; Multigner et *al*., 2010; Betarbet et *al*., 2000). Currently, intense scientific debates examine the indirect effects of pesticides on the health of food and water consumers. These debates focus specifically on the allowable concentration levels of individual molecules and on their interactions. In regard to the environment, pesticide residues unambiguously pollute water and soil resources. The impact of pesticides on biodiversity is more debated because pesticide use is correlated with landscape simplification, which reduces the habitats of biodiversity (Butchart et *al*., 2010). In any case, pesticides are suspected to be major contributors to losses of biodiversity, notably for common birds and aquatic invertebrates (Beketov et *al*., 2013).

These societal concerns call for public action. These concerns are addressed with different intensities and policy instruments across the world, ranging from command-and-control instruments (such as the ban on DDT adopted in the EU in the 70s) to market-based instruments (such as ad valorem taxes in Denmark). In this paper, we focus on the French case, which is characterized by significant pesticide use, a diversity of farm production and crop damage, a currently complex policy and many recent policy decisions at both national and european scales. The current French pesticide policy is obviously consistent with the European policy that mainly defines authorized and banned pesticides. The French pesticide policy includes national bans in addition to European ones. In November 2017, the European Parliament and Council reauthorized the use of synthetic pesticides with glyphosate for a period of 5 years. Similar to a few European countries, policy makers in France are considering the possibility of banning glyphosate in 2021 for farmers and have already voted to ban these pesticides for public use and private gardeners by 2019. The French policy goes further and includes some specific taxes for farmers who use synthetic pesticides, depending on their toxicity (and at a maximum of 5%). This policy also includes research efforts to develop alternatives; these efforts were significantly increased with the Ecophyto 1 plan, which was implemented in 2008. Finally, the most recent pesticide reform Eophyto 2+ that should be applied in 2021 includes new taxes for pesticide retailers unless pesticide retailers justify a decreasing of their sales.

Despite all the recent policy reforms, French pesticide policies regularly divide stakeholders, with environmental groups asking for more severe regulations and food and pesticide industries asking for the opposite. For French policy makers, defining the optimal pesticide policy is not straightforward due to scientific uncertainties regarding the health and environmental impacts and due to the multiple known, but imperfectly measured, trade-offs.

First, the optimal pesticide policy must obviously balance environmental and economic objectives. In the recent glyphosate debate, French farmers and pesticide lobbies stress that the banning of this herbicide will decrease their crop yields and increase their production costs, mostly due to the additional mechanical control of weeds that would become necessary. The income of the French farm sector would significantly decrease (estimates by Concorde 2017 and IPSOS 2017 vary between 1 and 2 billion euros; the average income of this sector in the last 5 years was approximately 13 billion euros). These results rely on the crucial assumption that farmers are technically and economically efficient, applying pesticides due to their marginal productivity and prices relative to crop prices. These results are based on the short-term view of fixed technologies and crop allocations. By contrast, other French scientific studies find that the total farm use of pesticides (including glyphosate and all other pesticides) can significantly decrease without reducing farmers' incomes (by 30% according to Jacquet et *al*., 2011, Boussemart et *al*., 2011, and Lechenet et *al*., 2014). These contradictory results rely on the crucial opposite assumption that some farmers are technically or economically inefficient. These studies also consider a larger set of alternatives to pesticides rather than solely considering mechanical control, including integrated cropping techniques and new crop allocations. These last studies are thus more relevant in the long run because it is well known that economic agents have more flexibility in addressing new constraints, as illustrated by Femenia and Letort (2016). French policy makers are thus currently informed by contradictory studies on the inevitable tension between farm competitiveness and pesticide use.

Second, French policy makers also have to manage the conflicts between different environmental objectives. The recent glyphosate debate again nicely illustrates some of these trade-offs. The same farm and pesticides lobbies stress that banning this synthetic pesticide will have a negative climate change impact by inducing farmers to manage weeds mechanically, which would contribute to more energy use and hence increase direct carbon emissions (IPSOS, 2017). Moreover, less carbon would be stored in the soil. By contrast, environmental groups suggest that banning glyphosate would not increase net carbon emissions if production systems are modified, for example, by developing associated crops to control weeds (Generation futures, 2017). The conflict between environmental objectives is however much more complex than these first ones. Some studies (such as Bareille and Letort, 2018) find that there are some substitutions between pesticides and mineral fertilizers for some crops and farmers, implying that, *ceteris paribus*, a constraint on pesticide use will increase fertilizer use, which may subsequently increase nitrogen pollution in waterways. French policy makers are well aware of this potential tension between the pollutions induced by the use of pesticides and fertilizers but lack of numerous scientific evidences.[1] Moreover, stricter French regulation on pesticides may reduce overall French farm production, which may be partially compensated by increased imports depending on trade regulations. These imports may come from countries using relatively more pesticides than French producers and may also induce land use changes and related changes in carbon emissions in these countries. These “leakage” effects are well known in the climate change literature, as well as in the more recent biofuel issue (Searchinger et *al*., 2008). The quantification of land use changes induced by the biofuel policies has recently been an intense empirical issue. These land use changes are not directly measured; instead, they are counterfactually simulated with market equilibrium models. These models are based on uncertain parameters, such as the reactions of agents to economic incentives (price and income elasticities), contributing to empirical contradictions. The existence of such leakage effects is

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[1] For instance, the former French Minister to Agriculture, Stéphane Travert, warned about the indirect impacts that a glyphosate ban would have on fertilizer-saving agricultural techniques like catch crops or no-tillage. Source: http://discours.vie-publique.fr/notices/173002015.html

now recognized in all French agri-environmental policy debates as the notion of imported deforestation. Again, empirical studies measuring these trade-offs are currently missing (Reboux et *al*., 2017).

In this complex context characterized by many trade-offs and uncertainties, French policy makers and more generally, the French society at large, have highlighted the need for transparent scientific results to guide their decisions and positions. Numerous synthetic reports have been published by French/European/World health and environmental agencies in recent years. However, the different economic and environmental trade-offs just mentioned are not simultaneously addressed and quantified at the global scale (Reboux et *al*., 2017).

Our main objective in this paper is to partially fill this gap by offering a macroeconomic quantification of some of the economic and environmental impacts of two contrasted French pesticide policies. The first simple but radical policy scenario is the implementation of significant pesticide taxes similar to those implemented in a few other countries and those often suggested in the academic economic literature (Carpentier et *al*., 2010). Hereafter, we refer to this first scenario as the tax scenario. The second contemplated policy scenario is more in the spirit of the recent reforms, and hereafter, we refer to it as the technological scenario. The latter favours the adoption of potentially new pesticide-saving technologies by boosting public/private researches and disseminations of their results to farmers. In other words, we clearly define two very contrasted and stylized policy scenarios because we assume that a policy-induced technical change occurs in the second scenario, while there is no price-induced technical change in the first scenario. We are not looking for the optimal French pesticide policy because we do not capture all the public costs of the two scenario, in particular those arising in the long run in the R&D scenario. We more modestly measure some economic and environmental trade-offs that such a policy must address.

For this purpose, we develop an original methodology with three distinctive features. First, we perform econometric estimations to identify the economic behaviour of French farmers regarding their use of pesticides and fertilizers and their acreage choice. In this way, we avoid any assumptions regarding whether they are technically or economically efficient or not. Second, we introduce all farm activities, including the often-neglected fodder crops consumed by livestock sectors. These first two distinctive features rely on the often-overlooked regional agricultural economic accounts produced by the French institute of statistics (INSEE). These yearly accounts include data from 1990 to the present, are publicly available and cover all farm activities. We develop generalized maximum entropy procedures to address the limited number of observations. This database does not separate the different types of farm technologies and pesticides but aggregates the synthetic and chemical pesticides used by both conventional and organic farmers. Our macroeconomic assessment is thus complement to microeconometric analyses performed with databases covering particular farm, technologies and/or pesticides. We find a large number of statistically significant price coefficients; hence, farmers' use of pesticides depends on netput prices. We find that the French price elasticity of pesticide use amounts to -0.8, which is higher than other available microeconometric estimates (but consistent with our method on aggregate data; see, e.g. Böcker and Finger, 2017). We also find significant variations in elasticities among activities, such as lower responses for cereals than vineyards, livestock and vegetable elasticities, and among French regions.

Our third distinctive feature is the simulation of some of the economic and environmental impacts of our two scenarios at the world level. We develop an original computable general equilibrium (CGE) framework, which is based on the standard global trade analysis project (GTAP)-Agr model (Keeney and Hertel, 2005). This model, which is based on the GTAP database, does not isolate pesticides from other chemical products such as mineral fertilizers. We thus improve the representation of the French economy by specifying the particular role of pesticides and mineral fertilizers used by French farmers and by introducing the previously estimated elasticities. This CGE framework allows us to simultaneously measure the impacts of our two scenarios on global economic indicators and the pesticide use of French farmers. We also measure the global net carbon emissions by taking into account the indirect effects occurring through market reorganization, induced by the livestock sectors for example. Ultimately, we provide some rudimentary estimates regarding the evolution of the nitrogen surplus in France. We find, as expected, that the tax scenario has a negative economic impact on the French farm and food processing sectors and leads to a reduction in their pesticide use. Reduced French production is partly compensated by increased imports, benefiting Latin American producers for instance. We obtain a meaningful reduction in French livestock production, which does not compensate for changes in global carbon emissions induced by global land use changes. We also obtain a higher French nitrogen surplus, as cereal yields and exports contract much more than French livestock production. On the other hand, our technological scenario leads to very small crop market effects, reduces the application of pesticides and increases French economic indicators. Interestingly, we also find that all of our environmental trade-offs are solved (including nitrogen and pesticide applications and carbon emissions), which is partly explained by increased French production of protein crops and reduced imports of these products. Finally, this scenario quantifies some of the economic benefits of R&D efforts.

This paper is organised as follows. Section two details our econometric efforts. Our simulated policy scenarios are analysed in section three. The last section concludes with some policy and research recommendations.

2. Econometric identification of French farmers' behaviour

The effectiveness of any pesticide policy partly depends on the behaviour of farmers. Some studies (such as Concorde 2017 and Jacquet et *al*. 2011) postulate the behaviour of farmers and then perform policy simulations with calibrated models. By contrast, many other studies analyse the behaviour of farmers with statistical techniques. The main results of current econometric studies are summarized in Skevas et *al*. (2013) and Böcker and Finger (2017). These scholars find some consistent results across studies such as higher price responses in the long run (compared to the short run) or at the aggregate level (compared to the individual level). However, some conflicting results remain, such as the overuse vs underuse of pesticides by farmers or the exact levels of the price responses for different pesticides and crops. These conflicting results can be partly explained by the datasets, statistical procedures and economic specifications used in these studies.

The economic specifications can be separated into three groups. The first group uses a production function approach where technological relationships are statistically estimated (recent French applications include Boussemart et *al*., 2013; Desbois et *al*. 2016, and Urruty et *al*., 2015). One critical challenge of this approach is controlling for the potential endogeneity of the explanatory variables (Griliches, 1957; Griliches and Mairesse, 1995), the results being often sensitive to the choice of instrumental variables. The second group relies on duality theory to directly estimate price elasticities (one recent French application is found in Fadhuile et *al*., 2016). These studies usually do not identify the underlying technological relationships and consider a limited set of decision variables (for example, focusing only on pesticide application without considering the use of fertilizers, cropping practices, and acreage decisions). The third group can be presented as a mix of the two previous groups with the explicit representation of some technological relationships and the explicit specification of exogenous price incentives on many interrelated decision variables (such as variable input applications and acreage choices). Carpentier and Letort (2012, 2014) explain the virtues of their structural approach and

Femenia and Letort (2016) provide a French application that focuses on pesticides. Their dataset is limited to individual cereal producers located in the French department La Meuse and covers a limited number of years (2007-2012). We elaborate on this approach and apply it to a larger (but less detailed) dataset. We implement this specification in both this statistical section and for the policy CGE simulation in the next section.

2.1. Economic specifications

We consider a multi-output representative regional-farm *r* maximizing its restricted profit $\Pi_{r,t}$ each year t. The modelled decision variables are the annual application of the variable inputs on each output and the acreage choices of some annual crops. The maximization programme is subject to the expected output and input prices, the level of fixed factors, technological possibilities and regulatory constraints. The yields are assumed to be crop-specific quadratic functions depending on the variable input applications with constant returns to acreage. Compared to the often-used damage control function, this quadratic function does not impose rigid separability of the variable inputs (Carpentier and Weaver, 1997). The restricted profit function is defined as the sum of the gross margins per hectare $\Pi_{k,r,t}$ for each output *k* multiplied by the respective acreage minus a cost function $C(S_{r,t}; \bar{S}_{r,t}; Z_{r,t})$ depending on the acreage allocation of endogenous areas $S_{r,t}$. This cost function captures all the constraints and benefits for crop diversification. These constraints can be due to the management of fixed inputs (capital and labour, noted $Z_{r,t}$) at the farm scale, decreasing returns to scale, crop rotations or risk diversification motives. This function ensures the convexity of the profit function, allowing the determination of the optimal acreage (Carpentier and Letort, 2014).

Formally, the maximization programme can be solved in two steps. In the first step, we solve for the optimal application of the variable inputs for each crop per hectare. In the second step, we solve for the optimal acreage choices. The first programme is given by (1):

$$\pi_{k,r,t} = \max_{\mathbf{x}_{k,r,t}} \left\{ \begin{array}{l} E\left(p_{k,r,t}\right) y_{k,r,t} - \sum_{i=1}^{I} E\left(w_{i,r,t}\right) x_{i,k,r,t} \\ \text{s.t.}\, y_{k,r,t} = f_{k,t}\left(\mathbf{x}_{k,r,t}\right) \end{array} \right\} \tag{1}$$

where $x_{i,k,r,t}$ is the quantity of the variable input i applied to one hectare of area k on region *r* at time *t*, $w_{i,r,t}$ is its price, $p_{k,r,t}$ is the price of output k and $y_{k,r,t}$ is the yield of output k. The operator *E*(.) refers to the expectations of the netput prices (see following section for the choice of their functional form). For sake of simplicity, we consider only two variable inputs:

pesticides ($i=1$) and fertilizers ($i=2$). The yield is equal to a function of the variable input application $f_{k,t}(\cdot)$. Formally, the production function is given by (2):

$$f_{k,t}\left(\mathbf{x}_{k,r,t}\right)=\alpha_{k,r}+\alpha_{t,k,r}t-\frac{1}{2}\left(\beta_{1,k,r}^{-1}\left(b_{1,k,r}-x_{1,k,r,t}\right)+\beta_{2,k,r}^{-1}\left(b_{2,k,r}-x_{2,k,r,t}\right)+2\beta_{12,k,r}^{-1}\left(b_{1,k,r}-x_{1,k,r,t}\right)\left(b_{2,k,r}-x_{2,k,r,t}\right)\right) \quad (2)$$

This quadratic production function includes easily interpretable parameters (Pope and Just, 2003). The parameters $\alpha_{k,r}$ and $\alpha_{t,k,r}$ represent the maximal yields of output k that depend on time (represented by a trend t), $\alpha_{t,k,r}$ representing technical progress. The parameters $b_{1,k,r}$ and $b_{2,k,r}$ represent the maximum required variable inputs to reach the maximal yields. The parameters $\beta_{1,k,r}$, $\beta_{2,k,r}$ and $\beta_{12,k,r}$ represent the responses of the yields to variable inputs and are directly related to the price responses (see below).

The resolution of (1) with (2) leads to the following functions (3) and (4):

$$x_{i,k,r,t}=b_{i,k,r}-E\left(w_{i,k,r,t}\right)E\left(p_{k,r,t}\right)^{-1}\frac{\beta_{j,k,r}^{-1}}{\beta_{i,k,r}^{-1}\beta_{j,k,r}^{-1}-\beta_{12,k,r}^{-2}}+E\left(w_{j,k,r,t}\right)E\left(p_{k,r,t}\right)^{-1}\frac{\beta_{12,k,r}^{-1}}{\beta_{i,k,r}^{-1}\beta_{j,k,r}^{-1}-\beta_{12,k,r}^{-2}} \quad (3)$$

with $i\neq j$ and:

$$y_{k,r,t}=\alpha_{k,r}+\alpha_{k,r,t}-\frac{E\left(p_{k,r,t}\right)^{-2}}{2\left(\beta_{1,k,r}^{-1}\beta_{2,k,r}^{-1}-\beta_{12,k,r}^{-2}\right)}\left(E\left(w_{1,k,r,t}\right)^{2}\beta_{2,k,r}^{-1}+E\left(w_{2,k,r,t}\right)^{2}\beta_{1,k,r}^{-1}-2E\left(w_{1,k,r,t}\right)E\left(w_{2,k,r,t}\right)\beta_{12,k,r}^{-1}\right) \quad (4)$$

where (3) is the demand function of the variable inputs, and (4) is the crop yield function. The estimations of the parameters in (3) and (4) allow the determination of the optimal gross margins $\pi_{k,r,t}^{*}$ that are needed to determine the optimal acreage choices. Formally, the second programme is given by (5) :

$$\begin{aligned}&\max_{\mathbf{s}_t}\Pi_{r,t}=\sum_{k=1}^{K}s_{k,r,t}\pi_{k,r,t}^{*}\left(\mathbf{x}_{k,r,t}\right)+\sum_{k=K+1}^{\bar{K}}\bar{s}_{k,r,t}\pi_{k,r,t}^{*}\left(\mathbf{x}_{k,r,t}\right)-C\left(\mathbf{s}_{r,t};\bar{\mathbf{s}}_{r,t},\mathbf{Z}_{r,t}\right)\\&\text{s.t.}\sum_{k=1}^{K}s_{k,r,t}+\sum_{k=K+1}^{\bar{K}}\bar{s}_{k,r,t}=UAA_{r,t}\end{aligned} \quad (5)$$

In the following, we consider that $\sum_{k=1}^{K}s_{k,r,t}=s_{tot,r,t}$, where $s_{tot,r,t}$ is the total area devoted to all the endogenous crops in region *r* in t.

For the cost function, we use a parsimonious entropic function (6):

$$C\left(\mathbf{S}_{r,t};\bar{\mathbf{S}}_{r,t},\mathbf{Z}_{r,t}\right)=A+\sum_{k=1}^{K}c_{k,r}S_{k,r,t}+a_r\sum_{k=1}^{K}S_{k,r,t}\ln\left(S_{k,r,t}\right) \tag{6}$$

The term A represents the fixed costs of the farm that do not depend on acreage choices. The vector of parameter $\mathbf{c}_r$ represents crop-specific costs (per area) that do not depend on variable inputs. The parameter a_r plays a key role in determining the optimal area. Indeed, by resolving (5), we obtain (7) :

$$S^*_{k,r,t}\left(\pi^*_{k,r,t}\right)=S_{tot,r,t}\frac{\exp\left(a_r\left(\pi^*_{k,r,t}-c_{k,r,t}\right)\right)}{\sum_{l=1}^{K}\exp\left(a_r\left(\pi^*_{k,r,t}-c_{l,r,t}\right)\right)} \tag{7}$$

The optimal acreage of crop k noted S* depends positively on S_{tot} and on the gross margin of k but negatively depends on the gross margins of the other crops. In particular, an exogenous shock on input prices impacts acreage decisions. Including the total land constraint S_{tot}, the expression of (7) leads, in the logarithm form, to (8):

$$\ln\left(\frac{S^*_{k,r,t}}{S^*_{l,r,t}}\right)=a_r\left(\pi^*_{k,r,t}-\pi^*_{l,r,t}\right)-a_r\left(c_{k,r,t}-c_{l,r,t}\right) \tag{8}$$

where *l* is the reference crop that saturates the total land constraint. Equation (8) shows that the evolution of the ratio of the optimal areas directly depends on the margin differences and the parameter a_r. If a_r is high, then the farmer can easily modify his/her optimal acreage. If parameter a_r is null, then the areas are independent of the margins and thus independent of market prices.

The pesticide prices impact farmers' choices. They obviously impact pesticide and fertilizer demands (relation (3)) but also on yields (relation (4)) and acreage choices (relation (8)). The aim of the econometrician is thus to statistically identify the deep parameters $\left(\boldsymbol{\alpha}_r,\boldsymbol{\beta}_r,\mathbf{b}_r,a_r,\mathbf{c}_r\right)$. In particular, the estimations of $\boldsymbol{\beta}_r$ allow the elasticities of yields and input demands regarding input and output prices to be determined, and a_r allows the elasticities of area regarding input and output prices to be determined.

2.2. Econometric procedures

Several issues prevent the direct estimations of the behavioural parameters. First, we do not observe the farmers' price expectations but only the observed prices. We thus assume that farmers have naïve anticipation for output prices but perfect anticipation for input prices. This assumption is common in most agricultural economics works with short-term profit-maximization problems due to the dynamic process of plant growth (Nerlove and Bessler, 2001; Carpentier and Letort, 2012). Indeed, farmers sow their land a few weeks after the harvest of campaign $t-1$ without knowing the output prices of campaign t, but pesticides and fertilizers are used during the spring of campaign t.

Second, we do not observe crop-specific input demand but only the regional-farm consumption of pesticides and fertilizers $\mathbf{X}_{r,t}$. This is a classical issue when estimating crop-specific input demand functions. We thus estimate (9):

$$X_{i,r,t} = \sum_{k=1}^{K} S_{k,r,t} x_{i,k,r,t} + \sum_{k=K+1}^{\bar{K}} \bar{S}_{k,r,t} x_{i,k,r,t} + \varepsilon_{i,r}^{X} \qquad (9)$$

where $\varepsilon_{i,r}^{X}$ is the random term accounting for unobservable heterogeneity among farmers and stochastic events that can impact production.

Due to the total land constraint, we estimate only $K-1$ acreage equation functions such that (10):

$$\ln\left(\frac{S_{k,r,t}^{*}}{S_{K,r,t}^{*}}\right) = a_r \left(\hat{\pi}_{k,r,t}^{*} - \hat{\pi}_{K,r,t}^{*}\right) - a_r \left(c_{k,r,t} - c_{3,r,t}\right) + \varepsilon_{k,r,t}^{S} \qquad (10)$$

where $\varepsilon_{k,r,t}^{S}$ is the random term accounting for unobservable heterogeneity. The optimal area devoted to crop *K* is determined by substituting the optimal area for the K-1 other crops into the total land constraint S_{tot}.

In total, we estimate a system composed of $\bar{K}$ yield equations, 2 input demand equations (for $i \in [1;2]$), and $K-1$ acreage equations. The crop yield equations are (11):

$$y_{k,r,t} = \alpha_{k,r} + \alpha_{k,r,t} - \frac{p_{k,r,t-1}^{-2}}{2\left(\beta_{1,k,r}^{-1}\beta_{2,k,r}^{-1} - \beta_{12,k,r}^{-2}\right)}\left(w_{1,k,r,t}^{2}\beta_{2,k,r}^{-1} + w_{2,k,r,t}^{2}\beta_{1,k,r}^{-1} - 2w_{1,k,r,t}w_{2,k,r,t}\beta_{12,k,r}^{-1}\right) + \varepsilon_{k,r,t}^{y} \qquad (11)$$

where $\varepsilon_{k,r,t}^{y}$ represents the error term. We estimate this system for each French region, assuming that the set of parameters is specific for each one. This decomposition into regions also allows the error terms to be disentangled from the regional fixed effects.

We estimate our system of equations using the generalized maximum entropy (GME) method (Golan et *al.*, 1996). Indeed, van Akkeren et *al.* (2002) show that the GME method has better finite-sample properties and is more robust regarding the distribution of errors than the usual method of moments[2]. In the GME, the estimated parameters are defined as the product of (endogenous) probabilities and (exogenous) support values. Assuming that the value of parameter θ_n ranges between $\left[z_{n1}, z_{nR}\right]$, the econometrician defines the set of support values $\mathbf{z}_n = \left[z_{n1}, z_{n2}, ..., z_{nR}\right]$ with the associated probability weights $\mathbf{P}_n = \left[P_{n1}, P_{n2}, ..., P_{nR}\right]$, where $P_{nr} \geq 0 \ \ \forall n \in \left[1; N\right]$ and $\forall r \in \left[1; R\right]$. Each parameter is defined as:

$$\theta_n = \sum\nolimits_{r=1}^{R} z_{nr} P_{nr} \tag{12}$$

This optimal probability distribution maximizes the entropic criteria defined by:

$$H\left(\mathbf{P}\right) = -\sum\nolimits_{m=1}^{m=M} P_m \ln\left(P_m\right) \tag{13}$$

In the GME method, the entropic criteria includes the probability distributions associated with both the deep parameters and error terms. Accordingly, this method avoids making assumptions regarding the specific distributions of these error terms. Tests can be performed using entropic ratio tests that are similar to the likelihood ratio test used in the maximum likelihood approach. Below, we use standard asymptotic results for statistical inference.

The GME method has gained popularity in recent years, but similar to Bayesian econometrics, it remains sensitive to the determination of the support values. In alignment with most studies using GME, we consider three support values for each parameter. Due to the agronomic interpretation of our parameters, we use some technical information to help us define the support values of some of the deep parameters. Specifically, we assume that the $\alpha_{k,r}$ parameter (maximum yield) represents between 50% and 150% of the observed maximal yield. We

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[2] Note that some studies on the estimation of pesticide demand have already used the GME method (e.g. Oude Lansink and Carpentier, 2001).

assume that the annual trend parameter $\alpha_{t,k,r}$ represents between -50% and 50% of the observed mean yield. The parameters $b_{1,k,r}$ and $b_{2,k,r}$ measure the variable inputs required to reach the maximum yields and are assumed to be between zero and 25% of the maximum observed crop receipts. For the crucial price response parameter $\boldsymbol{\beta}_r$, we rely on the values from prior studies to guide our support values. As seen from equation (4), these parameters are directly related to the yields elasticities with respect to variable input prices. When defining the support values of these crucial parameters, we assume that these yields elasticities are negative and higher than -0.5. The robustness of our econometric results for these support values is reported in the Appendix. In regard to the other crucial parameter a_r governing acreage decisions, we again rely on the literature and assume that the own price elasticity of land use is positive and lower than 0.5. Finally, we assume large negative and positive support values for the crop-specific cost parameters $\mathbf{c}_r$.

2.3. Data and descriptive statistics

We use the agricultural economic accounts (AEA) of the 21 former metropolitan and continental French regions (all metropolitan regions except Corsica) between 1991 and 2015. Produced by the INSEE (the French Institute of Statistics), this database provides information on the different elements of agricultural incomes (production, sales, intermediate inputs, subsidies, wages, profits, etc.).[3] In addition to providing information that covers a relatively long period of time, this database provides information on the values of different fodders (including prices), which is usually unavailable in other farm datasets.

We distinguish five outputs (i.e., $\bar{K}=5$): cereals, industrial crops (mostly oilseeds and sugar beets), corn silage, other fodder (mostly from grasslands) and other crops. This last category is an aggregate of likely pesticide-intensive crops such vegetables, fruits and vineyards. We consider that the acreage of the first three outputs is determined each year by the farmers, while the last two types of land are more permanent crops (vegetables are mostly grown on similar fields). The acreage of these two last types of outputs is treated as exogenous in the estimation procedure. Table 1 provides the summary statistics for the 21 (number of regions)*25 (number

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[3] See Annequin et *al*. (2009) for details on this database.

of years) observations.

The statistics for these areas highlight that the most cultivated lands are those used for other fodders, even if there are large disparities among the regions (notably between the regions of the Paris Basin and the ones in the mountains where permanent grasslands represent the main agricultural area). Cereals are the second most cultivated lands. The statistics on variable input consumption confirm that the two most consumed variable inputs used for crop activities are pesticides and fertilizers (seed expenditures are much lower). The AEA database only reports the aggregated consumption of pesticides; therefore, we are not able to distinguish between the different types of pesticides (insecticides, fungicides and herbicides) or between the different practices and their outputs (organic versus conventional farming). According to this database, pesticide applications have increased between 1991 and 2008 but have decreased since; 2015 levels are the same as 1991 levels. For this period, pesticide expenditures represent less than 8% of farmers’ incomes. Pesticide prices are rather stable over the first 15 years, and they modestly increase in the last 10 years (possibly due to the banning of some synthetic pesticides).

Table 1: Descriptive statistics (N=525)

	Mean	**S.D.**	**Min**	**Max**
price index of pesticides (1990 = 100)	123.49	95.15	92.67	665.19
price index of fertilizers (1990 = 100)	142.94	62.37	86.35	531.10
value of pesticides (€)	123.81	73.52	10.60	347.63
value of fertilizers (€)	142.45	77.28	29.98	565.34
price of cereals (€)	137.61	36.29	78.63	288.61
price index of industrial crops (1990 = 100)	72.18	21.02	39.63	154.07
price index of maize fodder (1990 = 100)	115.76	42.23	49.69	349.44
price index of other fodder (1990 = 100)	118.80	41.03	56.88	331.03
price index of other crops (1990 = 100)	101.88	24.46	57.29	229.19
cereals area (1000 Ha)	433.48	275.19	73.67	1339.48
industrial crop area (1000 Ha)	140.85	125.22	4.38	529.39
maize forage area(1000 Ha)	71.25	85.42	1.35	384.42
other fodder areas (1000 Ha)	613.27	356.01	23.33	1365.90
other crops area (1000 Ha)	128.86	154.15	6.32	775.72
yields of cereals (tons/Ha)	6.77	1.41	2.86	10.73
yields of industrial crops (quantity index/Ha)	16.01	6.73	7.06	48.13
yields of maize forage (quantity index/Ha)	4.78	1.85	0.07	13.02
yields of other fodders (quantity index/Ha)	2.78	1.32	0.67	6.48
yields of other crops (quantity index/Ha)	85.62	54.74	18.67	295.10

2.4 Econometric results

For each region, we estimate the econometric model composed of 34 deep parameters. The statistical tests reveal a serial autocorrelation in the error terms. We re-estimate the model correcting for this issue in a second step, which imply to remove the first year of observation. In addition, due to multicollinearity issues in our dataset between fertilizer and pesticide prices, we omit the second-order interactions between the two variable inputs in relations (3) and (4). We thus finally estimate 33 deep parameters. Table 2 reports the estimated deep parameters governing the biological/price responses to pesticides for all regions and outputs.

Table 2: Estimated response parameters to pesticide prices by region and crop.

	Cereals	Industrial crops	Corn silage	Other fodder	Other crops
Ile de France	0.19	1.00 *	1.03	0.49	15.24
Champagne Ardennes	0.55	1.41 *	1.11	0.30	11.79
Picardie	0.39	2.06 **	0.80	1.09	7.89 **
Haute Normandie	0.60 *	1.04 **	0.62	0.42	9.82 **
Centre	0.22	0.53 *	0.55	0.34	5.38
Basse Normandie	0.61	1.23 *	0.62	0.12	9.02 *
Bourgogne	0.38	0.32	1.19	0.26	7.52
Nord pas de Calais	0.50 *	3.06 **	0.70	0.76	1.29
Lorraine	0.03 **	0.06 **	0.08 *	0.00	1.29 *
Alsace	0.57 **	1.86	1.16	0.54	10.24
Franche comté	0.31	0.42	1.31 *	0.30 **	18.69
Pays de la Loire	0.48 **	0.73 **	0.55 *	0.17	5.92 **
Bretagne	0.17	0.90 **	0.60	0.27 *	4.08 *
Poitou Charentes	0.42 *	0.21	0.69	0.58 **	6.00 **
Aquitaine	0.93 **	0.37	0.51	0.35 **	2.21 **
Midi Pyrénées	0.31 *	0.15	0.76	0.36 **	2.87 *
Limousin	0.33 *	0.98	0.56 *	0.02	2.13
Rhône Alpes	0.90 **	0.78	1.08	0.22 **	0.74
Auvergne	0.47 **	0.47	1.01 *	0.00	7.20 *
Languedoc Roussillon	1.67 *	0.67 *	0.53	0.32 *	0.88 **
PACA	1.70 **	1.48	0.22	0.19	6.96 **

** and ** represent the 10% and 5% significance levels, respectively.*

The estimated parameters for cereals, industrial crops and other fodder are statistically significant in most regions (or almost), particularly in regions with mixed farms (e.g., Pays de le Loire). We also find that industrial crops are more price sensitive than cereals, which is consistent with Carpentier and Letort (2012). Corn silage and other fodder crops are less sensitive to pesticide prices, possibly because more complex crop rotations are implemented in the livestock farms (which are captured by the $\mathbf{c}_r$). The absence of response by maize in some regions may also be explained by the development of hoeing techniques, which decreases the required pesticide levels. Crop farms have less freedom to implement such alternative techniques and rely more on pesticide application to manage plant health. Finally, fodder prices vary less than the prices of cereals and industrial crops, which makes it more difficult to statistically identify price responses.

We find that these estimated parameters are robust to the choices of the support values (see Tables A1 and A2 in the Appendix). The parameters for fertilizers are estimated with less precision, which is probably due to the substitution of chemical fertilizers with organic fertilizers. In regard to the other estimated parameters, we include a trend in the crop yield equations that proxies the effects of technical changes and climate effects. These trends are statistically positive for cereals and industrial crops, representing 0.5% and 0.8% of the annual growth, respectively. These parameters illustrate the gains obtained using the same levels of inputs and considering technical progress or meteorological conditions. These parameters are not significant for other crops and fodders, which is possibly due to decreased R&D efforts for these activities.

Table 3: Aggregated estimated elasticities for France

		Cereals	Industrial crops	Maize forage	Other fodders	Other crops	Aggregated
Yield elasticities	Output price	0.07	0.19	0.26	0.17	0.10	
	Pesticide price	-0.04	-0.10	-0.14	-0.09	-0.06	
	Fertilizer price	-0.04	-0.07	-0.11	-0.08	-0.03	
Input own-price elasticities and crop-specific consumption	Pesticide price	-0.34	-1.30	-2.71	-1.01	-0.99	-0.82
	Fertilizer price	-0.23	-0.44	-1.15	-0.54	-0.43	-0.39
	Pesticide repartition	0.13	0.13	0.04	0.04	0.66	
	Fertilizer repartition	0.14	0.15	0.05	0.04	0.63	
Acreage elasticities	Cereal price	0.07	-0.14	-0.14			
	Industrial crop price	-0.05	0.18	-0.04			
	Maize forage price	-0.01	-0.01	0.10			
	Pesticide price	-0.007	0.02	0.01			
	Fertilizer price	-0.01	0.03	0.02			

Table 3 reports the estimated elasticities aggregated at the national scale. The aggregated own-price elasticity of pesticide application is estimated to be -0.82 (and remains at -0.78 and -0.80 in the robustness checks when the support values are divided by two or multiplied by two for all the crops and regions). This value lies in the upper range of those found in the microeconometric literature. It aligns with the utilization of aggregated data and the consideration of the diversity of agricultural outputs. We note that the latest microeconomic attempts in France find comparable elasticities (Fadhuile et *al*., 2016). Moreover, we find that the pesticide demand for cereals is more inelastic than for other crops (Table 3). Our estimated elasticity for cereals is indeed close to the median of previous estimations (Böcker and Finger, 2017) that usually focus on these outputs. We find higher own price elasticities for other categories, particularly for corn silage. Such high levels of elasticities have been estimated in the past for cereals and aggregated agricultural outputs (Carpentier and Weaver, 1997, Chambers and Lichtenberg, 1994, Chen et *al*., 1994), but they lie in the upper range of those found in the literature (Böcker and Finger, 2017). The literature rarely estimates pesticide elasticities for corn silage and other crops, which complicates the verification of our results. However, these discussion on crop-specific elasticities may be complicated as the crop-specific parameter $b_{1,k,r}$ is not precisely estimated, implying that our crop-specific input demands are neither not precisely estimated. The joint estimation of such parameters using the farm-scale equation (10) is always a tricky task (Carpentier and Letort, 2012) and even more so when there is a limited number of observations. We find that the other crops category represents the largest share of pesticide expenditures and the fodder crops the smallest share, which is consistent with the agronomic literature (Urruty et *al*., 2015, IONOSYS, 2016a, PEREL, 2015). Less consistent is our finding that the shares of pesticide expenditures for cereals and industrial crops are similar, implying a per-hectare application for cereals that is low. However, this does not raise any doubts regarding the sign and level of the aggregated elasticity, which is significantly different from 0 at the 5% level, or the fact that crop-specific pesticide demand is sensitive to pesticide prices (see table 2).

We also compute the price elasticities of crop yields. Our estimated crop yield elasticities are consistent with the economic literature, with lower levels for cereals and higher levels for industrial crops. We find that the highest yield elasticities are for corn silage, which may indicate that a higher price in the previous period (i.e., the anticipated price is higher) corresponds to a lack of fodder for livestock feeding. Finally, we find that the acreage elasticities are lower than the yield elasticities, which is consistent with Carpentier and Letort (2012). This result illustrates that it is more difficult for farmers to modify their acreage than to modify their practices at the intensive margins.

Overall, our econometric results show that crop and input prices influence farmers' decisions, which aligns with the assumption that regional farm optimize at the aggregate scale. Our results imply that a pesticide tax will effectively modify pesticide use, which is the aim of our tax scenario in the simulation exercise. We also find a significant positive yield trend for cereals and industrial crops, possibly capturing technical progress. In our second technological scenario, we explore the impacts of increasing R&D efforts to reduce pesticide use.

3. CGE policy simulations

All public policies have some direct and indirect effects on economic and environmental indicators. The indirect effects are generally more difficult to measure but may eventually counterbalance the direct ones, leading to complex policy debates. Global economic models are the inescapable tools for measuring these effects when considering major change in public policies. Below, we elaborate on the GTAP-Agr framework, which has been utilized to assess the indirect effects of several agri-environmental policies, including those that affect the use of biofuel (Hertel et *al*., 2010), Genetically Modified Organisms (Mahaffey et *al*., 2016) and organic farming (Bellora et Bureau, 2016) and a ban on glyphosate (Brookes et *al*., 2017).

3.1. The starting GTAP-Agr framework

The GTAP-Agr framework is a comparative static CGE model accounting for a large diversity of goods produced by many sectors (Keeney and Hertel, 2005). This framework covers the world and considers the heterogeneity of climatic and topographic conditions, distinguishing between several agro-ecological zones within each country. The GTAP-Agr model distinguishes firms, which maximize their profits, and households, which maximize their utility. By default, this model assumes that economic agents are price takers. The GTAP-Agr model departs from a textbook CGE model mostly due to its rich specification of agricultural and food sectors and markets. Pervasive farm policies are also finely modelled; the specificities of farm production and food consumption are captured by nested structures of globally regular production/utility functions.

The GTAP-Agr model relies on the GTAP database, which compiles social accounting matrices for many countries. The quality of this database continuously improves and is beneficial for several types of global economic analysis (Corong et *al*., 2017). The last available database covers the 2011 economic flows. This GTAP database includes 20 agricultural and food products and explicitly considers land as a primary factor of production. This database is also well suited for measuring carbon emissions linked to land use changes. The GTAP database distinguishes energy crops and livestock products, which are responsible for some greenhouse gas (GHG) emissions.

3.2. The specifications of the French economy

The GTAP-Agr framework cannot be directly used to perform simulations of French pesticide policies, in particular because pesticides are not isolated from the other variable inputs used by the agricultural sector. One strategy consists of tailoring policy shocks into the model structure (for example, Brookes et *al*. introduce taxes on chemicals, labour, capital and also land productivity shocks to assess the impacts of a glyphosate ban). This strategy is easy to implement in the CGE framework, but it does not explicitly reflect the response of economic agents to the policy. The second strategy consists of modifying the model structure, with product/factor disaggregation and economic specifications that differ by country (for example, Adams et *al*., 1997). We pursue this strategy by developing new specifications for the French economy inside the GTAP-Agr framework. We built a new social accounting matrix for the French economy using 2011 economic data. We start with the macroeconomic tables produced by the INSEE. Fortunately, French trade data are similar to the GTAP-Agr trade data. Then, we disaggregate the farm and food sectors using additional statistical information provided by the French Ministry of Agriculture, including the agricultural economic accounts. Information on farmers' use of pesticides is obtained from these economic accounts. We assume that these pesticides are offered by a perfectly competitive, multi-product chemical industry. This industry also offers mineral fertilizers. However, we do not isolate pesticides used by non-farmers due to missing economic values.

In regard to economic specifications applied to the farm sectors, we depart from the standard nested CES/CET specifications implemented in the GTAP-Agr framework. Rather, we implement the supply/demand equations described in the previous section. Specifically, we build a quadratic production function for each crop and an entropic cost function that governs land allocation (indeed this approach is locally similar to the standard CET specification). The price parameters of these production/cost functions are calibrated using the national econometric elasticities calculated in the previous section. Pesticide use by crops is not estimated with great precision. We rely on the technical literature (IONOSYS 2016a, 2016b, PEREL, 2015) to provide initial value shares. For the three animal activities that we explicitly isolate (livestock, pigs and poultry) we proceed similarly. We construct a quadratic production function for each type of animal activity. The level of production depends on the level of use of different feeds (cereals, oil meals, maize fodder, other fodder, and compound feeds). We also construct an entropic cost function that specifies the number of animals. Here, we obtain the price responses from a literature review, adopting a substitution elasticity of 0.5 for feed commodities (Suh and Moss, 2016).

3.3. Results of the tax scenario

We first simulate the economic and environmental impacts of an ad valorem tax of 50% on pesticides, assuming that the deep parameters are policy invariant. This tax level approximates the current level operated in Denmark. Moreover, according to our estimated price elasticity of pesticides, this tax should reduce French pesticide use by approximately 40*% ceteris paribus*, which is close to the objective of the initial Ecophyto plan defined in 2008.

We indeed find that this tax would decrease farmers' use of pesticides by 37%. The difference is explained by crop price effects (see below). Table 4 below reports the evolution by crops and the main impacts on the French market. The obtained reductions are consistent with our elasticities. The application of pesticides to cereal areas declines the least (by 17%), which translates into lower wheat yield and production. This subsequently creates a shortage in the world wheat market and increases French wheat prices. This output price effect slightly mitigates the direct impact of the pesticide tax on yield and production. Overall, French wheat production declines by 4%. The impact of the pesticide tax on the oilseed sector is greater due to both higher initial applications of pesticides and higher price sensitivity: French oilseed production declines by 9%. It also appears that the application of pesticides on corn silage nearly disappears (reduction by 86%). This result is consistent with our previous estimated elasticity (where the highest elasticities for pesticide application concerned the maize) and again, the assumption of policy-invariant deep parameters. The market price of corn silage increases significantly (by 14%), thus limiting the reduction of corn silage production through an acreage effect. Corn silage areas slightly increase (by 3%) to the detriment of cereal areas. Because the application of pesticides is initially low on other fodder areas, the introduction of the pesticide tax has a limited effect on their production. We still obtain a significant increase in the price of other fodder (by 6%), which is pushed up by the corn silage price (i.e. its closest substitute for livestock feeding). The areas devoted to wine, fruits and vegetables are also nearly unchanged, and their production declines, which is similar to the yield effects (by 1%).

Table 4: French market impacts of the tax scenario (in % with respect to the observed values in 2011 expressed in euros). The tax level represents 50% of the 2011 pesticide price.

	Area	Yield	Production	Price	Pesticide use
Wheat	-0.8	-2.7	-3.5	0.9	-17.1
Oilseed	0	-9.4	-9.4	1.7	-61.7
Sugar beets	1.5	-6.9	-5.4	4.2	-56.5
Forage maize	2.7	-11.1	-8.4	13.7	-85.9
Grasslands	0	-2	-2	5.6	-42
Beverages	0	-0.8	-0.8	0.3	-49.6
Vegetables and fruits	0	-1.4	-1.4	0.4	-49.5
Milk			-1.6	1.7	
Cattle meat			-1.9	1.2	
Pork meat			-1.4	1.3	

Interestingly, we find that our tax scenario has a non-marginal impact on the animal sectors. The French production of milk, cattle, pigs and poultry declines between 1% and 2%, due to less fodder availability and the higher prices of other feeds (including oil meals, by 1%). As a consequence, the animal market prices increase due to the higher production costs.

The French final consumption of food products is assumed price and income inelastic. We thus observe a very limited decrease in French food consumption (0.2% for dairy and meat products). The reduction in French food production is thus compensated by trade flows (table 5). We find significant decreases in French exports (up to 9% for sugar and rapeseeds) and significant increases of French imports (up to 14% for sugar and 7% for soybeans). These trade impacts enhance farm and food production in other countries. We obtain the largest production impacts in other EU member states (production of oilseeds and sugar increases by nearly 1%, see table 5). The impacts on third countries are more limited, due to import protections and preferences (captured using the standard Armington model for trade flows). The positive impact on animal production is only discernible for other EU member states.

Table 5: World market impacts of the tax scenario (in % with respect to the observed levels for 2011)

	French exports	French imports	USA production	Brazil production	Rest EU production
Wheat	-5.5	6	0.4	0.3	0.5
Oilseed	-8.8	7.1	0.1	0.2	0.7
Meat	-1.7	4.2	0	0	0.1
Dairy products	-2.8	5.7	0	0	0.3
Sugar	-8.7	14.5	0	0.1	0.9
Vegetables and fruits	-0.8	2.3	0	0.1	0

The production impacts on other countries may seem modest in terms of percentages (Table 5), but they are consistent with the French share in the world food markets (French production represents less than 5% of world production for most products). The increase of production in other countries is the coupled result of the intensification of production and the expansion of the agricultural area. Overall, the amount of world acreage devoted to arable crops increases by 32 thousand hectares. Malaysian and Indonesian areas devoted to palm oil increase by 2 thousand hectares (to compensate for reduced French rapeseed oil production). The expansions of agricultural areas are at the expanse of pasture areas (19 thousand hectares) and lead to deforestation (14 thousand hectares). These land use changes, mostly located in Brazil and USA, lead to a “one shot” 5.7 million tons of carbon emissions. We also obtain an increase in direct carbon emissions due to the increased use of chemicals in other countries (by 0.9 million tons) and reduced carbon stored in biomass (by 2.1 million tons). Overall carbon emissions increase by 8.8 million tons, which represents roughly 10% of the annual carbon emissions from French agricultural sector (Pellerin et *al.*, 2017). The reduction in worldwide animal consumption (due to the increase of the animal product prices) is not sufficient to counterbalance the carbon emissions related to land use changes and crop intensification in other countries.

Therefore, it appears that the French pesticide tax does not solve the trade-off problem between French pesticide use and (global) climate change at the global level.[4] At the French level, we

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[4] We are not able to accurately measure the increasing use of pesticides in other countries as the GTAP database does not distinguish pesticides from other chemical products. However, a good approximation is given by the total use of chemical products for farming activities in other regions because price effects are limited in those countries. This total use increases by 0.08%. Given that our tax scenario leads to a 37% reduction in French pesticide use, the world use of pesticides for farming very likely decreases, benefiting the health of the average food consumer.

also obtain an increase in nitrogen surplus by 2 kg/ha.[5] Three complementary reasons explain this result. First, the total French use of mineral fertilizers slightly increases by 1%, which is mostly explained by an increase in the output prices (notably maize price). Second, French imports of oilseed products also increase (by 2% for soya meals). Third, French animal production decreases (see previous discussion), which partly compensates the increase due to the two points mentioned above.

Finally, the pesticide tax negatively affects French economic welfare. As expected, farmers are the most penalized: farm value added decreases by 638 million euros, mainly due to a 19% reduction in land prices. The food industry also suffers from the tax (by 261 million euros), as it processes fewer French farm products. On the other hand, the tax receipts of the government increase (by 859 million euros), but French consumers suffer from an increase in food prices. In total, French economic welfare, as measured by the equivalent variation, decreases by 108 million euros. It should be clear that this welfare criteria only includes the market effects captured by our CGE framework, which is not sufficient for defining the optimal pesticide policies, which should also take into account long-term human health and environmental effects (such as reduced water pollution from pesticides). More modestly, our results provide a macroeconomic assessment of some economic and environmental trade-offs that a simple pesticide tax alone cannot resolve unless a credible announcement of a significant pesticide tax could induce important technological change. This is the purpose of our technological scenario.

3.4. Results of the technological scenario

Although the current French pesticide policy is complex, its main philosophy is to avoid a punitive version and foster a positive version by supporting research and development on pesticide-saving technologies and farming practices. There are many possibilities, such as organic farming or using genetically modified (GM) crops, that have pros and cons as well as supporters and opponents. Our CGE framework with aggregated data does not permit us to individually analyse these alternatives. Golub et *al.* (2009) show how to combine detailed engineering and agronomic studies in a CGE framework to analyse GHG saving technologies. We follow their example and rely on our previous statistical results indicating that the French farm sector was able to produce more annually with the same level of variable inputs (yield

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[5] The nitrogen surplus is computed as the sum of mineral nitrogen applications and animal dejections (in nitrogen equivalent) over the UAA (CORPEN, 2006).

increasing technology). In the technological scenario, we assume that French R&D efforts are tailored to technologies and practices reducing pesticides while maintaining crop yields. We consider that these new technologies are available at no cost, illustrating the break-even of such policies.

To implement this scenario in our CGE framework, ideally, we should identify the required level of R&D expenditures and the time necessary to develop these technological improvements. However, this is clearly beyond the scope of this paper and not easy to perform with the available databases. There are indeed many economic studies on policy-induced innovations. Alston (2018) summarizes this literature and finds that there are high social payoffs for agricultural R&D investment, which implies a very significant failure of the government in terms of the provision of agricultural R&D. This author also recognizes that it is very difficult to clearly document the payoffs for different technologies. Accordingly, we simulate a very simple technological scenario where we assume that the technical change reduces pesticide use per hectare by 30% for all crops. This level is obtained from academic papers produced during the Ecophyto 1 negotiations (see the introduction). In practice, we reduce the value of the parameters $\mathbf{b}_{1,r}$ (i.e., the vector of maximum required amount of pesticides to reach the maximal yield for each output k).

Table 6 below shows the evolution by crops and the main impacts on the French market. We find that pesticides are reduced by 30% for each crop. In fact, the price effects of this scenario are very limited. The most discernible impact is a reduction in the price of sugar beets (by less than 1%). The production, acreage and yield impacts are also muted. The most notable result is a small reduction in fodder outputs and the corresponding small increase in their prices, which stems from the fact that the initial application of pesticides on these areas is smaller than applications on arable crops. Therefore, these arable crop activities become more profitable following technological improvement, leading to a small acreage reallocation. For example, the sugar beet area increased by nearly 1% while the corn silage area decreased. The reduced availability of fodder crops has a very marginal impact on livestock production (bovine production reduced by 0.01%) due to the substitution between the different types of feeds.

Table 6: French market impact of the technological scenario (in % with respect to 2011 values). The technological scenario consists in a reduction of 30% of the $b_{1,r}$.

	Area	Yield	Production	Price	Pesticide use
Wheat	0.1	0	0.1	0	-30
Oilseed	0.2	0	0.2	0	-30
Sugar beets	0.7	-0.1	0.6	-0.5	-30
Forage maize	-0.5	0.3	-0.2	0.3	-30
Grasslands	0	0	0	0.1	-30
Beverages	0	0	0	0	-30
Vegetables and fruits	0	0	0	0	-30
Milk			0	0	
Cattle meat			0	0	
Pork meat			0	0	

Because the impacts on the French output market are marginal, the world impacts are logically also very limited. For example, the world area devoted to arable crops and palm oil decreased by 0.5 and 0.3 thousand hectares, respectively (because French sugar beet and oilseed output both increase). There was only a small increase in global pasture areas (by 0.9 thousand hectares) and no distinguishable effect on forest areas. These limited land use changes lead to marginal carbon saving in soils. In fact, the main carbon impact is savings from chemical production activities. In total, this carbon emission is reduced by 0.2 million tons in this scenario. At the French level, we find no impact on nitrogen surplus. The very limited decrease in nitrogen exports caused by the increase in animal production is compensated by the reduction in French imports of protein crops. Finally, this scenario improves the economic welfare of French farmers (by 829 million euros) and marginally, that of the food industry (by 12 million euros). As we assume that the technological improvement is a free lunch, the expenditures of the French government remain stable. French consumers benefit from slightly lower prices (primarily for sugar and vegetable oils). In total, French economic welfare increases by 1611 million euros. This level is higher than the initial reduction in pesticide expenditures (by 825 million euros) due to the general equilibrium effects on the markets that benefit the French economy (terms of trade and allocation effects). Again, this level does not take into account all the health and environmental impacts induced by the reduced level of French pesticide applications and only provides an indication of the value of R&D expenditures that could be devoted to reduce the application of pesticides by 30%.

4. Concluding remarks

Pesticide use by farmers has generated a growing debate in France regarding its economic, environmental and health impacts. This paper contributes to these debates by offering an original macroeconomic quantification of some of the economic and environmental impacts. First, we statistically identify the influence of prices on pesticide use for all farm activities over the last 25 years. We find that the prices of crops and pesticides influence their use in many French regions and for many crops. The overall estimated own-price elasticity of pesticide demand amounts to -0.8, pesticide application on cereals being less price sensitive than other crops. This estimation lies in the upper range of the literature but is coherent with other estimates based on aggregate data (Böcker and Finger, 2017). Second, we simulate the market and welfare effects of two very different and thus illustrative reforms of French pesticide policy. Our CGE simulations, that account for the market adjustments, show that a 50% tax on pesticides will reduce French farmers' pesticide consumption by 37%. This reduction would, however, have some side effects. The French farm and food industry would lose nearly 1 billion euros annually, and the nitrogen surplus would increase by 2 kg/ha. Moreover, world net carbon emissions would increase by approximately 9 million tons, mostly due to land use changes in other countries. Some deforestation would occur in some Latin American countries. These emissions represent roughly 10% of the annual carbon emissions from French agricultural sector (Pellerin et al., 2017). We also find that the French animal sector would be significantly affected, mainly through less fodder availability.

We find that our second technological policy scenario solves these economic and environmental trade-offs, but such a scenario could only emerge in the long run due to inevitable innovation delays. Indeed, this second illustrative scenario relies on the crucial assumption of free-lunch new technologies. It might be that some alternative technologies are not implemented because they require some costly and specific investments in machines or knowledge. Our analysis is indeed limited by the quality of our databases: information on farm labour and capital devoted to crop protection are not easily accessible. It would be interesting for future research to gather these information. A more detailed representation of the production processes, such as the distinction of several pesticides (herbicides, fungicides and insecticides) or the consideration of biological processes (organic farming and crop rotation), would also improve our macroeconomic assessment (Chavas et *al*. 2010).

In the meantime, our analysis shows that French regulators are faced with economic and environmental trade-offs. We contribute by quantifying these trade-offs to help regulators sort out the lobbies’ arguments. We highlight that a significant tax on pesticides would have side effects on several dimensions. However, these negative side-effects do not mean that regulators should maintain the existing legislative context. In contrast, it means that a pesticide taxation scheme could effectively reduce pesticide use, but other instruments should be jointly implemented to limit these side-effects.

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Appendices

Table A1: Response parameters to pesticide prices with support values divided by two

	cereals	**industrial crops**	**maize forage**	**other fodders**	**other crops**
Ile de France	0.31	0.88	0.71	0.34	15.78
Champagne Ardennes	0.65	1.12	0.76	0.30	13.70
Picardie	0.56 **	1.63 **	0.66	0.65	7.40 **
Haute Normandie	0.69 **	0.96 *	0.54	0.34	8.45 *
Centre	0.32	0.44	0.43	0.27	5.38
Basse Normandie	0.68 *	1.00	0.53	0.14	7.72
Bourgogne	0.48 *	0.34	0.75	0.21	8.30
Nord pas de Calais	0.59 *	2.41 **	0.54	0.54	2.13
Lorraine	0.03 **	0.05 **	0.05	0.00	0.70
Alsace	0.64 **	1.67	0.90	0.41	10.79
Franche comté	0.39 *	0.38	0.98	0.29 **	13.91
Pays de la Loire	0.48 **	0.56 **	0.41	0.18	5.72 **
Bretagne	0.23	0.72 *	0.54	0.28 *	4.36 **
Poitou Charentes	0.54 **	0.26	0.51	0.41 *	4.50 **
Aquitaine	0.94 **	0.37	0.45	0.24	2.67 **
Midi Pyrénées	0.45 **	0.20	0.50	0.24 **	2.79 **
Limousin	0.38 *	0.67	0.45	0.03	2.34
Rhône Alpes	0.95 **	0.68	0.76	0.15 **	1.26 *
Auvergne	0.53 **	0.45	0.67	0.01	6.33 *
Languedoc Roussillon	1.21 *	0.45	0.35	0.23 *	1.12 **
PACA	1.45 **	1.25	0.16	0.11	7.02 **

** and ** represent the 10% and 5% significance levels, respectively.*

Table A2: Response parameters to pesticide prices with support values multiplied by two

	cereals	industrial crops	maize forage	other fodders	other crops
Ile de France	0.12	0.97 *	1.07	0.50	12.82
Champagne Ardennes	0.46	1.44 *	1.17	0.21	9.33
Picardie	0.28	2.16 **	0.81	1.03	6.89 *
Haute Normandie	0.47 *	0.96 *	0.62	0.69	9.66 **
Centre	0.15	0.54 *	0.55	0.30	4.28
Basse Normandie	0.52	1.21 *	0.61	0.09	9.02 *
Bourgogne	0.33	0.23	1.30	0.22	7.04
Nord pas de Calais	0.40	3.11 **	0.69	0.77	0.70
Lorraine	0.03 *	0.05 **	0.10 **	0.00	1.50 *
Alsace	0.51 **	1.84	1.18	0.54	8.85
Franche comté	0.24	0.33	1.32 *	0.34 **	18.95
Pays de la Loire	0.42 **	0.75 **	0.56 **	0.13	5.75 **
Bretagne	0.12	0.92 **	0.59	0.22	3.73 *
Poitou Charentes	0.28	0.11	0.70	0.63 **	6.53 **
Aquitaine	0.82 **	0.24	0.50	0.37 **	1.83 *
Midi Pyrénées	0.24	0.07	0.81	0.36 **	2.79 *
Limousin	0.28	1.10	0.57 **	0.01	1.73
Rhône Alpes	0.90 **	0.76	1.14	0.13 *	0.72
Auvergne	0.42 **	0.35	1.06 **	0.00	7.15 *
Languedoc Roussillon	1.67 **	0.70 *	0.56	0.34 **	0.59
PACA	1.74 **	1.48	0.23	0.20	6.83 **

** and ** represent the 10% and 5% significance levels, respectively.*

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