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How do farmers manage their biodiversity through time? A dynamic acreage allocation model with productive feedback

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**Contribution presented at the XV EAAE Congress, “Towards Sustainable Agri-food Systems:
Balancing Between Markets and Society”**

August 29th – September 1st, 2017

Parma, Italy



**UNIVERSITÀ
DI PARMA**



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Abstract:

Previous studies on productive value of biodiversity underlined the fact that crop diversity increases crop yields. Here, we focus on the management of crop diversity for wheat, winter barley and rapeseed productions, what we call biodiversity productive capacity. We introduce biodiversity productive capacity into a structural dynamic model with supply, variable input demand and acreage functions. We estimate the model on a sample of French farms from 2007 to 2012. We highlight that biodiversity indicators influence the yield of crops and variable input uses. We find evidences that farmers manage their acreage in order to benefit for biodiversity productive capacity.

Keywords: Dynamics; Ecosystem services; Land-use; Crop Diversity

JEL classification: Q12; Q24; Q57; D92

Acknowledgements

This research was funded by the EU's Horizon 2020 program under grant agreement n°633838 (PROVIDE project, <http://www.provide-project.eu/>). This work does not necessarily reflect the view of the EU and in no way anticipates the Commission's future policy.

1 Introduction

It is widely recognized that human activities and especially modern agriculture have negative impacts on biodiversity (MEA, 2005). Simplification of habitat, from natural areas to arable lands (and monoculture), has decreased biodiversity levels. Because biodiversity contributes greatly to the ecosystem functioning, this loss threatens the provision of valuable ecological functionalities. It is a crucial issue for our society but also for the sustainability of agriculture. Indeed, these functionalities are at the basis of supporting ecosystem services, which provide suitable agricultural production conditions (MEA, 2005). Few authors have underlined the productive value of biodiversity for crop farms (see Di Falco, 2012 for a review). These authors have usually estimated the effects of biodiversity, measured by biodiversity indicators, using primal production functions or a reduced form of profit functions. Because direct indicators which measure species density in point maps (e.g. Gregory et al., 2005) are often unavailable in database, indirect indicators based on land-use, as crop diversity, are usually computed. This approach is highly influenced by landscape ecology which postulate that landscape structure, defined by both its composition and configuration, determine species dynamics and thus biodiversity density (Burel and Baudry, 2003). These indicators indicate the level of ecosystem services at the farm scale. From our point of view, this literature emphasizes two main empirical results. First, the crop diversity increases mean yield and reduces variance yield. This has lead authors to consider both a productive value of biodiversity (Chavas, 2009) and an insurance value of biodiversity (Baumgärtner, 2007). Second, crop diversity of previous year increases current production (Di Falco and Chavas 2008). This result suggests that productive effects of biodiversity persist over time.

Thus, biodiversity level, measured by crop diversity, depends on current and past acreage decisions. In this case, a dynamic model is necessary to represent production and acreage decisions. Here, we propose a dynamic acreage model considering that farmers manage their biodiversity as a capital. In the same way as firms take some investment decisions to benefit from productive capacity of capital, we consider that farmers take their cropland decisions to take advantage of the productive capacity of biodiversity. Thus, our objective is not only to evaluate the productivity of biodiversity, but also to confirm that farmers make cropland decisions with the aim of maintaining their current and future productive capacity. Compared to the other studies interested in biodiversity productivity, we take the analysis further, considering farmers' behavior in terms of land allocation. This may be relevant especially for the impact analysis of economic incentives on biodiversity management, and for the evaluation of agro-environmental measures designed to maintain and promote biodiversity.

To our knowledge, few papers have considered the dynamics of acreage allocation within a dynamic theoretical farm-level model. An exception is the work of Orazem and Miranowski (1994) who build a dynamic model of acreage allocation. They assume that farmers make their acreage allocation decisions conditional on their current stock of soil capital, which depends on past acreage allocation. Orazem and Miranowski consider that some crops increase future soil quality and thus have positive productivity effects. The main idea of this paper is quite close to our paper. Nevertheless, there are several key differences. First, their soil indicator is defined by crop, while our biodiversity indicator is implemented at farm level. This does not have the same meaning. Technically, their assumption leads to the soil indicator for a crop depending on the past acreage of all crops, but on the current acreage for only the crop considered. Our biodiversity indicator depends on current and past acreages of all crops. This specification is coherent with Di Falco and Chavas (2008) but complicates the derivation of acreage equations. Second, they do not consider the potential effects of soil quality on input use. This obliges them to impose identifying restrictions and leads to less efficient estimation of parameters associated to the productive effects of soil quality. Here, we propose to estimate together acreage, input application and output supply equations.

Another interesting paper is Thomas (2003) who presents a dynamic model of nitrogen management at farm level. He considers that farmers manage their soil fertility through fertilization application decisions and crop rotation decisions. Thomas (2003) measures farmers' fertilizer application decisions considering that farmers take account for nitrogen accumulation, i.e. for nitrogen stock available for the next period and resulting from current production decisions. Like Orazem and Miranowski (1994), Thomas (2003) provides a framework to explain crop rotation decisions with a temporal lag in the acreage decisions. Although his dynamic optimization program is quite similar to ours, the theoretical model differs on three main points. First, he focuses on the effect of nitrogen stock on fertilizer decisions. He does not consider the productive effects from crop rotations on soil quality such as biological control. Second, its state variable, the carry-over-nitrogen, is a function of past nitrogen levels over plots and does not depend on current acreage decisions. Third, he assumes that farmers can instantaneously adjust their land allocation, while Oude Lansink and Stephanou (2001) show that area adjustments are quite slow.

Indeed, Oude Lansink and Stephanou (2001) propose a dynamic model of acreage allocation in order to derive dynamic measures of scope and scale economies. Contrary to Orazem and Miranowski (1994) and Thomas (2003), they do not estimate a structural model and rely on the estimation of reduced form equations. The originality of their acreage model is the presence of adjustment costs. They consider that output-specific areas evolve over time, and that these area adjustments are costly.

These costs are often associated with the under-utilizing of fixed inputs or with the reorganization of the farm operation. Adjustment costs have already been used in investment and employment literature, which interpret these costs as adjustment costs of a capital and/or labor. The adjustment cost function captures the fact that productivity effects of quasi-fixed inputs are not instantaneous, because producers incur additional costs in adjusting their stock of capital or labor. To our knowledge, adjustment costs for land allocation were only considered in Oude Lansink and Stefanou (2001). Carpentier and Letort (2012, 2014) used a similar cost function within a static multi-output acreage allocation model. In this case, these costs are interpreted as the implicit costs linked to the management of both crop rotation constraints and quasi-fixed input constraints.

Our work is also based on the concept of adjustment costs for land allocation, but our modelling is different on one important point. In Oude Lansink and Stefanou (2001)'s work, the long-term productive effects of crop diversity are captured by the cost function. Indeed, their dual approach does not allow them to differentiate these productive effects from the adjustment costs associated with adjusting areas. Similarly, utilization of the implicit cost function in the static acreage literature does not allow examining the beneficial effects of crop diversification. Our framework allows disassociating the benefits and the costs of crop diversification. Another interesting feature of our model is that we use the primal approach which allow the explicit specification production and adjustment costs functions. Primal approach can be useful to test different alternative specification as Gardebroek and Oude Lansink (2004, 2008) within a dynamic investment model, or to study environmental problems as Femenia and Letort (2016) within a static land allocation model. In our model, the specification of production technology allows us explicitly analyzing the impacts of biodiversity productive capacity on output yields.

The next section presents the theoretical model and a discussion on its economic interpretation. In the third part, we propose an empirical counterpart to this theoretical framework. A set of output supply and inputs demand equations and first order conditions of acreage choices are estimated on a sample of French farms from 2007 to 2012. The fourth part presents the results. The last section concludes.

2 The dynamic model of acreage decisions

In this paper, we consider biodiversity productive capacity as a quasi-fixed input. Inspired from the investment literature, we develop a model combining a primal multi-output farm model with specific dynamics of quasi-fixed inputs. The multi-output farm model is presented in the first part. The dynamic framework is described in the second one.

2.1. The multi-output model of acreage decisions

The modelling framework is based on a price-taker farmer who maximises its total restricted profit function Π_t . The farmer produces multiple outputs ($k = 1, 2, \dots, K$) for which he chooses the optimal quantity of variable inputs and the optimal allocation of land given the amount of fixed inputs application given their price and production anticipations.

Total restricted profit function of year t is defined as the sum of the gross margins per hectare π_{kt} of each output k multiplied by their respective acreage s_{kt} share minus a cost function $C(\mathbf{s})$ depending on acreage allocation:

$$\Pi_t(\mathbf{x}_t, \mathbf{z}_t, B_t, \mathbf{s}_t) = \sum_{k=1}^K s_{kt} \pi_{kt}(B_t, \mathbf{x}_{kt}, \mathbf{z}_t) - C_t(s_{1t}, \dots, s_{Kt}) \quad (1)$$

With the cost function $C_t(\mathbf{s})$ assumed to be convex in \mathbf{s} . In a static framework, farmers choose their acreage according the following optimization problem:

$$\max_{s_k} \Pi_t(x_{ikt}, z_{lt}, B_t, s_{kt}) \quad \text{s.c.} \quad \sum_{k=1}^K s_{kt} = 1 \quad (2)$$

The gross margin π_{kt} of output k is derived from this following optimization problem:

$$\pi_{kt} = \max_{x_{ikt}} \left\{ \begin{array}{l} p_{kt} y_{kt} - \sum_{i=1}^I w_{it} x_{ikt} \\ \text{s.t. } y_{kt} = F_{kt}(B_t, \mathbf{x}_{kt}, \mathbf{z}_t) \end{array} \right\} \quad (3)$$

where y_{kt} is the yield of the output k per hectare, x_{ikt} ($i = 1, 2, \dots, I$) is the quantity of variable input i applied for output k per unit of land at time t , z_{lt} ($l = 1, 2, \dots, L$) is the quantity of fixed input l at time t and B_t is the biodiversity indicator. $F_{kt}(B_t, \mathbf{x}_{kt}, \mathbf{z}_t)$ is the production function that is non-decreasing in \mathbf{x}_{kt} and strictly concave in \mathbf{x}_{kt} .

This model has two interesting features. First, it relies on a primal approach. Contrary to dual models, primal models allow a precise specification of the technology which is well-suited to the analysis of environmental problems (Femenia and Letort, 2016). Here, the specification of production technology allows us analyzing productivity of biodiversity. We consider one biodiversity indicator based on crop diversity. Crop diversity improves several ecosystem services (Hennessy, 2006) such as nutrient stock, soil structure (Mäder et al., 2002), pollination (Kennedy et al., 2013) and biological control (Letourneau et al., 2011).

The second interesting feature is the utilization of cost function in the total profit function. This kind of cost function has already been used in investment and employment literature. Authors interpret it as adjustment costs linked to quasi-fixed input management. They capture the non-instantaneous nature of profitable effects of quasi-fixed inputs. To our knowledge, adjustment costs for land allocation were only considered in Lansink and Stefanou (2001). Based on a dual model, they have analyzed the economies of scale and scope in Dutch farms. They found that farmers have incentives for specialization but that high adjustment costs prevent them to do so. Carpentier and Letort (2012) used a similar cost function within a static multi-output acreage allocation model. They interpret these costs as the implicit costs linked to the management of crop rotation and quasi-fixed input constraints. Here, we use the same interpretation of the cost function. However, as we capture some crop rotation effects into the production functions, our cost function should represent mainly the farm fixed input constraints. We thus capture the benefits of crop diversification in the gross margins π_{kt} and the costs of crop diversification in the cost function.

In addition, the adjustment cost model offers a methodological advantage. In the investment literature, it provides a simple dynamic theoretical framework for the determination of outputs and inputs, preventing an immediate adjustment. This type of model allows us to integrate dynamics in a simple way. We present the dynamic framework in the next part.

2.2. The dynamic framework

Productivity of biodiversity can be assess within a static model but biodiversity levels will be misjudged because land-use dynamics is not considered. Indeed, acreage decisions affects biodiversity dynamics and thus biodiversity levels in the future (Di Falco and Chavas, 2008). We thus need to consider that farmers maximize their acreage decisions, taking into account that their acreage decisions impact current and future biodiversity productive capacity levels. Here, we assume that farmers maximize the expected value of the stream of future discounted profits over the whole period:

$$\max_{s_t} E_t \left\{ \sum_{t=1}^T \left(\frac{1}{1+r_t} \right)^{t-1} \Pi_t(\mathbf{x}_{kt}, \mathbf{z}_t, B_t, \mathbf{s}_k) \right\} \quad (4)$$

Where $j = [1,2]$, r_t is the interest rate for period t and where biodiversity j evolves according to:

$$B_t = (1-\delta)B_{t-1} + g(s_{kt}) \quad (5)$$

And

$$\sum_{k=1}^K s_{kt} = 1 \quad (6)$$

We propose a capitalistic dynamic form for the biodiversity equations. Biodiversity productive capacity in t depends on current acreages (in t) but also on past acreages (years before t). The $g(\cdot)$ function is the biodiversity indicator that depends on s_{kt} . Farmers can manage this part each year. The $(1-\delta_t)$ term represents the inherited part of the biodiversity productive capacity from years before t . They depend on past acreage choices. Farmers cannot manage this part in t . Like the depreciation rate on the investment literature, we consider that the δ_t term ranges between 0 and 1. In the extreme case where $\delta_t = 1$, the past acreage decisions have no effects on current production. In the case where $\delta_t = 0$, past acreage decisions have the same effects on current production than current acreage decisions. Equation (5) assumes that farmers manage their acreages in order to benefit from current and future productive effects at the same time. Previous researches have highlighted beneficial effects of biodiversity on production over more than two years even if these effects decreased in time (Hennessy 2006, Di Falco and Chavas 2008). On the technical side, we can explain the positive productive effects of current acreage diversification by the biological protection and the net primary productivity enhancement, while positive effects of past acreage diversification capture the effects of crop rotation. In this case, the productive effects of current acreage can be interpreted as a spatial choice and the productive effects of past acreage as a temporal choice.

Let $V_t(B_t)$ be the maximum value of the function in (4) at the period t where B_t is the state variable of the model. According to the maximum principle, the dynamic optimization problem can be resolved using the Bellman equation:

$$V_t(B_t) = \max_{s_t} E \left\{ \Pi_t + \frac{1}{1+r} [V_{t+1}(B_{t+1})] \right\} \quad (7)$$

Equation (7) illustrates the inter-temporal problem faced by farmers. The first-order conditions associated with the maximization of $V_t(B_t)$ according to x_{ikt} is, for inputs $i = 1, \dots, I$ and for output $k = 1, \dots, K$ are defined by:

$$p_{kt} \frac{\partial F_{kt}}{\partial x_{kt}} - w_{kt} = 0 \quad (8)$$

For optimal levels of B_t , farmers apply variable inputs such that the marginal cost of the last applied input unity equals its marginal benefit. The calculation of first order conditions for acreage decisions

are more complex. Farmers have to optimize s_{kt} according to past acreage choices and anticipating their marginal effect on $V_{t+1}(B_{t+1})$. The first order conditions for acreage are defined by:

$$\frac{\partial V_t}{\partial s_{kt}} = \frac{\partial \Pi_t}{\partial s_{kt}} + \frac{1}{1+r} E \left[\frac{\partial V_{t+1}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt}} \right] = 0 \quad (9)$$

$$\text{With } E \left[\frac{\partial V_{t+1}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt}} \right] = \frac{\partial \Pi_{t+1}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt}} + \frac{1}{(1+r)} E_t \left[\frac{\partial V_{t+2}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt}} \right] \quad (10)$$

Because of $\frac{\partial B_t}{\partial s_{kt-1}} = (1-\delta) \frac{\partial g(s_{kt-1})}{\partial s_{kt-1}} = (1-\delta) \frac{\partial B_t}{\partial s_{kt}}$, we have:

$$E \left[\frac{\partial V_{t+1}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt}} \right] = (1-\delta) \frac{\partial \Pi_{t+1}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt+1}} + \frac{(1-\delta)}{(1+r)} E \left[\frac{\partial V_{t+2}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt+1}} \right] \quad (11)$$

Finally, following a recursive reasoning, we obtain:

$$E \left[\frac{\partial V_{t+1}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt}} \right] = \sum_{i=1}^{\infty} \frac{(1-\delta_j)^i}{(1+r)^{i-1}} E \left[\frac{\partial \Pi_{t+i}}{\partial B_{t+i}} \frac{\partial B_{t+i}}{\partial s_{kt+i}} \right] \quad (12)$$

The first order condition for acreage choice s_{kt} is then:

$$\frac{\partial \Pi_t}{\partial s_{kt}} + \sum_{i=1}^{\infty} \frac{(1-\delta_j)^i}{(1+r)^i} E \left[\frac{\partial \Pi_{t+i}}{\partial B_{t+i}} \frac{\partial B_{t+i}}{\partial s_{kt+i}} \right] = 0 \quad (13)$$

$$\text{with } \frac{\partial \Pi_t}{\partial s_{kt}} = \pi_{kt} + \sum_{j=1}^k s_{jt} \frac{\partial \pi_{jt}}{\partial B_t} \frac{\partial B_t}{\partial s_{kt}} - \frac{\partial C_{kt}}{\partial s_{kt}} \quad (14)$$

$$\text{and } \frac{\partial \Pi_{t+i}}{\partial B_{t+i}} \frac{\partial B_{t+i}}{\partial s_{kt+i}} = \sum_{j=1}^K s_{jt+i} \frac{\partial \pi_{jt+i}}{\partial B_{t+i}} \frac{\partial B_{t+i}}{\partial s_{kt+i}} \quad (15)$$

To interpret the equation (13), let us compare the first order conditions of acreage in different models.

In a static framework, as in Letort and Carpentier (2012), the conditions become:

$$\pi_{kt} = \frac{\partial C_{kt}}{\partial s_{kt}} \quad (16)$$

In this case, the optimal acreage for crop k is obtained when its gross margin (depending only on variable inputs) is equal to its marginal cost of adjustment.

In a static framework with a productive effect of biodiversity as defined by Di Falco and Perrings (2005) or Di Falco and Chavas. (2006 and 2009), we have these conditions:

$$\pi_{kt} + \sum_{j=1}^k s_{jt} \frac{\partial \pi_{jt}}{\partial B_t} \frac{\partial B_t}{\partial s_{kt}} = \frac{\partial C_{kt}}{\partial s_{kt}} \quad (17)$$

In this case, the marginal benefit of one additional unit of area k is defined as the gross margin of crop k plus the marginal profitability of biodiversity productive capacity linked to the reorganization of total acreage on the other outputs. These effects include the productivity of biodiversity and the variable input savings due to biodiversity productive capacity. These marginal benefits should be equal to marginal cost of adjustment. Comparing our approach with acreage literature (e.g. Carpentier and Letort, 2012), relation (17) illustrates the separation of the beneficial effects of crop diversity from the implicit cost function. Relation (17) also illustrates the importance for the literature on the productivity of biodiversity to consider the impact of adjustment costs to explain biodiversity levels at the farm scale.

In our dynamic framework, the conditions are defined by:

$$\pi_{kt} + \sum_{j=1}^k s_{jt} \frac{\partial \pi_{jt}}{\partial B_t} \frac{\partial B_t}{\partial s_{kt}} = \frac{\partial C_{kt}}{\partial s_{kt}} - \frac{(1-\delta)}{(1+r)} \left[\sum_{j=1}^K s_{jt+1} \frac{\partial \pi_{jt+1}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial s_{kt+1}} \right] \quad (18)$$

These conditions state that the marginal revenue per hectare for crop k at time t (equals to gross margin of crop k plus the marginal profitability of biodiversity productive capacity) should be equal to marginal cost adjustment minus the discounted expected marginal value of biodiversity gain at time $t+1$ (considering two periods). In other terms, farmers take into account the future productive effects of biodiversity in making their current acreage decisions. Considering the discounted expected marginal value of biodiversity gain at time $t+1$ as the future benefits of current biodiversity productive capacity, relation (18) can also be interpreted as the equality between adjustment costs due to current acreage and the sum of the current and future benefits due to current acreage.

3 The empirical model

In this section, we propose an empirical counterpart to the theoretical framework. The data and the sample used for the application are described in the first sub-section. The set of estimated equations composed of output supplies, input demands and first order conditions for acreage choices are presented in the second sub-section.

3.1.Data and variables description

We use an analytical accounting dataset from a sample of farms located in the French territorial division, *La Meuse*, observed between 2007 and 2012. The dataset provides information on acreage, yields, output prices and, contrary to most of alternative French economic database, provides the variable input quantities applied per crop. Femenia and Letort (2016) use this database to estimate a static acreage model and simulate pesticide taxation policies. Because we consider dynamics of acreage choices, we select farms that are at least identified two years in a row. We explain farmers' choices on the three main crops of the region, i.e. wheat (26% of the total acreage), winter barley (14% of the total acreage) and rapeseed (17% of the total acreage). Note that permanent grasslands represent 28% of the total acreage but their evolution relies on medium to long-term strategies. To avoid corner solutions in the model, we select farms with these three outputs, providing a sample of 771 observations which represents more than 80% of the initial farm sample.

Like several cited studies, we measure crop diversity $g(s_{kt})$ with a Shannon index, *i.e.* an entropy measure based on land shares. This indicator corrects for species abundance and sample size and is well suited to measure habitat diversity (Mainwaring, 2001). We thus compute $g(s_{kt})$ as:

$$g(s_{kt}) = -\sum_{k=1}^K s_{kt} \ln s_{kt} \quad (11)$$

where s_{kt} is the land share devoted to crop k . $g(s_{kt})$ increases when habitat diversity increases, *i.e.* when biodiversity increases (Burel and Baudry, 2003). We compute the Shannon index based on all farms' outputs. They include wheat, winter barley, rapeseed, spring barley, peas, sunflower, diester rapeseed, other diester production, forage maize, potatoes and permanent grasslands. Except permanent grasslands, spring barley and forage maize which represent respectively 28%, 7.5% and 5% of the total acreage, other productions are marginal productions, each representing less than 2% of the total acreage.

Table 1 presents the description statistics of the variables used in the empirical analysis. We have deflated prices by the national consumption price index. In addition, we use regional input price indexes from the French Department of Agriculture and monthly climatic variables at the municipality level from *Météo France*¹. In order to take into account for soil heterogeneity, we also

¹ We only use climatic variables that are likely to impact crop production, *i.e.* average rainfall, temperature, solar radiation and number of frost days. We use these information to consider biological cycles of vegetation and pest, *i.e.* from February to July for crop yields and from April to June for variable input application.

use a soil condition index at the municipal level from the *Chambre d'Agriculture de Lorraine* (Hance, 2007).

Table 1: Descriptive statistics (N = 771)

	Mean	Median	Q1	Q3	Min	Max
Wheat yield (100 kg/Ha)	72.22	72.50	67.02	78.39	38.95	106.96
Winter barley yield (100 kg/Ha)	65.33	66.10	58.42	72.79	33.27	89.24
Rapeseed yield (100 kg/Ha)	33.95	34.19	29.91	38.38	7.96	49.30
Wheat price (€/100 kg)	16.15	15.95	13.03	18.51	3.82	28.32
Winter barley price (€/100 kg)	14.20	14.14	11.10	16.69	7.58	30.82
Rapeseed price (€/100 kg)	33.62	32.74	29.00	37.94	19.96	57.78
Fertilizer on wheat (constant €/Ha)	126.72	119.97	108.76	136.55	3.80	210.15
Fertilizer on barley (constant €/Ha)	110.20	103.38	95.03	118.19	3.15	211.05
Fertilizer on rapeseed (constant €/Ha)	125.72	119.46	107.62	136.47	3.54	247.84
Pesticides on wheat (constant €/Ha)	162.20	160.07	132.94	186.06	44.43	326.58
Pesticides on barley (constant €/Ha)	154.86	153.11	124.65	181.54	41.28	357.65
Pesticides on rapeseed (constant €/Ha)	217.65	214.93	183.62	249.87	63.24	423.47
Fertilizer price index	1.13	1.03	1.00	1.34	0.91	1.51
Pesticides price index	0.98	0.97	0.94	1.00	0.94	1.01
Wheat area (Ha)	53.04	46.47	32.24	68.49	9.19	169.42
Winter barley area (Ha)	28.47	24.50	16.35	37.56	4.46	94.11
Rapeseed area (Ha)	35.33	31.47	19.66	45.73	0.77	123.59
Total area (Ha)	206.87	191.76	143.34	252.40	67.43	552.41
Biodiversity index	1.53	1.53	1.41	1.65	0.95	1.93

3.2. Empirical model and econometric strategies

We explain supply, input application and acreage choices for three outputs: soft wheat ($k=1$), winter barley ($k=2$) and rapeseed ($k=3$). They are produced on areas S_1 , S_2 and S_3 . We consider two variable inputs: pesticides ($i=1$) and fertilizers ($i=2$). The specification of our model requires to impose some functional forms for production functions and adjustment cost function. We use the same forms as those employed by Carpentier and Letort (2012) and Femenia and Letort (2016). For each output k , we use a quadratic production function:

$$F_{kt}(\mathbf{x}_{kt}) = \alpha_k - \sum_{i=1}^2 \sum_{j=1}^2 0.5 \gamma_{ijk} (\beta_{ik} - x_{ikt}) (\beta_{jk} - x_{jkt}) \quad (19)$$

The advantage of this functional form is the simple interpretation of the parameters. The parameter α_k represents the maximum yield of output k , the vector of parameters $\boldsymbol{\beta}_k \equiv (\beta_{1k}, \dots, \beta_{2k})$ corresponds to the required level of variable inputs to reach the maximum yield of crop k . These two sets of parameters depend on biodiversity productive capacity B_t , soil quality and pedo-climatic characteristics m_t . The matrix $\boldsymbol{\Gamma}_k \equiv [\gamma_{ijk}]$ determines the curvature of the function. A positive definite matrix guarantees the concavity of the production function.

The adjustment cost function is approximated by the quadratic form:

$$C_t(\mathbf{s}) = g + \sum_{k=1}^K g_{0k} s_{kt} + 0.5 \sum_{k=1}^K \sum_{m=1}^K g_{km} s_{kt} s_{mt} \quad (20)$$

The terms g and g_{0k} are parameters to be estimated. The parameter g_{0k} depends on farm characteristics, such as their capital, machinery and labor endowment, and the matrix $\mathbf{G} \equiv [g_{km}]$ is symmetric. The adjustment cost functions correspond to the reorganisation of farms' fixed inputs. Because the fixed inputs are public inputs, they can be at the source of scope and scale economies. The parameters g_{km} ($k \neq m$) indicate if the farms benefit from scope economies if $g_{km} > 0$ (scope diseconomies if $g_{km} < 0$). The parameters g_{kk} indicate if the farms benefit from scale economies if $g_{kk} < 0$ (scale diseconomies if $g_{kk} > 0$).

Like Gardebroeck (2004), we assume rational price anticipation for input and output prices². Following Lucas' critique (1976), this assumption is often realized in dynamic optimization problem. Solving the farmer's optimization problem leads to input demand and output supply equations in matrix notation:

$$\mathbf{x}_{kt} = \boldsymbol{\beta}_k - p_{kt}^{-1} \boldsymbol{\Gamma}^{-1} \mathbf{w}_t \quad (21)$$

$$y_k = \alpha_k - p_{kt}^{-2} \mathbf{w}_t' \boldsymbol{\Gamma}^{-1} \mathbf{w}_t \quad (22)$$

And to first order conditions for acreage choices:

$$\begin{aligned} \pi_{kt} - \sum_{j=1}^k s_{jt} (\ln s_{kt} + 1) (p_{jt} \alpha_{1j} - \mathbf{w}_t \boldsymbol{\beta}_{1j}) - \left(g_{0k} + \sum_{m=1}^K g_{km} s_{mt} \right) \\ + \frac{(1-\delta)}{(1+r)} \left[\sum_{j=1}^k s_{jt+1} (\ln s_{kt+1} + 1) (p_{jt+1} \alpha_{1j} - \mathbf{w}_{t+1} \boldsymbol{\beta}_{1j}) \right] = 0 \end{aligned} \quad (23)$$

Based on Lansink and Stefanou (2001), we fix r_t at 0.04. This economic model fully explains the farmers' production decisions. For output k , the marginal costs (the derivation of the adjustment cost function) of area k equals its marginal benefits (the gross margin plus the current and future benefits due to biodiversity productive capacity). Production decision equations and Euler equations are typically estimated by GMM (see Hansen and Sargent, 1982) implemented in SAS software. In order to integrate the total land constraint, we choose rapeseed as crop reference. We thus estimate the

² Alternative forms of price anticipation do not change the signs of the parameter but do change the amplitude of the effects.

difference of relation (23) between wheat and rapeseed and between winter barley and rapeseed (see e.g. Femenia and Letort, 2016 for more details).

Our empirical model has potentially two main limitations. First, diversity index is not recalculated from the predicted acreage shares. The reason is we only derive and estimate the first order conditions for acreage, and not the analytical solution of acreage choices. Anyway, the GMM estimation corrects for the endogenous issue of the biodiversity indicators. Second, we do not consider the possibility of corner solutions. All farms produce the three outputs considered in the application. In addition to the standard potential problem of selection bias, this assumption limits the results concerning the biodiversity. Diversity index varies according to (i) the number of crops produced and (2) the uniform repartition of crops on total area. Given that the number of crops is fixed and cannot change over time, the variation of biodiversity index is only due to a change in allocation of land between crops.

4 Results and discussion

The estimation results are presented in a first sub-section. Some simulations of public policies are proposed in the second sub-section in order to illustrate the interest of the approach.

4.1. Estimation results

The estimation results are presented in Table 2. The R^2 of the three yield lie between 0.19 and 0.25. The quality of adjustment is significantly higher for fertilizer applications (R^2 between 0.60 and 0.70) than for pesticide applications (R^2 between 0.07 to 0.10). This issue has already been highlighted by Carpentier and Letort (2012) and reflect heterogeneity among farmers' production conditions.

Due to space limitation, estimated parameters of control variables are not reported here. However, they do display the expected signs. All yield supply parameters are significantly estimated and respect the theoretical sign. Farmers use more inputs when their price increase relatively to output prices. Like Femenia and Letort (2016), we find that fertilizers and pesticides are substitute inputs. The concavity of the production functions is respected ($\gamma_{kf}\gamma_{kp} - \gamma_{kfp}^2 > 0$). The average potential yield α_{0k} display the expected signs. Parameters β_{0ik} display the expected signs.

With regard to the effects of biodiversity productive capacity on (i) average potential yield and (ii) average required use of pesticides, our model provides useful insights. First, we find that crop diversity increases yields of wheat and winter barley. Biodiversity productive capacity increases potential yields for wheat and winter barley. We do not find any significant effect of biodiversity

productive capacity on rapeseed. To our knowledge, this is the first time that we find that someone finds that crop diversity increases winter barley yields. It confirms that crop diversity increases cereal yields. However, it stresses the need to interpret carefully the results from empirical applications explaining aggregate crop yields by crop diversity: some crops are sensible to crop diversity, others not.

Table 2: GMM estimation of supply and variable input functions (N=771)

	Wheat	Winter barley	Rapeseed
Yield supply			
<i>Average potential yield</i>			
α_{0k}	68.64 *** (4.21)	60.68 *** (5.34)	33.77 *** (2.75)
α_{1k}	2.50 * (1.19)	3.21 ** (1.14)	0.33 (0.39)
<i>Curvature parameters</i>			
γ_f	845.50 *** (127.30)	408.06 *** (62.97)	-25.16 * (54.64)
γ_p	1128.59 *** (251.20)	630.60 *** (141.10)	106.54 * (26.53)
γ_{fp}	-936.53 *** (936.53)	-462.11 *** (71.02)	137.54 * (23.42)
R^2	0.191	0.246	0.192
Fertilizer demand			
<i>Average required use</i>			
β_{0fk}	132.05 *** (23.17)	108.98 *** (18.79)	125.59 *** (22.31)
β_{1fk}	-2.45 (3.32)	-0.44 (3.18)	-0.93 (4.58)
R^2	0.708	0.641	0.605
Pesticides demand			
<i>Average required use</i>			
β_{0pk}	207.59 *** (16.44)	190.12 *** (12.25)	306.59 *** (12.39)
β_{1pk}	-28.00 ** (9.91)	-18.39 ° (9.82)	-56.58 *** (10.04)
R^2	0.076	0.067	0.096
Acreage			
g_{0k}	104.25 ** (36.68)	-165.52 *** (38.50)	(Ref)
g_{km}	-3.79 * (1.49)	-3.81 ° (2.02)	2.08 (1.51)
Biodiversity dynamics			
δ	0.84 *** (0.06)		

°, *, **, *** significance level at 10%, 5%, 1% and 0,1%. Standard errors in brackets.

Second, we find that biodiversity productive capacity influences variable input demands. Di Falco and Chavas (2006) have already found the beneficial effect of biodiversity productive capacity on pesticide application based on the estimation of the variance of cereal yields, concluding to the positive impacts of biodiversity productive capacity on risk reduction. Here, we extend their results confirming that biodiversity productive capacity is a substitute to pesticides. The impact of biodiversity productive capacity on fertilizer application is not significant in the three fertilizer demand functions. However, because fertilizer and pesticides are substitute inputs ($\gamma_{kfp} < 0$), we find indirectly that biodiversity productive capacity decrease fertilizer application. Estimation of our structural model suggests that farmers manage biodiversity productive capacity in order to increase average yields and reduce variable input applications. The biodiversity productive capacity increases gross margins of the three outputs. The complementarities in the production function illustrates that farmers have incentives to diversify their acreage.

For the estimation of acreage functions, the estimation produce quite good quality results. All parameters (except g_{12}) are significantly different from 0 at 10%. The parameters g_{01} (measuring the difference of fixed costs between wheat and rapeseed) is positive, meaning that wheat incurs more costs for fixed inputs than rapeseed. We find a negative value for g_{02} , meaning that winter barley incurs more costs for fixed inputs than rapeseed. As the determinant of $\mathbf{G} \equiv [g_{km}]$ is positive, the concavity of the profit function is verified. We find significant negative terms for g_{kk} for both wheat and winter barley, underlying that farmers have some incentives to specialize to decrease the marginal costs incurs by the management of the fixed inputs. The estimation of our model without the indirect effects of biodiversity productive capacity in the acreage equations display positive and significant parameters for the g_{kk} . Combined with the results in the gross margins, this result is very interesting because it illustrates that we do have separate the benefits and the costs of diversification. Our results are coherent with Lansink and Stefanou (2001) or Chavas and Di Falco (2012) which have found opposite strengths between diversification and specialization (though for different motives and based on the estimation of dual restricted profit function). The interpretation of the estimated parameters from our adjustment cost function are however subject to limits because the estimated parameters capture the difference between true parameters for wheat and barley and the ones of rapeseed.

Finally, these results provide information about the management of the productive effects of biodiversity. The parameter δ associated to the dynamic effect of biodiversity productive capacity is equal to 0.84 (significantly different from 0 at 0.1%). It shows that farmers manage their acreage to benefit from productive effects of past acreage. The high value of δ supports our empirical choices to examine acreage choices on two periods. Our results are robust to different levels of discount rate (δ

remains between 0.83 and 0.85) and different forms of price expectation (δ remains between 0.80 and 1). Our result is similar to Di Falco and Chavas (2008) which found that biodiversity productive capacity effects from past year are lower than current ones. We confirm that the inherited part of biodiversity productive capacity is low, i.e. that biodiversity productive capacity is mostly managed through current acreage decisions. This result may surprise agricultural economists. Indeed, they use to consider that the effects of biodiversity productive capacity are mainly dynamic because of crop rotation. We have to recall that the high value of δ does not mean that farmers do not use crop rotations. Indeed, we do not observe acreage spatial choices. We thus assume that farmers optimize their crop rotation association between two periods. Because δ is lower than one, it does mean that the increase of acreage diversity in one period increase yields and variable input savings in the future periods, which can be interpreted as more suitable possibilities for crop rotation. Two empirical limits may affect the estimation of δ . First, our crop diversity indicator does not vary much between two periods. This may biased the estimation of δ and overvalue it. Second, we only estimate the acreage choices of three outputs. However, our sample is constituted of heterogeneous farmers, some of them presenting a high degree of specialization for wheat, other a high level of diversification. Existence of corner solution limits the accuracy of our estimation and impact the estimation of δ .

Some lessons about public policies may be drawn from the model and results presented in this paper. This paper shows that public policies, which aimed at reducing a pollutant input as pesticide taxation, have a double positive impact on environment: (i) a direct impact associated to the input reduction (Femenia and Letort, 2016), and (ii) an indirect impact associated to the increase of marginal productivity of biodiversity. In fact, according the theoretical model and the results, we have

$$\frac{\partial y_{kt}}{\partial B_t \partial x_{kit}} = \sum_{j=1}^I \gamma_{ijk} \frac{\partial \beta_{jk}}{\partial B_t} < 0 \text{ for each input } i \text{ and each crop } k. \text{ An input reduction leads to an increase}$$

of marginal productivity of biodiversity. After implementing the policy, farmers are then encouraged to diversify their crops since the productive capacity of biodiversity on crop yields is higher.

Conversely, public policies, which encourage crop diversity as proposed in agro-environmental contracts, may allow to reduce the amount of variable inputs. Farmers who adopt some agro-environmental measures by integrating a wide diversity of crops in their rotation cropping, perceive some payments in compensation of revenue loss. If the total impact of biodiversity on production decisions are not considered, these payments calculated from the estimated revenue loss and environmental benefits, are probably misevaluated.

5 Conclusion

Our structural microeconomic model allows for simultaneous estimation of supply, variable input demand and acreage functions. Inspired by multicrop microeconomic and investment literatures, our approach takes into account for (i) the productivity of biodiversity, (ii) the dynamics of the biodiversity productive capacity and (iii) the adjustment costs linked to fixed input management. We find that high levels of biodiversity productive capacity lead to augmentation of yields and to variable input savings. However, we find that management of fixed inputs increase with biodiversity productive capacity. The technical complementarities provide incentives to diversification whereas management of fixed input provides incentive for specialization. To our knowledge, this is the first time that costs and incomes of biodiversity productive capacity are taken into account in the same time. Previous researches have usually focused on a single dimension of biodiversity productive capacity, or in a dual restricted profit function, which do not allow for a full understanding of the economic and ecosystem mechanisms. The addition of the dynamic framework provides also new insights on the intertemporal management of biodiversity. We confirm that farmers manage biodiversity productive capacity like capital. Our model allows for a generalization of biodiversity productive capacity management models that are proposed in the economic literature. Because we rely on investment literature, our model offers large possibilities of extensions, e.g. we can introduce heterogeneous adjustment costs or threshold effects into the biodiversity dynamics.

Our model can provide new insights on the effectiveness of agri-environmental policies because it expresses the evolution of acreage diversity management regarding market fluctuations. Our results may benefit to the design of suitable agri-environmental measures (AEM) that can lead to a win-win situation where both biodiversity and agricultural profitability increase. This need has already been stressed by Omer et al. (2007) on a study based on stochastic production function with introduction of a biodiversity indicator. However, an analysis based on production function is not sufficient to evaluate the “correct incentives” (Omer et al., 2007). We think that our model can give this kind of information because it express farmers’ responses to economic incentives and their effects on biodiversity management. For the moment, we do not deal with this issue, because the analysis of current AEM effectiveness require mobilization of special econometric methods in order to overcome the auto-selection bias. However, the approach developed in this paper is a good basis for future work in this area.

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