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Biodiversity Productive Capacity in Mixed Farms of North-West of France: a Multi-output Primal System

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Abstract

Previous studies on the productive value of biodiversity emphasized that crop diversity increases crop yields. Here, we focus on the productivity of crop diversity and permanent grasslands for crops and milk. Using a GMM approach, we estimate detailed production functions using a sample of 3960 mixed farms from the FADN between 2002 and 2013. We highlight that permanent grasslands enhance crop production. We confirm that crop diversity increases crop and milk yields. Permanent grasslands and crop diversity are however substitute inputs. We also find that both of these biodiversity productive capacities influence variable input productivities. These results suggest the potential adaptations of farmers' choices to environmental measures.

Keywords: ecosystem services, agriculture, permanent grassland, crop diversity

JEL classification: Q12, Q57, D22

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1. Introduction

Modern human activities and, notably, agriculture have degraded biodiversity. Conversions of natural areas to arable lands have reduced the number of suitable habitat for biodiversity. The reduction of the number of crops have amplified this issue (Kleijn *et al.*, 2009). This trend has led to interrogations on the possibility to combine intensive agriculture and biodiversity. Protection of biodiversity is crucial because biodiversity contributes to ecosystem functioning thanks to the interactions of species with each other. Ecosystem functioning influences the provision of many ecosystem services that are valorized by our societies (MEA, 2005). Certain authors consider that among the diversity of beneficiaries, the highest value of biodiversity accrues to farmers through its beneficial effects on production (Perrings, 2010).

Supporting and regulating ecosystem services have been increasingly recognized as an input for agriculture (Zhang *et al.*, 2007). Supporting ecosystem services include notably nutrient cycles and regulating ones regroup *e.g.*, pest control. As they rely on species richness and abundance (MEA, 2005), we refer to these services as the “biodiversity productive capacity”¹. Because they can either increase or decrease agricultural yields, an essential part of farmers’ work is to manage biodiversity (Chavas, 2009). Famous examples of management of biodiversity productive capacity are crop rotations and biological control (Bianchi *et al.*, 2006).

Several economic studies have analyzed the effects of biodiversity productive capacity on crop farms. Most of these studies have estimated production functions with biodiversity productive capacity considered as an input². These studies have found that biodiversity has productive and insurance values. The insurance value is linked to the seminal hypothesis of “diversity-stability” proposed by MacArthur (1955) that emphasizes the complementary role of species on ecosystem resilience. Biodiversity productive capacity is linked to the “over-yielding” hypothesis, *i.e.*, species diversity increases net primary production. Several empirical studies have confirmed these hypothesis (Hooper *et al.*, 2005). We focus here on the productive dimension of biodiversity.

Previous studies on biodiversity productive capacity have emphasized that crop diversity increases wheat, cereal and crop yields. This information is useful for policymakers because it highlights that high yields are compatible with diversified landscape. However, previous studies have four main limits that narrow the available knowledge on farmers’ biodiversity management. Indeed, they do not

¹ Chavas (2009) and Chavas and Di Falco (2012) refer to them as the “productive value of biodiversity”.

² This method is often used in ecosystem services valuation studies (Perrings, 2010). Just and Pope (2001) have stressed the interest of production estimation methods to get new insights on technology and farmers’ choices.

estimate the biodiversity productive capacity considering (i) several productions, (ii) several kinds of biodiversity, (iii) the interactions between variable inputs and biodiversity productive capacity and (iv) the potential endogenous bias linked to the simultaneity of choice between variable inputs and yields. These limits may hinder the efficient implementation of policy measures. Our objective is to overcome these limits by assessing the productivity of crop diversity and permanent grasslands for crops and milk.

Assuming that farmers maximize their short term profit, we estimate a structural primal model with two production functions (cereals and milk) and two biodiversity habitats (crop diversity and permanent grasslands) on an unbalanced sample of mixed farms from the FADN (Farm Accountancy Data Network) between 2002 and 2013. Farms are located in northwest France, region with diversified landscapes. We estimate our model thanks to the general method of moment (GMM). We find that (i) crop diversity is an input for cereals and milk, (ii) permanent grasslands are an input for cereals, (iii) crop diversity and permanent grasslands are substitutes and (iv) both biodiversity productive capacities are substitutes for mineral fertilizers and pesticides.

The next section details the limits of the existing literature. The third section presents the theoretical model. We then present the empirical segment. The fifth section presents the results. We discuss them in the last section.

2. Literature review

Since the seminal works of Heisey *et al.* (1997) and Smale *et al.* (1998), the analysis of biodiversity productive capacity has benefited from a growing empirical literature in economics (*e.g.*, Bangwayo-Skeete *et al.*, 2012; Chavas and Di Falco, 2012; Di Falco *et al.*, 2010; Donfouet *et al.*, 2017; Finger and Buchmann, 2015; Matsushita *et al.*, 2016). These studies estimate the productivity and/or the profitability of biodiversity for agriculture. Most of them use primal approaches to estimate marginal effects of biodiversity on mean and/or variance yield. As measures of biodiversity are tricky, they rely on biodiversity indicators such as habitat-friendly landscape elements (*e.g.*, Klemick, 2011) or diversity indicators based on land-use (*e.g.*, Di Falco and Perrings, 2005; Omer *et al.*, 2007).

All these studies have found that biodiversity is an input for agricultural outputs. Studies based on profit analysis have also concluded to a profitable effect of biodiversity. It appears that (i) biodiversity has decreasing marginal returns on both yield and profit (Di Falco and Chavas, 2006; van Rensburg and Mulugeta, 2016), (ii) crop diversity is a suitable strategy for risk management (Di Falco and Chavas, 2009; Di Falco and Perrings, 2005) but mainly (iii) when pesticide applications are low (Di Falco and Chavas, 2006). These evidences support the idea that biodiversity has an insurance value (Baumgärtner, 2007), especially for the driest years (Di Falco and Chavas, 2008).

Despite the usefulness of these results, there are several disadvantages in this literature. First, studies have usually analyzed the effect of biodiversity on a single output. Most of the studies have examined the effects of biodiversity productive capacity on crop yields. To our knowledge, only van Rensburg and Mulugeta (2016) and Finger and Buchmann (2015) have analyzed animal and forage systems. There are needs to investigate the effect of biodiversity on other productions.

Second, these studies focus on a single kind of biodiversity habitat. They usually focus on crop diversity because they consider it as the main habitat of biodiversity within many agro-ecosystems. However, crop-orientated agroecosystems present a lower heterogeneity than many other agroecosystems with several landscape elements from crops to semi-natural elements. These areas are important because there are productive cross-effects between them, *e.g.*, Klemick (2011) found that forest fallows provide productive spillovers for crops. We believe that more studies need to be conducted on spillovers from semi-natural areas to better understand farmers' behavior regarding them. Donfouet *et al.* (2017) have stressed a similar concern in their conclusion.

Third, there are still several uncertainties on the relationships between biodiversity productive capacity and conventional inputs. It is an important issue in a context where input prices are expected to increase. To our knowledge, only Di Falco and Chavas (2006) have examined these relationships and have found that pesticides and crop diversity are substitutes. The lack of knowledge on the relationship to other variable inputs prevents the optimal implementation of instruments to promote biodiversity and/or reduce the application of polluting inputs.

Fourth, most of the cited studies have estimated production functions. We argue that they do not capture farmers' behavior, notably regarding their response to prices. If most of the cited studies have instrumented biodiversity indicators, none of them has attempted to account for the endogeneity between yields and variable input applications. It implies that they consider that farmers manage biodiversity but not variable inputs. Therefore, the conclusions of these studies may be biased. Similar critics can be done on the estimation of profit functions.

The objective of our study is to overcome these four issues.

3. Theoretical Model

We consider that a farmer maximizes his restricted profit function Π_t on variable inputs (noted X_t) each year t according to his quasi-fixed input dotation (noted Z_t). The vector Z_t contains information on available labor, capital and land at the farm scale but also on farm biodiversity productive capacity (noted B_{jt} , $j \in [1; J]$). We assume that these inputs are fixed in the short term. He buys inputs at the

market price (noted \mathbf{w}_t) and produces \mathbf{Y}_t agricultural goods that are sold at the price \mathbf{p}_t . Contrary to previous studies, we thus consider that farmers manage their variable inputs given the biodiversity productive capacity. This assumption appears weaker than the one usual one, particularly in developed countries and in the short term.

We can write the farmer's program as follows:

$$\begin{aligned} \text{Max}_{\mathbf{Y}_t, \mathbf{X}_t} \Pi_t(E(\mathbf{p}_t), E(\mathbf{w}_t), \mathbf{Z}_t) = \\ \Pi_t(\mathbf{Y}_t^*(E(\mathbf{p}_t), E(\mathbf{w}_t), \mathbf{Z}_t), \mathbf{X}_t^*(E(\mathbf{p}_t), E(\mathbf{w}_t), \mathbf{Z}_t), \mathbf{Z}_t \mid (\mathbf{Y}_t, \mathbf{X}_t, \mathbf{Z}_t) \in T) \end{aligned} \quad (1)$$

where \mathbf{Y}_t^* and \mathbf{X}_t^* are, respectively, the optimal amount of output and input vectors considering market information $(E(\mathbf{p}_t), E(\mathbf{w}_t))$. The Esperance terms return the farmer's anticipation of market prices. $(\mathbf{Y}_t, \mathbf{X}_t, \mathbf{Z}_t) \in T$ is the production set, which technically constrains the farmer. According to McFadden (1978), T is bounded compact and quasi-convex in $\mathbf{X}_t, \mathbf{Y}_t$ for each \mathbf{Z}_t .

We consider that the farmer produces K outputs (each noted Y_{kt}) with market price p_{kt} ($k \in [1; K]$). The farmer allocates his inputs between his K outputs (noted \mathbf{X}_{kt}) such that $\mathbf{X}_t = \sum_k \mathbf{X}_{kt}$. We can write Problem (1) as:

$$\begin{aligned} \text{Max}_{Y_{kt}, \mathbf{X}_{kt}} \Pi_t(E(\mathbf{p}_t), E(\mathbf{w}_t), \mathbf{Z}_t) = \\ \sum_k \pi_{kt}^*(Y_{kt}^*(E(p_{kt}), E(\mathbf{w}_t), \mathbf{Z}_t), \mathbf{X}_{kt}^*(E(p_{kt}), E(\mathbf{w}_t), \mathbf{Z}_t), \mathbf{Z}_t \mid (Y_{kt}, \mathbf{Y}_{-kt}, \mathbf{X}_{kt}, \mathbf{Z}_t) \in T_k) \end{aligned} \quad (2)$$

where π_{kt}^* is the optimized margin of k and Y_{kt}^* its production. T_k is the feasible input set for each k . Note that T_k depends on the other productions (contained in \mathbf{Y}_{-kt}).

We decompose Y_{kt}^* such that:

$$\pi_{kt}^*(p_{kt}, w_{kt}, Z_{kt}) = E(p_{kt})s_{kt}^*y_{kt}^* - E(\mathbf{w}_t)s_{kt}^*\mathbf{x}_{kt}^* \mid (y_{kt}, \mathbf{y}_{-kt}, \mathbf{x}_{kt}, \mathbf{z}_t) \in T_k \quad (3)$$

where s_{kt}^* is the optimized area allocated to k on t , y_{kt}^* is the optimized yield of k on t , \mathbf{x}_{kt}^* is the optimized application of variable inputs by area of k on t and \mathbf{z}_t is the amount of fixed input by area. We have $\mathbf{Z}_t = \mathbf{z}_t \sum_k s_{kt}$. The production function $y_{kt}(\mathbf{x}_{kt}, \mathbf{z}_t)$ is the frontier of T_k for each production. y_{kt} is a quasi-concave function of \mathbf{x}_{kt} . T_k considers the joint technologies that exist in multi-output firms (depending on \mathbf{y}_{-kt}).

Assuming I variable inputs, the farmer solves Problem (1) on x_{ikt} (the variable input i per area dedicated to k) with Equation (3) such that:

$$s_{kt}^* \left(E(p_{kt}) \frac{\partial y_{kt}}{\partial x_{ikt}} - E(w_{it}) \right) + \sum_{l \in [K] \setminus \{k\}} s_{lt}^* E(p_l) \frac{\partial y_{lt}}{\partial y_{kt}} \frac{\partial y_{kt}}{\partial x_{ikt}} = 0 \quad \forall i \in [1; I] \text{ and } \forall k \in [1; K] \quad (4)$$

where $\partial y_{lt} / \partial y_{kt}$ is the productivity of the output jointness between outputs k and l . In the case of crops and milk, the production jointnesses are manure application on crops and crop inter-consumption for cow feed. Equation (4) means that given his price expectations, his fixed input dotation (including his biodiversity levels), the farmer optimizes in the same time y_{kt} , s_{kt} and x_{ikt} . The farmer applies x_{ikt} on s_{kt}^* until the sum of the anticipated marginal productivity of x_{ikt} on y_{kt} and its indirect marginal productivities on y_{lt} ($l \neq k$) equals $E(w_{it})$.

Equation (4) illustrates farmers' input management in multi-output farms. This equation is useful for the statistical application for two reasons. First, (4) stresses the need to correct for endogenous bias on x_{ikt} when we estimate production functions. Second, Equation (4) means that farmers optimize the variable input application on each output. Because we only know X_{it}^* in our dataset, Equation (4) enables the determination of X_{ikt}^* . Assuming that $s_{kt}^* > 0 \forall k \in [1; K]$, we have:

$$\frac{\partial y_{kt}}{\partial x_{ikt}} \bigg/ \frac{\partial y_{lt}}{\partial x_{ilt}} = \frac{E(p_{lt}) + \sum_{m \neq l}^K E(p_{mt}) \frac{s_{mt}^*}{s_{lt}^*} \frac{\partial y_{mt}}{\partial y_{lt}}}{E(p_{kt}) + \sum_{m \neq k}^K E(p_{mt}) \frac{s_{mt}^*}{s_{kt}^*} \frac{\partial y_{mt}}{\partial y_{kt}}}$$

Assuming a single anticipation $E(p_{kt})$ for each farmer and $\partial y_{mt} / \partial y_{kt}$ constant in t ($\forall (k, m) \in [1; K] \times [1; K]$), we achieve the optimality condition:

$$\frac{\partial y_{kt}}{\partial x_{ikt}} \bigg/ \frac{\partial y_{lt}}{\partial x_{ilt}} = c; \quad \forall (k, l) \in [1; K] \text{ and } \forall i \in [1; I] \text{ with } c \in R^* \quad (5)$$

Ratios of marginal input productivities are equal at the optimum ($\forall i \in I$). We use relation (5) as the parameter restrictions in the empirical mode, allowing the allocation of the observed X_{it}^* between the K outputs. This relation determines X_{ikt}^* and x_{ikt}^* . More details are available in the next section.

In our empirical model, we estimate the yields of milk and cereals to determine the productivity of B_{jt} . We instrument the variable inputs by their demand determinants. Representing production jointness, our econometric model is specified to isolate the productivity of B_{jt} which is disentangled from technical complementarities. The addition of the restrictions (5) on the parameters allow the allocation of the input between several outputs. With the instrumentation of variable inputs and the utilization of restrictions (5), our model captures a large portion of the farmers' behavior.

4. Empirical model, biodiversity indicators and summary statistics

4.1. Biodiversity indicators

We select two kinds of biodiversity habitats \mathbf{B}_t : crop diversity (noted B_{1t}) and permanent grasslands (noted B_{2t}). We assume that they are adapted to different species. We measure B_{1t} with the Shannon index, which is an indicator that is usually used to measure crop diversity. This index has the advantage (i) to correct for species abundance, (ii) to not be sensitive to sample size and (iii) to be well suited to measuring habitat diversity (Mainwaring, 2001). The Shannon index is an entropy measure based on land shares but, as we measure crop biodiversity, we correct for permanent grasslands shares (s_{Kt}). We compute B_{1t} as follows:

$$B_{1t} = \sum_{k=1}^{K-1} \frac{s_{kt}}{(1 - s_{Kt})} \ln \left(\frac{s_{kt}}{(1 - s_{Kt})} \right)$$

B_{1t} takes the value 0 when the farm has a monoculture and increases when habitat diversity increases. Landscape ecologists have highlighted that B_{1t} increases when biodiversity increases (Burel and Baudry, 2003). Productivity of B_{1t} captures an augmentation of ecosystem services such as biological control or soil functioning.

We choose B_{2t} as the proportion of permanent grasslands in the utilized agricultural area (UAA), *i.e.*, $B_{2t} = s_{Kt}$. Permanent grasslands share is notably a proxy of the number of permanent semi-natural landscape elements (*e.g.*, hedgerows - Thenail, 2002) that are susceptible to have productive effects on milk and crop productions. These effects are (i) the wind-break effect, (ii) the furniture of habitat for insects involved in biological control, (iii) the influence on hydrological flux, (iv) the reduction of erosion and (v) the contribution to a microclimate (Baudry *et al.*, 2000). High share of permanent grasslands increases also landscape complexity and provides suitable habitat for insects involved in biological control (Aviron *et al.*, 2005). Both effects will be captured in the productive capacity of B_{2t} .

4.2. Empirical model

We consider two outputs in our model: cereals ($k=1$) and milk ($k=2$). The two outputs are produced on separated areas S_{1t} and S_{2t} . S_{2t} is equal to the total size allocated to maize silage, temporary grasslands and permanent grasslands. We measure cereal and milk yields in quantity by area. For cereals, we estimate a log-linear production function:

$$\ln(y_{1t}(\mathbf{x}_{1t}, \mathbf{B}_t, \mathbf{z}_t)) = \beta_{01} + \sum_{i=1}^4 \beta_{i1} x_{it} + \sum_{j=1}^2 \beta_{j1} B_{jt} + \beta_{121} B_{1t} B_{2t} + \sum_{l=1}^3 \beta_{l1} z_{lt} + \varepsilon_{1t} \quad (6)$$

We consider four variable inputs: mineral fertilizer ($i=1$), pesticides ($i=2$), seeds ($i=3$) and fuel ($i=4$). The three fixed inputs l are available labor, farm capital and UAA. We add an interaction term β_{121} between B_{1t} and B_{2t} to capture their non-linearity effects on yields. ε_{1t} is the error term which captures the unobserved heterogeneity. We introduce climatic variables and a fixed effect for each farmer in ε_{1t} to limit this bias.

We also estimate a log-linear production function for milk:

$$\ln(y_{2t}(\mathbf{x}_{2t}, \mathbf{B}_t, \mathbf{z}_t)) = \beta_{02} + \sum_{i=1}^4 \beta_{i2} x_{it} + \sum_{j=1}^2 \beta_{j2} B_{jt} + \beta_{122} B_{1t} B_{2t} + \sum_{l=1}^3 \beta_{l2} z_{lt} + \varepsilon_{2t} \quad (7)$$

Because the FADN does not provide information on forage yields, we must interpret the productivities of B_{jt} and the four variable inputs on milk as a function of B_{jt} productivities on forage. In addition to the four previous variable inputs (which benefit milk production through forage production), we add purchased feed ($i=5$) and health and reproduction expenses ($i=6$). ε_{2t} is the error term of Equation (7). Similar to Equation (6), we also add control variables and a fixed effect to reduce the unobserved heterogeneity biases. Note that because we do not know x_{ikt} in our database, we use x_{it} in Equations (6) and (7). Thus, the β_{ik} in Equations (6) and (7) do not only represent the marginal productivity of input i on output k . These variables measure the product of the marginal productivity of i on k by an input repartition factor. This last factor captures the relative input needs of cereals and forage production. The β_{ik} measure two effects that are impossible to separate. However, as our parameters of interest are the β_{jk} , we only have to verify that β_{ik} are positive for each i and k . We use Equation (5) to allocate the x_{it} between cereals and milk. Equation (5) asserts the following:

$$\beta_{11}/\beta_{12} = \beta_{21}/\beta_{22} \quad (8)$$

$$\beta_{21}/\beta_{22} = \beta_{31}/\beta_{32} \quad (9)$$

$$\beta_{31}/\beta_{32} = \beta_{41}/\beta_{42} \quad (10)$$

Another solution to allocate the variable inputs would have been to use the repartition function based on areas (Just *et al.*, 1990), but it would require nonlinear econometrics in our case.

As permanent grasslands are statistically linked to milk production, there is a risk that a portion of B_{2t} captures the effect of organic fertilization. We thus add proxies of organic nitrogen application in Equations (6) and (7) using a formula provided by the French Ministry of Agriculture based on the

number of animal units at the farm scale (CORPEN, 2006). We distinguish two kinds of organic manure: cattle manure and manure from other livestock. This addition disentangles the productive effects of permanent grasslands from organic fertilization. A similar issue concerns the inter-consumption of cereals for cattle feed; however, it represents less than 5% of animal feed in our sample. We do not control for inter-consumption in our application.

We instrument x_{it} in Equations (6) and (7) by their demand functions, assuming naïve anticipation for output prices and rational anticipation for input prices. We also use decoupled subsidies and the milk quota as additional instruments. These random variables do not influence the short-term choices and do capture the heterogeneity among our sample. We also instrument total labor using farm partners' labor.

We estimate the system composed of Equations (6) and (7) and restrictions (8), (9) and (10) with the instrumentation of the six variable inputs using GMM. GMM corrects for potential heteroscedasticity. We estimate the within transformation of Equations (6) and (7) to capture farmers' fixed effect. The constant terms β_{0k} in Equations (6) and (7) capture the average technical progress. In addition to GMM, we run a seemingly unrelated regression (SUR) and three-stage least square (3SLS) estimations to illustrate the interest of the endogenous correction on variable inputs. We also estimate a second model (Model 2) without the parameter constraints (8), (9) and (10) using GMM and the within transformation. Finally, in a third model (Model 3), we replace the interaction term between B_{1t} and B_{2t} with interaction terms between B_{jt} and x_{ilt} (for $j \in [1,2]$ and $i \in [1,2]$) in the equation of cereal yields, such that:

$$\ln(y_{1t}(\mathbf{x}_{1t}, \mathbf{B}_t, \mathbf{z}_t)) = \beta_{01} + \sum_{i=1}^4 \beta_{i1} x_{it} + \sum_{j=1}^2 \beta_{j1} B_{jt} + \sum_{i=1}^2 \sum_{j=1}^2 \beta_{ij1} x_{it} B_{jt} + \sum_{l=1}^3 \beta_{l1} z_{lt} + \varepsilon_{1t} \quad (11)$$

These crossed terms add information on the relationship between the biodiversity productive capacities and the variable inputs. Additional instruments are computed as demand functions multiplied by B_{jt} . The interaction terms in this third model does not allow the utilization of Equation (5).

4.3. Description of the data and variables

We use the FADN on three NUTS2 regions of northwest of France from 2002 to 2013: Brittany ("*Bretagne*" in French), Lower Normandy ("*Basse-Normandie*") and Western Loire ("*Pays-de-la-Loire*"). These regions are orientated towards breeding (*e.g.*, they produce approximately 60% of French milk) and present diversified acreages with high shares of permanent grasslands, *e.g.*, 700,000

ha for Lower Normandy in 2006 (AGRESTE Bretagne, 2009). We only select dairy farms that have allocated area to cereals, maize silage and temporary grasslands. The sample is constituted of 999 farms that are observed in the sample for 3.96 years on average, *i.e.*, 75.8% of the FADN dairy farms in these regions. We estimate our model on 3,960 observations.

Because we use 2002 data from for anticipated prices only, we can consider that the set of financial supports were relatively homogenous during our sample period. Indeed, farms from our sample only confront the 2008 Common Agricultural Policy (CAP) reform. The most notable changes are the suppression of fallow obligations, the gradual increase of milk quotas and the extension of decoupled subventions.

Table 1 presents the descriptive statistics. As input prices are not available in the FADN, we compute the quantity index for each input using the farm's purchases and average regional prices (base 100 in 2010). We have deflated prices and subsidies by the national consumption price index. Here, cereals include the production of soft wheat, durum wheat, rye, spring barley, winter barley, escourgeon, oat, summer crop mix, grain corn, seed corn, rice, triticale, non-forage sorghum and other crops. The yields of crops are computed in constant euros using a Paasche index based on the mean price of each cereal in 2010. We use individual prices for milk. We have also added climatic variables, but we do not report them in Table 1.

Table 1: Descriptive statistics (N=3960)

	Mean	Median	Q1	Q3	Min	Max
Cereal yield (constant €/Ha)	1,064.14	1,074.04	918.15	1,217.05	58.65	2455.44
Milk yield (kg/Ha)	6,111.58	6,171.39	4,553.45	7,852.81	276.81	20,909.08
log(cereal yield)	6.942	6.979	6.822	7.105	4.071	7.806
log(milk yield)	8.718	8.727	8.423	8.968	5.623	9.947
Crop diversity (B1)	1.246	1.207	1.021	1.496	0.206	2.287
Permanent grasslands (B2)	0.10	0.015	0	0.14	0	0.89
UAA (Ha)	90.01	77.62	55.18	110.39	15.59	382.88
Main forage area (Ha)	60.95	53.64	37.27	76.39	8.16	290.9
Fertilizer (quantity index)	9,899.41	8,028.13	4,778.82	12,821.8	0	87,025.84
Pesticides (quantity index)	6,402.45	4,843.92	2,754.69	7837.9	0	71907
Seeds (quantity index)	6,866.18	5,575.39	3,567.07	8,462.67	0	73,701.09
Fuel (quantity index)	57.19	47.58	30.56	72.89	0	311.41
Cow feed (quantity index)	282.52	225.19	131.31	368.81	1.702	2803.41
Health and reproduction (quantity index)	54.2	42.77	25.9	74.32	0	407.17
Cattle fertilizer (kg)	8,871.66	7,456.86	5,093.1	10,886.7	735.81	45,234.26
Other livestock fertilizer (kg)	2,076.85	0	0	0	0	95850
Capital (1000€)	299.88	258.30	158.94	383.41	0	3,822.41
Labor (annual worker unit/100)	218.19	200	150	272	100	1200

Milk and cereals are the most profitable outputs of our farm sample. On average, 56.75% of the revenues originate from milk production, and 9.82% originate from cereal production. The

byproducts of milk production are less profitable than cereals. Some farms have other activities, notably pig production (for 11% of farms).

5. Results

Table 2 reports the GMM estimation of Model 1. We find that crop diversity increases both cereal and milk yields. Permanent grasslands increase cereal yields but do not affect milk yields. Interestingly, both biodiversity indicators interact negatively with each other for cereal yields, suggesting that they are non-cooperating inputs. Permanent grasslands increase cereal yields only when its marginal productivity (equals to $0.261 - 0.217 B_{1t}$) is positive, *i.e.*, when crop diversity is lower than 1.20. Based on the distribution of crop diversity, permanent grasslands increase cereal yields in 46% of our observations. Similarly, crop diversity increases cereal yields in 89% of our observations (when $B_{2t} < 0.35$). At the average level of B_{2t} , increasing crop diversity from an equally distributed acreage between three crops ($B_{1t} = 1.099$) to an equally distributed acreage between four crops ($B_{1t} = 1.386$) increases cereal yields by 2.3% and milk yields by 2.6%. Permanent grasslands does not influence cereal yields at the average level of B_{1t} . In the case where $B_{1t} = 1$, an increase in B_{2t} from 0.1 to 0.2 leads to an increase of cereal yields by 0.4%.

All fixed inputs have null productivity except UAA, which decreases milk yields. UAA captures the lower yields per area of extensive farms. The null productivity of other fixed inputs highlights the difficulty of measuring them effectively. Cattle manure decreases crop yields, but organic fertilization proxies are non-significant otherwise (at 5%). This finding suggests a lack of efficient management for this public input, which may be due to the existence of legislative constraints on the application of organic fertilizers. The specification of alternative organic fertilization proxies does not influence the significance and the sign of the productivity of B_{2t} or the variable input productivities.

The productivities of the variable inputs are all significantly positive in both productions, except for pesticides (non-significant). The results show that the parameter restrictions are significant at 5%. Estimations of Model 2 (Table A1 of appendices) emphasize that pesticide productivity is significantly negative for milk yields. Most of the parameters are non-significant. The negative sign of pesticide productivity in Model 2 is linked to changes in pesticide application through time. Indeed, French legislation has provided signals to reduce pesticide utilization in the last year of our sample. As milk yields have increased over the whole sample period and pesticide utilization has decreased, this negative sign may be due to the unbalanced structure of our sample. Nevertheless, the comparison of estimations between Models 1 and 2 highlights that the addition of restrictions corrects for the

negative productivity of pesticides. Restrictions also increase the significance of other parameters. The comparison of SUR estimations of Model 1 (see Table A2 in appendices) with GMM estimations also highlights the importance of instrumentation for the estimation of variable input productivities. It underlines the usefulness of the assumption of profit-maximizing farmers. Our instrument equations display R^2 equal to 0.12 to 0.25, which is a classic issue for variable input demand functions.

Table 2: GMM estimations of Model 1 (N=3960)

	log(y_cereals)	log(y_milk)
Biodiversity productive capacity		
B1	0.077** (0.026)	0.096** (0.028)
B2	0.261* (0.123)	0.042 (0.13)
B1*B2	-0.217* (0.093)	-0.069 (0.11)
Variable inputs		
Fertilizer	0.001*** (0.0003)	0.01** (0.0003)
Pesticides	0.0001 (0.0003)	0.0001 (0.0002)
Seeds	0.001° (0.0005)	0.001* (0.0004)
Fuel	0.34** (0.108)	0.276** (0.09)
Cow feed		0.099*** (0.010)
Health and reproduction		0.193* (0.091)
Organic fertilizer proxies		
Cattle fertilizer/UAA	-0.094* (0.041)	-0.115° (0.07)
Other livestock fertilizer/UAA	-0.016 (0.013)	-0.022 (0.013)
Fixed inputs		
UAA	-2.50.10 ⁻⁴ (2.65.10 ⁻⁴)	-9.15.10 ⁻⁴ * (4.16.10 ⁻⁴)
Capital/UAA	-0.0001 (0.0004)	-0.0006 (0.0005)
Labor/UAA	-3.57 (2.42)	2.45 (2.63)
Technical progress	-0.002 (0.015)	0.002 (0.002)
Restrictions		
Restriction 1	-2.109* (1.045)	
Restriction 2	-2.170* (1.044)	
Restriction 3	-2.310* (0.959)	

°, *, **, *** significance level at 10%, 5%, 1% and 0.1%. Standard errors in brackets.

The addition of control variables is crucial in our estimation. The omission of meteorological information leads to negative productivities of certain variable inputs. The estimation of our model without fixed effects also displays negative productivities. As all properties of the variable and fixed inputs are consistent with theory in the GMM estimation of Model 1, we confirm the results of biodiversity productive capacities on cereals and milk. Robustness checks based on the 3SLS and SUR estimations of Model 1 (Table A1 in Appendices) and the GMM estimation of Model 2 (Table A2 in Appendices) display the same significant signs for biodiversity indicators, although the levels of estimated productivity are different. The differences are more important for variable input productivities. Our robustness checks highlight that we do need to correct for heteroscedasticity and endogenous biases. These checks confirm that (i) B_{1t} increases crop and milk yields, (ii) B_{2t} increases crop yields and (iii) B_{1t} and B_{2t} are non-cooperating for crops.

The GMM estimation of Model 3 is available in Table 3. As we can no longer use restrictions, we correct the negative parameters for pesticide productivity on milk by the addition of an interaction term with a trend such as in Model 2b (see Table A2 in appendices). The parameters are overall less significant than in the two previous models, but our additional parameters are significant. We find that the interaction terms between the biodiversity indicators and the variable inputs are all significantly negative. The augmentation of biodiversity indicators decreases the productivity of both pesticides and fertilizers. This finding suggests that the biodiversity productive capacities are both non-cooperating inputs for fertilizers and pesticides. It appears that biodiversity productive capacities influence marginally more productivity of pesticides than that of fertilizers. At the average points, crop diversity decreases the fertilizer productivity by 70%, and permanent grasslands reduce it by 15%. Similarly, crop diversity decreases the pesticide productivity by 57%, and permanent grasslands reduce it by 23%. The first-order productivities of the biodiversity indicators remain significant and confirm previous results. At average points, productivities of B_{1t} and B_{2t} in Model 3 are consistent with those of Model 1.

Table 3: GMM estimations of Model 3 (N=3960)

	log(y_crops)	log(y_milk)
Biodiversity		
B1	0.929*** (0.248)	0.095*** (0.027)
B2	2.804*** (0.589)	0.038 (0.055)
Variable inputs		
Fertilizer	0.007** (0.002)	0.0004 (0.0004)
Fertilizer*B1	-0.004* (0.002)	
Fertilizer*B2	-0.011*** (0.003)	
Pesticides	0.013** (0.004)	0.004° (0.002)
Pesticides*B1	-0.006* (0.003)	
Pesticides*B2	-0.030*** (0.008)	
Pesticides*trend		-0.0008* (0.0003)
Seeds	0.001 (0.001)	0.002 (0.0007)
Fuel	0.190 (0.157)	0.420 (0.176)
Cow feed		0.066*** (0.012)
Health and reproduction		0.246** (0.090)
Organic Fertilizer proxies		
Cattle fertilizer/UAA	0.037 (0.058)	-0.066 (0.0005)
Other livestock fertilizer/UAA	0.019 (0.019)	-0.025 (0.017)
Fixed inputs		
UAA	-3.38.10 ⁻⁴ (5.28.10 ⁻⁴)	-5.58.10 ⁻⁴ (4.59.10 ⁻⁴)
Capital/UAA	-0.0003 (0.0005)	-0.0004 (0.0005)
Labor/UAA	-8.440 (6.079)	1.863 (4.892)
Technical progress	0.001 (0.002)	0.005* (0.002)

°, *, **, *** significance level at 10%, 5%, 1% and 0.1%. Standard errors in brackets.

6. Discussion and conclusions

Our paper extends the current knowledge on biodiversity productive capacity to (i) several kinds of biodiversity, (ii) several productions and (iii) the interactions with conventional variable inputs.

6.1. First order effects of biodiversity productive capacity

First, we confirm that crop diversity is an input for cereals. This is the first time that we find it in the oceanic part of Europe (except Donfouet *et al.* (2017) in all France), which stresses that crop diversity is also useful for wet regions. This may explain the augmentation of crop diversity in our studied regions between 2007 and 2010 (Desjeux *et al.*, 2015). Second, we find that crop diversity is also an input for milk. We interpret it as an increase in forage yields. Forages appear sensitive to biological control and crop rotations. This finding also might suggest that cows benefit from more diversified feed. To our knowledge, this is the first time in economics that someone finds that crop diversity benefits to other output than crops.

We also find that permanent grasslands increase cereal yields, confirming agronomical and ecological studies on the potential benefits of permanent grasslands and related landscape elements on crop production. The positive productivity of permanent grasslands on cereals emphasizes a productive spillover between semi-natural areas towards arable lands. Klemick (2011) highlighted a similar result on fallow forests in Brazil. This result may explain the augmentation of grassland shares on crop-orientated French LAU1 regions (Desjeux *et al.*, 2015), although they are significantly lower than in dairy regions. However, Desjeux *et al.* (2015) have shown that permanent grasslands have declined in our case study regions. Our results suggest that this decline may be due to the lower productivity of permanent grasslands compared to crop diversity productivity. It also might be due to legislative constraints, which increase the cost of permanent grassland management (Nilsson, 2009).

Under the assumption that farmers maximize their profit, we find that biodiversity productive capacities increase yields, suggesting that farmers do manage biodiversity. The cost of their management is equal to the sum of their marginal productivities. We do not find any conflict between high yields and biodiversity but we highlight that the productivity of permanent grasslands is lower than the productivity of crop diversity.

6.2. Second order effects of biodiversity productive capacity

One of our most interesting results is the negative interaction term between crop diversity and permanent grasslands in cereal production, which suggest that both biodiversity productive capacities

are substitutes. This finding could confirm the recent results of landscape ecology; *e.g.*, Martel *et al.* (2015) have found that landscapes with low hedgerow density need a high complexity of crop mosaic to achieve the same level of biological control of landscapes with higher hedgerow density. We conclude that farmers have no incentives to increase both biodiversity productive capacities at the same time. This explication is consistent with the observations of Desjeux *et al.* (2015) who observed a trade-off between crop diversity and permanent grasslands in most LAU1 regions of France.

In Model 3, we emphasize that both biodiversity productive capacities do interact with variable inputs. We find that crop diversity is substitute for pesticides, confirming the result of Di Falco and Chavas (2006) on the variance of cereal yields. In addition, our results suggest that crop diversity is substitute for fertilizer. Kim *et al.* (2001) have highlighted that soil quality and fertilizer are substitutes in the short term in USA. Because crop diversity increases soil quality, our results confirm their previous analysis. However, Kim *et al.* (2001) have also found that soil quality and fertilizer are complements in the long term. We cannot confirm this result because farmers are only present for four consecutive years in our sample. We should only consider our results valid in the short term. Moreover, we stress that our estimation of biodiversity productive capacities are consistent locally and within intensive agricultural regions. The relationship between variable inputs and biodiversity productive capacity may be different in developing regions where variable inputs are limiting inputs.

We find evidence that permanent grasslands are substitute for pesticides and fertilizers in the short term. This finding confirms the beneficial role of permanent grasslands and the attached elements of biological control (Baudry *et al.*, 2000). It appears that crop diversity interacts more with variable inputs than permanent grasslands, confirming its more important role in agricultural production. However, in contrast to crop diversity, permanent grasslands play a higher role in crop protection than in crop fertilization, which is consistent with ecological studies (Baudry *et al.*, 2000). These results are consistent in the short term and within intensive agricultural regions.

In sum, we have found that (i) crop diversity is an input for both crops and milk, (ii) permanent grasslands are an input for crops, (iii) crop diversity and permanent grasslands are substitutes, and (iv) both biodiversity productive capacities are substitutes for mineral fertilizers and pesticides. These results are robust to econometric methods and production function specifications. Our results also contribute, to a larger extent, to the discussions on the benefits of mixed farming (Ryschawy *et al.*, 2012).

6.3. Methodological limitations

We have stressed the interest of our method for yield estimations in multi-output farms. Our method provides theoretically consistent results for variable input productivities. We have highlighted that the omission of the variable input instrumentation leads to biased parameters. However, our work continues to suffer from additional limits. One limit is due to the estimation of the within transformation of Equations (6) and (7), which only allows explaining a small portion of the total variability. Others limits are linked to potential additional endogenous biases and our biodiversity indicators.

6.3.1. Additional endogenous biases

Contrary to previous studies, we have assumed that biodiversity productive capacities are fixed in the short term and that farmers optimize variable input applications. However, similar to variable inputs, acreage shares decisions are simultaneous to objective yields decisions which may lead to endogeneity biases. Multicrop microeconomic models have stressed the sensitivity of farmers' acreage choices to prices and policies. However, if acreage price elasticities are high between cereals, they are fixed between cereals and other outputs, at least in the short term (Carpentier and Letort, 2012). This fixity is notably due to diversification costs that prevent farmers from significantly modifying their acreage each year. We can thus consider our biodiversity indicators as "predetermined" and exogenous. The instrumentation of the Shannon index by its lagged value in Di Falco and Chavas (2008) illustrates the quasi-fixity of acreage shares.

The hypothesis of "predetermined" biodiversity is less correct in the long term. In this case, we should consider biodiversity productive capacities as quasi-fixed inputs and instrument them. Long-term optimization is interesting because biodiversity productive capacities enhance future production (Di Falco and Chavas, 2008), notably due to crop rotations (Hennessy, 2006). As highlighted by Carpentier and Gohin (2015), works on crop rotation suffer from several biases. The adaptation of our model using a dynamic integration of biodiversity indicators into acreage models may overcome these issues.

6.3.2. Biodiversity indicators and potential confounders

The distinction of several biodiversity indicators is a crucial point of our study. However, our biodiversity indicators suffer from several biases. First, the choice of the indicators relies highly on data availability. The mobilization of FADN data compels us to rely on indicators computed at the

farm scale. Instead, landscape ecologists compute these indicators at the landscape scale (Burel and Baudry, 2003). However, as emphasized by Donfouet *et al.* (2017), there are no significant differences of crop diversity productivity according to the scale of the indicator computation in previous studies. Second, farmers' CAP declaration of permanent grasslands may be underreported due to constraining legislative specificities. Third, we assume that biodiversity indicators are suitable proxies of real biodiversity levels but there are no evidence that the relationships between them are linear. Fourth, biodiversity indicators based on landscape structure do not consider farmer practices. If landscape elements can enhance agricultural production, the expressions of the related functionalities depend on agricultural practices, *e.g.*, intensive chemical practices decrease biodiversity (Omer *et al.*, 2007). This finding may partly explain our results on the interactions between the biodiversity productive capacities and the variable inputs. Moreover, if biodiversity indicators do capture the landscape's availability to provide a habitat to insects involved in biological control, they also capture a potential increase of pest pressures (Bianchi *et al.*, 2006).

Additional issues may originate from the potential biases linked to economic confounders, *e.g.*, indicators can inform on fixed input organization. These issues are common to all economic studies on the valuation of biodiversity productive capacity. If we have attempted to capture these effects in our estimation, certain results may be due to remaining confounders.

6.4. Implications for environmental policies

Policymakers aim to increase the levels of environmental quality and biodiversity due to their beneficial effects on social welfare. Under the assumption that farmers maximize their profit, our results can benefit to policymakers because they emphasize the incentives encountered by farmers managing biodiversity. The first-order effects highlight that both crop diversity and permanent grasslands increase cereal and milk yields, suggesting that there are no conflict between high yields and biodiversity. We highlight however that crop diversity is more productive than permanent grasslands. The second-order effects stress the difficulty of designing optimal sets of instruments targeting crop diversity and permanent grasslands at the same time. Instruments providing incentives to the enhancement of crop diversity also favor a decrease of permanent grasslands and *vice-versa*. This substitution is amplified because crops and permanent grasslands are competitors for land and farmers have limited UAA. Thus, cross-compliance requirements introduced in the CAP 2014 reform may lead to counterintuitive acreage evolutions. Indeed, crop-orientated regions (with high dotation of crop diversity) receive incentives to enhance ecological focus areas and permanent grasslands; this,

in turn, leads to a decrease of marginal productivity of crop diversity and finally, assuming profit-maximizer farmers, to a reduction of crop diversity.

Finally, we want to emphasize the optimistic implications of the Model 3 results. We find that variable inputs and biodiversity productive capacity are substitutes, at least in the short term and in intensive agricultural regions. Thus, the taxation of polluting inputs would provide incentives to farmers to increase biodiversity productive capacities. Because we do find that biodiversity and variable inputs are non-complementary, biodiversity augmentation should not suffer from any mitigation effects. Similarly, biodiversity subventions should encourage farmers to reduce the application of fertilizers and pesticides. Environmental policies can reach several objectives together.

If our results provide new insights on biodiversity management, they only concern yields (*i.e.* the biodiversity effects at the intensive margin). To really improve policy measures, future researches should focus on the effects of biodiversity on acreage choices (*i.e.* the biodiversity effects at the extensive margin), notably in a dynamic framework. This would better characterize the existing conflicts between agriculture and biodiversity.

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Appendices

Table A1: SUR and 3SLS estimations of Model 1 (N=3960)

	SUR		3SLS	
	log(y_cereals)	log(y_milk)	log(y_cereals)	log(y_milk)
Biodiversity productive capacity				
B1	0.132*** (0.021)	0.193*** (0.017)	0,132*** (0.021)	0.110*** (0.033)
B2	0.281* (0.115)	-0.048 (0.093)	0,225° (0.119)	-0.154 (0.139)
B1*B2	-0.210* (0.093)	-0.067 (0.075)	-0,197* (0.095)	-0.023 (0.111)
Variable inputs				
Fertilizer	3.3E-5 (3.1E-4)	0.0001 (0.0001)	-0,0001 (0.0001)	0.0005 (0.0005)
Pesticides	0.0001 * (0.0006)	0.0004* (0.0001)	0,0002 (0.0003)	-0.003** (0.0001)
Seeds	0.0001 (0.0005)	0.0004** (0.0004)	0,0001 (0.0001)	-0.001 (0.0009)
Fuel	0.007 (0.006)	0.020 (0.016)	-0.043 (0.055)	0.502** (0.16)
Cow feed		0.049*** (0.002)		0.134*** (0,013)
Health and reproduction		0.081*** (0.008)		0.209° (0,123)
Organic fertilizer proxies				
Cattle fertilizer/UAA	0.044 (0.030)	0.165*** (0.025)	0.006 (0.037)	-0.310*** (0.07)
Other livestock fertilizer/UAA	-0.014 (0.012)	-0.017° (0.009)	-0,033* (0.014)	-0.063*** (0.018)
Fixed inputs				
UAA	-2.39.10 ⁻⁷ (2.40.10 ⁻⁴)	-8.7.10 ⁻⁶ *** (1.95.10 ⁻⁶)	5.9.10 ⁻⁶ ° (3.5.10 ⁻⁶)	-2.6.10 ⁻⁷ (4.12.10 ⁻⁶)
Capital/UAA	-0.0001 (0.0004)	0.001*** (0.0003)	-0,0002 (0.0004)	-0.001 (0.0005)
Labor/UAA	-0.529 (0.717)	2.057*** (0.579)	7.798* (3.126)	14.34** (4.84)
Technical progress	-0.011* (0.005)	-0.003 (0.002)	-0,019 (0.019)	-0.001 (0.003)
Restrictions				
Restriction 1	-2.376* (0.943)		-5.036*** (1.213)	
Restriction 2	0.30 (2.005)		3.582 (3.047)	
Restriction 3	0.754 (0.919)		8.765** (3.236)	

°, *, **, *** significance level at 10%, 5%, 1% and 0.1%. Standard errors in brackets.

Table A2: GMM estimations of Model 2 (N=3960)

	Model 2a		Model 2b	
	log(y_crops)	log(y_milk)	log(y_crops)	log(y_milk)
Biodiversity				
B1	0.081** (0.026)	0.117*** (0.030)	0.075** (0.027)	0.090** (0.034)
B2	0.234° (0.126)	-0.049 (0.134)	0.225° (0.126)	-0.101 (0.139)
B1*B2	-0.207* (0.094)	0.002 (0.116)	-0.195* (0.094)	0.012 (0.121)
Variable inputs				
Fertilizer	0.002*** (0.001)	0.0001 (0.0005)	0.002*** (0.001)	0.0005 (0.0005)
Pesticides	0.0003 (0.0004)	-0.002** (0.001)	0.0003 (0.0004)	0.005° (0.003)
Pesticides*trend				-0.001* (0.0004)
Seeds	0.001° (0.001)	0.001 (0.0008)	0.001° (0.001)	0.001 (0.0008)
Fuel	0.118 (0.131)	0.539 (0.139)	0.136 (0.131)	0.518 (0.143)
Cow feed		0.101*** (0.014)		0.101*** (0.014)
Health and reproduction		0.189° (0.113)		0.171 (0.121)
Organic fertilizer proxies				
Cattle fertilizer/UAA	-0.045 (0.048)	-0.167* (0.079)	-0.050 (0.048)	-0.192* (0.080)
Other livestock fertilizer/UAA	-0.006 (0.013)	-0.032 (0.019)	-0.006 (0.014)	-0.040° (0.021)
Fixed inputs				
UAA	3.70.10 ⁻⁴ (3.21.10 ⁻⁴)	-0.0005 (0.0005)	3.80.10 ⁻⁴ (3.21.10 ⁻⁴)	-0.0007 (0.0005)
Capital/UAA	0.001 (0.001)	-0.0009 (0.0005)	0.001 (0.001)	-0.001° (0.0006)
Labor/UAA	-4.186 (3.950)	4.556 (4.739)	-4.304 (3.952)	7.503 (4.953)
Technical progress	-0.016 (0.026)	0.002 (0.002)	-0.018 (0.026)	0.004 (0.003)

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