Biodiversity productive capacity in milk farms of North-West of France: a multi-output primal system

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Summary

It is widely recognized that human activities and especially agriculture have negative impacts on biodiversiy. However, biodiversity can also benefit to farmers through its positive effects on production. This two-way causality relationship between biodiversity and agriculture has raised numerous authors to examine the behaviour of farmers regarding environment. However, only few empirical studies have analysed biodiversity management considering previous results in production economics. Indeed, they usually do not take into account farmers' strategic choices. These studies did notably not correct for the endogenous bias linked to simultaneity of choices between input and output levels and did not take into account market evolution. On the other hand, production economic studies have rarely introduced ecological feedbacks in the production function and prefer to analyse environmental effects in an ex-post way.

On this paper, we estimate crop and milk primal production functions of a sample of mixed farms of western France. Our sample is composed of 3984 FADN observations from 2002 to 2014 in French regions of Bretagne, Basse-Normandie and Pays-de-la-Loire. We estimate the biodiversity productive capacity taking into account for the variable input endogenous biases and joint technology specificity. Using General Method of Moment, we estimate log-linear of both production functions with addition of variable input demand functions as instruments of variable input levels. We measure biodiversity through the utilization of landscape metric indicators. We examine the effect of two kind of biodiversity: arable land biodiversity and permanent grassland biodiversity. Our preliminary results seem to confirm previous results of the literature on the productive effect of arable land biodiversity on crop production. For the first time in empirical economics analysis, we find that permanent grasslands enhance crop production. On the other side, milk production is less sensible to biodiversity. Biodiversity productive capacity also influence the productivity of variable inputs. Our results can be useful for policymakers as they bring new insights on the management of biodiversity by farmers.

Capacité productive de la biodiversité dans les fermes en polyculture-élevage du Nord-Ouest de la France : un système primal multi-produit

Mots-clés : Services écosystémiques ; Agriculture ; Prairie permanente

Il est largement reconnu que les activités humaines et notamment l'agriculture ont des impacts négatifs sur la biodiversité. Cependant, la biodiversité peut également bénéficier aux agriculteurs par ses effets positifs sur la production. Cette double relation de causalité entre la biodiversité et l'agriculture a conduit certains auteurs à examiner le comportement des agriculteurs vis-à-vis de l'environnement. Cependant, peu d'études empiriques ont analysé les capacités productives de la biodiversité en tenant compte rigoureusement des choix stratégiques des agriculteurs et définis par l'économie de la production. Ces auteurs n'ont notamment pas corrigé le biais d'endogénéité lié à la simultanéité des choix entre niveaux d'intrants et de produits et n'ont pas relié leurs estimations aux évolutions des marchés. D'autre part, les études empiriques en économie de la production ont rarement introduit l'effet des capacités productives de la biodiversité dans la fonction de production et préfèrent analyser les effets environnementaux de manière ex-post.

Dans cet article, nous estimons les fonctions de production primales des céréales et du lait sur un échantillon de fermes mixtes de l'ouest de la France. Notre échantillon est composé de 3984 observations du RICA de 2002 à 2014 dans les régions Bretagne, Basse-Normandie et Pays-de-la-Loire. Nous estimons la capacité productive de la biodiversité en prenant en compte les biais d'endogénéité liés à l'application des intrants variables et la spécificité technologique conjointe. En utilisant la Méthode des Moments Généralisés, nous estimons les deux fonctions de production log-linéaire où nous instrumentons les intrants variables par leurs fonctions de demande. Nous mesurons la biodiversité grâce à l'utilisation d'indicateurs métriques de composition du paysage. Nous examinons l'effet de deux types de biodiversité : la biodiversité des terres arables et la biodiversité des prairies permanentes. Nos résultats préliminaires semblent confirmer les résultats antérieurs de la littérature sur la capacité productive de la biodiversité des terres arables sur les céréales. Pour la première fois dans une étude d'économique empirique, nous constatons que les prairies permanentes améliorent le rendement céréalier. D'autre part, la production laitière est moins sensible à la biodiversité. La capacité productive de la biodiversité influe également sur la productivité des intrants variables. Nos résultats peuvent être utiles aux décideurs publiques, car ils apportent de nouvelles connaissances sur la gestion de la biodiversité par les agriculteurs.

1. Introduction

Over the last decades, modern human activities and notably agriculture have degraded biodiversity (Butchart et al., 2010). Conversions of natural areas such as forest or permanent grasslands to arable lands have reduced the number of suitable habitat for the biodiversity. The trend to reduce the number of crops on arable lands towards monoculture have even amplified this issue, because of the reduction of available habitat and the increasing of variable input application (Kleijn et al., 2009). However, biodiversity is at the basis of ecosystem functioning. Indeed, species interact with each other and with the physico-chemical characteristics of the ecosystem, contributing to its richness and its well-functioning. The well-functioning of ecosystem is crucial for our societies as it influences the provision of many ecosystem functionalities (*e.g.* carbon, nitrogen and phosphorus cycles) which are valorized by our societies (Haines-Young and Potschin, 2010). Our societies benefit notably from regulating services which protect natural and anthropic valuable assets or from cultural services which contribute to possible recreational activites (*e.g.* hunting, walking, *etc.*). Thus, reduction of biodiversity levels threatens the well-being of our societies (MEA, 2005).

These declines have encouraged policymakers to propose regulatory measures aiming to conserve biodiversity, notably since the Rio Biodiversity Convention (1992). In Europe, policymakers have encouraged to internalize the environmental costs linked to their activity through the promotion of voluntary agro environmental measures (AEM), the cross-compliance to some practices (*e.g.* crop diversification in the last program of the Common Agricultural Policy) or, sometimes, through the introduction of tax on variable inputs (*e.g.* tax pesticides in Danemark). For all of these instruments, the aim is to encourage farmers to modify their practices in order to maintain biodiversity and ecosystem functionalities. Policymakers hope that the set of instruments will modify farmers' behavior towards reduction of variable input application and acreage diversification. Indeed, according to production economics and the producer program, farmers maximize their profit according to the economic context trough input management (Mundlak, 2001). As the introduction of environmental policies modifies the economic context, they may influence the optimization process and thus the choice of inputs. However, these instruments do not present the same level of effectiveness. This is obviously linked to the different degree of voluntariness of the instruments, but also because farmers' choices rely on their technology. The form of the technology, notably regarding the relations of cooperation or substitution between inputs, impacts farmers' choices because it influences the agricultural goods production. The impact of the instruments depends thus on the targeted input and its relationships with the other inputs.

Despite the well-known inputs such as labor, capital, land and the intermediate consumptions (*i.e.* variable inputs[1]), the role of "supporting" and "regulating" ecosystem services (MEA, 2005) have been more and more recognized recently as an input for agricultural production (Zhang et al., 2007). The first category of services includes for example the mineral cycles, the soil formation, the primary production and the second one regroups notably disease and pest control. As these services rely on species richness and abundance (Haines-Young and Potschin, 2010), we refer to these processes as the "biodiversity productive capacity"[2]. Because these processes can either increase or decrease agricultural yields, an essential part of the work of farmer is to manage biodiversity (Chavas et al., 2010). Famous example of the management of biodiversity productive capacity is the implementation of fallow area, tillage reduction practices (Wu and Babcock, 1998), crop rotations (Hennessy, 2006) or biological control (Bianchi et al., 2006). Biodiversity is thus both an input for agriculture and an output for society. If policymakers want to increase biodiversity levels, their choice of instruments needs to integrate the evolution into the producer program linked to the biodiversity productive capacity. However, there is a lack of knowledge regarding the biodiversity productive capacity. First, we do not know how many the biodiversity productive capacity impact agricultural yields, or at least, not for all agricultural goods. Second, we do not know how biodiversity productive capacity interact with other inputs. These two points are crucial for policymakers because they condition the farmers' behaviour regarding biodiversity. The effectiveness of the instruments depends on these processes and relationships.

Several economic studies have examined empirically the effect of biodiversity productive capacity on agricultural production through the econometric estimation of a primal production function (*e.g.* Chavas and Di Falco, 2012; Di Falco and Chavas, 2008; Di Falco et al., 2010; Smale et al., 1998) or a dual production function (Omer et al., 2007). Their method is to introduce a biodiversity indicator based on land-use into the production function and to estimate the productivity of this indicator. They all conclude to an increase of mean yields and a decrease of variance yields. Similar studies have analyzed the effect of habitat diversity on profit (Di

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[1] In the case of agriculture, the most used variable inputs are fertilizers, pesticides, seeds, fuel, energy, feed and animal health and reproduction expenditures.

[2] Similarly, Chavas (2009) and Chavas and Di Falco (2012) refers to these processes as the "productive value of biodiversity".

Falco and Perrings, 2005; van Rensburg and Mulugeta, 2016) and have found a positive profitable effect of biodiversity.

On this paper, we propose to rely on the same method. However, we aim to overcome four limits of the previous studies. Indeed, we estimate the biodiversity productive capacity into a primal system taking into account for (i) several productions, (ii) several kinds of biodiversity, (iii) the interactions between conventional variable inputs and biodiversity productive capacity and (iv) the potential endogenous bias linked to the simultaneity of choice between variable inputs and objective yields. We will explain in more details these issues in the next section.

We estimate our model trough a primal system model integrating two production functions (cereals and milk). For both productions, we estimate the productive capacity of two kinds of biodiversity (the one living onto arable lands and the one living onto permanent grasslands). Into the production function, we add the application of six kinds of variable inputs and we examine the productive interactions of the two kinds of biodiversity with these inputs. We estimate our system on a representative and unbalanced sample of mixed farms from the FADN (Farm Accountancy Data Network) between 2002 and 2014. The farms are located on the North-West of France and produce a least cereals and milk. North-West of France has notably a diversified acreage (with still a large part of permanent grasslands) and presents a high density of mixed farming. Mixed farming is interesting for our question because (i) it requires that farmers manage their inputs for several productions and (ii) these farms present a more diversified acreage. We estimate our model thanks to general method of moment (GMM). This method allows correcting for endogenous bias on the application of variable inputs thanks to the introduction of exogenous instruments.

The next section provides a critical review of the literature on the subject. We present the theoretical model on the third section. The fourth section presents the empirical model, the econometric strategy and the biodiversity indicators which are used into the study. The fifth section presents the data and the sixth section presents the results. We then discussed the results, notably regarding the potentiality for policymakers to improve the effectiveness of their instruments. The final section concludes and gives indications for future researches.

2. Critic literature review

2.1. Literature review

From the late eighties and first “ecological economics” works, environmental quality is sometimes considered as a productive input (Barbier, 2007; Costanza et al., 1997). This introduction is partly due to previous works in ecology and agronomy where it was found that biodiversity has positive effects on landscape functionalities. Here, we review the literature on the biodiversity productive capacity in agriculture in empirical economics but also on agronomy and ecology. We stress the need to overcome some issue in empirical economics, notably based on previous agronomical and ecological findings.

2.1.1. Agronomical and ecological literature

Since the first hypothesis of diversity-stability (MacArthur, 1955), the ecological literature has examined intensively the effect of diversity on ecosystem functionalities. Several empirical studies have underlined the complementary role of species on ecosystem resilience (Holling, 1973; Hooper et al., 2005), but on the evolution of ecosystem production. Some studies have notably proved that biodiversity increases the net primary production (Costanza et al., 2007; Hector et al., 2002; Tilman et al., 1996, 1997), confirming the hypothesis of the "over-yielding" effect (Hooper et al., 2005).

Agronomy has also tried to benefit from the functionalities provide by biodiversity in order to increase the effectiveness of modern agricultural practices. Some of them are today well known from farmers. Among them, crop rotations are applied by most of farmers. Indeed, suitable crop rotation enhances the yield of following productions through its beneficial role on biological protection, nutrient stock and soil structure (Hennessy, 2006). Other famous practices which enhance can enhance economic margins are no-tillage practices and other soil reduced practices (Wu and Babcock, 1998) or the management of bee populations for some cash crops and vegetable productions (Kremen et al., 2004). In the context of our study, those examples are more related to arable land management and thus to the productive effects of arable land biodiversity. Arable lands are indeed suitable habitats for many species and it appears that habitat quality increases as crop diversity increases (Bertrand et al., 2016).

The evidences of the productive effects of permanent grasslands are much scares. The work of Tilman on the effect of the diversity of grasslands on ecosystem production is maybe the main source of knowledge. Indeed, it appears that, similarly to crop diversity, grassland diversity enhances mean yield and reduces variance yield (Tilman et al., 1996, 1997, 2006). However, there are few studies which have found evidences of the productive effect of grasslands on other productions. Nevertheless, this does not prevent scientists to study the impact of other key landscape elements which are usually found in rich permanent grassland landscapes.

In North-West of France, permanent grasslands constitute an important part of the landscape composition. With the presence of many hedgerows, they constitute a traditional landscape which is called “Bocage”. If hedgerows provide several functions which are valorized by society (*e.g.* water filtration), they can also benefit to farmers. Indeed, it seems that hedgerows provide several productive functions such as wind-break (both for livestock and crops) (Kort, 1988), erosion-brake, microclimate contribution (water retaining, albedo effect, etc.), wood and energy production or birds and insect habitat which can improve pest management (Aviron et al., 2005; Baudry et al., 2000a). However, these functionalities are not easily valorised by farmers, notably because they are substitute with other inputs such as capital. Indeed, hedgerows increase complexity of capital management. This has led some farmers to remove hedgerows in order to enlarge their field (Lotfi et al., 2010). As a consequence, it is today complex to find the real effect of hedgerow on production. For example, Thenail (2002) found that dense hedgerow landscapes were associated with smaller farms which have less machinery and thus lower milk productivity. Scale economies and substitutability between conventional and natural inputs increase the complexity of statistic identification of the productive capacity of hedgerows.

2.1.2. Economic literature

The analysis of biodiversity productive capacity on agriculture has recently benefited from a growing empirical literature in economics. These researches estimate through statistical methods the marginal effects of biodiversity in production or profit functions of several agricultural goods. Most of them estimate through a primal approach the biodiversity productive effect on production or estimate a risk premium through a dual model. As measures of biodiversity are tricky, they focused on biodiversity indicators such as habitat-friendly landscape elements like hedgerows or afforested lands (Klemick, 2011; Ofori-Bah and Asafu-Adjaye, 2011; Omer et al., 2007; van Rensburg and Mulugeta, 2016; Sauer and Abdallah, 2007) or landscape diversity indicators based on land-use (Chavas and Di Falco, 2012; Di Falco and Chavas, 2008, 2009; Di Falco and Perrings, 2005; Matsushita et al., 2016; Omer et al., 2007; Smale et al., 1998). Most of the literature focuses only on the effect of crop diversity on farm production and profitability because crop diversity can be considered as the main source of biodiversity within many agro-ecosystems, especially in developed countries (Di Falco and Perrings, 2003; Di Falco and Chavas 2008). They all found that biodiversity is a productive input of agricultural outputs which enhances mean yields and reduce variance yields.

Regarding the form of the production technology, it seems, similarly to other inputs, that biodiversity has decreasing marginal returns on both yield and profit (Di Falco and Chavas, 2006; van Rensburg and Mulugeta, 2016). It appears that biodiversity is especially important for the year of dryness, underlying that more diverse acreage retain more the available water (Di Falco and Chavas, 2008). Moreover, there are some that agrochemical inputs and biodiversity are substitute inputs (Di Falco and Chavas, 2006). However, these relations are not well understood, especially because of the high levels of agrochemical input utilization.

It appears that, in addition to its positive production effect, crop diversity is a suitable strategy for risk management (Di Falco and Chavas, 2006, 2009; Di Falco and Perrings, 2005). Whereas previous crop diversity studies have focused on portfolio choices and associated risk market reduction (Chavas, 2008), the interesting results on mean and variance yield have conducted researches to focus more on risk production. These evidences contribute to the idea that biodiversity has an insurance value and that it is a possible substitute to financial insurance (Baumgärtner, 2007).

2.2. Limits of the existing literature

If we do not challenge the agronomical and ecological literature, there are several drawbacks in the economic literature. First, studies have usually analyzed the effect of biodiversity on a single production function (wheat in most cases). However, we can expect to find different effects according to products. Among the diversity of studies analyzing the productive effects of biodiversity through econometric estimations (Chavas and Di Falco, 2012; Di Falco and Chavas, 2006, 2008, 2009, Di Falco and Perrings, 2003, 2005; Di Falco et al., 2010; Heisey et al., 1997; Matsushita et al., 2016; Ofori-Bah and Asafu-Adjaye, 2011; Omer et al., 2007; van Rensburg and Mulugeta, 2016; Sauer and Abdallah, 2007; Smale et al., 1998), only van Rensburg and Mulugeta (2016) have analyzed a livestock grazing system. All other studies have examined the biodiversity productive effect on crop agroecosystems. There are some needs to investigate the effect of biodiversity on other kinds of productions.

Second, these studies do not analyze the farm as a whole but focus usually on a single kind of biodiversity (arable lands, grasslands or perennial habitats). We criticize this choice because it does not examine the productive cross-effects between these kinds of habitats. Yet, there are some evidences that these areas are not isolated between each other. For example, Klemick (2011) found that forest fallows have positive productive externalities on agricultural production. This is an evidence of productive spillovers between a special kind of biodiversity (*i.e.* biodiversity living in forest fallow) and agricultural good growing on arable lands. Moreover, most of the empirical economics studies have examined a crop oriented agroecosystem[3]. To our knowledge, only one study has examined the effect of biodiversity on production within grassland agroecosystems (van Rensburg and Mulugeta, 2016). We believe that more researches deserve to be conducted on (i) these more marginal areas and (ii) on the spillovers of the different biodiversity towards a set of productions. This would allow a better understanding of farmers' behavior regarding the management of semi-natural landscape elements such as grasslands, forests or hedgerows. Indeed, in the case of mixed farms with milk and crop production, permanent grasslands dedicated to forage production can benefit from the biological protection from diversified arable lands. Milk cows can also benefit from a better yield when arable land biodiversity increases. Indeed, it may increase *(i)* levels of produced forages *(ii)* the diversity of cow feed and *(iii)* cow health because they are less sensible to pest invasion. These three effects can increase sensibly milk yields. Moreover, ecological and agronomical literature on permanent grasslands and attached landscape elements underline the possible productive effects of these elements on forage (maize silage and temporary grasslands) productions, and thus, indirectly, milk production.

Third, if we know that biodiversity can increase yields, we do not know as much on the relationships between biodiversity productive capacity and others inputs. The substitutability between conventional inputs (*e.g.* mineral fertilizer, pesticides, *etc.*) and biodiversity productive capacity is an issue of increasing importance in a context where conventional input prices are suspected to become higher (notably through their taxation). To our knowledge, only Di Falco and Chavas (2006) have examined these relationships, in the case of pesticides in Sicily, and found that they are substitute. As a consequence, the last CAP reform promoting crop diversification may result on pesticide use reduction. However, we do not know the relationship with other variable inputs, notably with mineral fertilizers which are also at the source of major environmental concerns. If fertilizer and biodiversity have complementary productive effects, the last CAP reform may result on fertilizer use intensification. As the choice of the optimal set of instruments for promoting biodiversity and/or reduce utilization of a societally undesirable inputs depends on the relationships of biodiversity productive capacity and the other inputs, there is a need to intensify the research on this question.

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[3] They justify the study of the impact of crop diversity because crop diversity is the main source of biodiversity within many European agroecosystems (Di Falco and Chavas, 2008).

Fourth, most of the cited studies use a primal approach to measure the effect of biodiversity on production. However, they have often failed to capture farmers' behavior. Indeed, the production analysis studies examine the effect of biodiversity indicators on production functions. However, none of them have ever try to connect those production functions to market prices. Thought, microeconomic theories underline that producers increase their production when output prices increase relatively to input prices (Mundlak, 2001). We argue that cited studies do not consider these fluctuations and neglected it in their methodological choices. Indeed, if most of them have analyzed the biodiversity production effect through the instrumentation of biodiversity indicators, they do not instrument others inputs (Chavas and Di Falco, 2012; Di Falco and Chavas, 2008; Di Falco et al., 2010; Omer et al., 2007; Smale et al., 1998). The application level choices of these inputs are however considered as simultaneous: farmers choose objective production levels and application levels of variable inputs given their technology and the economic context. The instrumentation of biodiversity but not of the other inputs supposes that farmer manage their biodiversity but not the other inputs. As a consequence, the conclusions of their studies may be biased, notably if biodiversity is substitute or complementary to variable inputs. In addition to the econometric biases, the assumption of exogenous variable inputs implies that these studies minimize the role of the farmer. Indeed, the farmer optimizes his profit with the management of biodiversity, quasi-fixed inputs (labor, capital and land) and variable conventional inputs (taking into account both the form of his production technology and market prices). As the quasi-fixed inputs can be consider as fixed in the short term, the farmer optimizes his current profit only through the management of biodiversity and conventional inputs. Thus, it is not right to only focus on biodiversity management and not the management of variable inputs[4]. Similar critics can be done on the estimation of profit function parameters (van Rensburg and Mulugeta, 2016). In addition to these biases, the analysis of the effect of biodiversity on profit function is necessarily fuzzy as they do not distinguish the portfolio strategy and the production effect. Contrary to previous studies, we rather consider that, in developed countries and in the short term, farmers manage their variable inputs according to the levels of biodiversity. From our opinion, this assumption seems weaker than the opposite.

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[4] This omission is notably underlined in the case of Di Falco and Chavas (2008) which study the productive effect of biodiversity in an agroecosystem of Northern Italy but do not introduce any conventional inputs on their analysis. However, the critic has to be nuanced in the case of case studies in developing countries where the use of conventional inputs is minimal and where farmers rely mostly on labor and biodiversity (Chavas and Di Falco, 2012).

Our study aims to overcome these four issues. In response to the three first issues, we present our theoretical model in the next section. The issue of non-instrumentation of conventional inputs is discussed in the empirical model section.

3. Theoretical Model

We consider that a farmer maximizes each year *t* his restricted profit function Π_t on variable inputs according to his quasi-fixed input dotation. 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}, $j \in J$). We make the assumption that these inputs are fixed in the short term. Considering his fixed input dotation and the economic context, the farmer optimizes only the application of variable inputs in order to maximize his short term profit. The vector X_t informs on the application level of the *I* variable inputs that the farmer use on his farm (noted X_{it}, $i \in I$). He buys these inputs at the market price (noted w_t, where w_t is the vector of the *I* elements w_{it} $i \in I$). According to variable input allocations and fixed input dotation, the farmer produces Y_t agricultural goods which are sold at the price p_t on agricultural markets.

We can write the producer program of the farmer as:

$$Max_{X_{it}} \Pi_t (E(p_t), E(w_t), Z_t) = \Pi_t (Y_t^*(E(p_t), E(w_t), Z_t), X_{it}^*(E(p_t), E(w_t), Z_t), Z_t \mid (Y_t, X_t, Z_t) \in \mathrm{T}) \qquad (1)$$

where Y_t^* and X_{it}^* are respectively the optimal amount of output and input levels considering the set of market information $(E(p_t), E(w_t))$. The Esperance terms return to the anticipation of market prices by the farmer. $(Y_t, X_t, Z_t) \in \mathrm{T}$ is the production set which technically constrained the farmer.

We consider that the farmer produces *K* outputs on its farm and that he produces Y_{kt} for the k^{th} output. The k^{th} output ($k \in K$) is sold at the market price p_{kt}. The farmer allocates the inputs between his *K* outputs (noted X_{ikt}) such that $X_{it} = \sum_k X_{ikt}$. Assuming constant costs for fixed input management and indivisibility between outputs for fixed inputs[5], we can write (1) as:

$$Max_{X_{ikt}} \Pi_t (E(p_t), E(w_t), Z_{kt}) = \sum_k \pi_{kt}^* (Y_{kt}{}^*(E(p_{kt}), E(w_{it}), Z_t), X_{ikt}{}^*(E(p_{kt}), E(w_{it}), Z_t), Z_t \mid (Y_{kt}, Y_{-kt}, X_{ikt}, Z_t) \in \mathrm{T}_k) \qquad (2)$$

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[5] Note that we can also allow for the division of the fixed input between the *K* outputs. In this case, we note K_{kt} such as $K_t = \sum_k K_{kt}$.

where π_{kt} is the margin of each production and π_{kt}^{*} is the optimized margin. T_k is the visible input set for each output Y_{kt}. As we are in a multi-output farm, note that the visible input set for each Y_{kt} depends on other productions. The technology is characterized by an increasing function, linearly homogenous and strictly quasi-convex.

In a certain economic context, we can write π_{kt} as:

$$\pi_{kt}(p_{kt}, w_{kt}, Z_{kt}) = p_{kt}Y_{kt} - \sum_k w_{it}\, X_{ikt} \mid (Y_{kt}, Y_{-kt}, X_{ikt}, Z_t) \in \mathrm{T}_k \tag{3}$$

Assuming constant return to acreage, we can write (3) as

$$\pi_{kt}(p_{kt}, w_{kt}, Z_{kt}) = p_{kt}s_{kt}y_{kt} - \sum_k w_{it}\, s_{kt}x_{ikt} \mid (y_{kt}, y_{-kt}\, x_{ikt}, z_t) \in \mathrm{T}_k \tag{4}$$

where s_{kt} is the area allocated to each production *k* on year t, y_{kt} is the yield of output *k* on year t, x_{ikt} is the amount of variable input *i* by area allocated to each output and z_t is the amount of fixed input by area. We thus have $X_{it} = \sum_k s_{kt}x_{ikt}$ and $Z_t = z_t \sum_k s_{kt}$. The constant return to acreage assumption is often used as a simplification in multicrop econometric models for the analysis of extensive margins and crop diversification motives (Carpentier and Letort, 2014).

The production technology T_k regroups the production function of each production $F_{kt}(x_{ikt}, z_t)$. Taking into account the constant return to acreage assumption, $F_{kt}(x_{ikt}, z_t)$ represents the yield of output *k* in year *t*. It is assumed that $F_{kt}(x_{ikt}, z_t)$ verifies for each input *i* and output *k* that $\frac{\partial F_{kt}(x_{ikt}, z_t)}{\partial x_{ikt}} > 0$.

In the case of multi-output firm, a joint technology allows for scope economies. Assuming two production, we can write that $F_1(x_{i1t}, B_{jt}, z_t, Y_2 | Y_2 > 0) \geq F_1(x_{i1t}, B_{jt}, z_t\, Y_2 | Y_2 = 0)$. The production of the first input increases when there is a specific second production. Our model takes into account for these specificities.

Solving (1), the farmer solves for each input *i* and each product *k* the following first order conditions:

$$E(p_{kt})\frac{\partial F_{kt}}{\partial x_{ikt}} - E(w_{ikt}) = 0 \tag{5}$$

Considering the economic context, his fixed input dotation and his biodiversity levels, the farmer optimizes in the same time Y_{kt}^{*} and X_{ikt}^{*}. This classic relation is crucial for two reasons. First, it illustrates the farmers' behavior regarding input management and stresses the need to correct for the endogenous bias. Second, this relation has powerful meanings in the case of a multi-output firm.

Regarding the first point, equation (5) illustrates that, when the farmer sows his production, he has already chose the optimal levels y_{kt}^* and x_{ikt}^* given the anticipated economic context and his fixed input dotation. The choice of y_{kt}^* is simultaneous with the choice of x_{ikt}^*. For the econometric estimation of the production function parameters, this led to endogenous biases. In order to overcome the endogenous biases linked to the simultaneous choices of y_{kt}^* and x_{ikt}^*, we instrument application levels of each variable input by the market price of both inputs and outputs. Indeed, the market ratios $\frac{E(p_{kt})}{E(w_{it})}$ and $\frac{E(w_{jt})}{E(w_{it})}$ influences the choices of x_{ikt}^*. We expect notably that an increasing of $\frac{E(p_{kt})}{E(w_{it})}$ will lead to an increasing consumption of x_{ikt}. These ratios are sometimes used for the estimation of variable input demand functions (*e.g.* Carpentier and Letort, 2012). We thus instrument the variable input application levels by their demand functions.

Regarding the second point, equation (5) means that the marginal productivity in value is equal to the cost of the last unity of input. This classical result is useful in the case of a multioutput farms. Indeed, in the economic dataset, we do not have the information on the X_{ikt}^* but only on the X_{it}^*. We use this relation in the empirical study to allocate the X_{it}^* (the total amount of variable input *i* bought and applicate at the farm scale) between the *K* outputs. Indeed, in the case of a multi-output producer, equation (5) means that the farmer will optimize these conditions on each output, leading to:

$$E(p_{kt})\frac{\partial F_{kt}}{\partial x_{ikt}} = E(p_{lt})\frac{\partial F_{lt}}{\partial x_{ilt}}\ ,\ \ l \neq k \tag{6}$$

For each output, the farmer applies variable inputs until the cost of the last unity of variable input equals the anticipated marginal productivity in value. At the optimum, the farmer will thus equal his marginal productivity in value of each output.

Assuming $E(p_{kt})$ is constant for each couple *(farmer, year)*[6], we thus reach the optimal condition:

$$\frac{\partial F_{kt}}{\partial x_{ikt}} \Big/ \frac{\partial F_{lt}}{\partial x_{ilt}} = c;\ \ \forall\ (k,l) \in K \text{ and } \forall\ i \in I \text{ with } c \in R \tag{7}$$

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[6] The farmer anticipates to sell his production at the same single price in year *t*.

At the optimum, the ratio of the marginal productivity of each input is equal. This last relation is crucial for the analysis because it contains the optimization process of the farmer. This imposes restrictions on the production function parameters which include the farmer's economic behavior. We use these restrictions for our econometric estimation.

In our empirical model, we estimate the production functions $F_{kt}(\cdot)$ of milk and crops on a sample of mixed farms of western France. We want to estimate the effects of B_{jt} into the two production functions, taking into account for their interactions with the variable inputs. The estimation of the parameters of the two functions use the parameter constraints (7) on the optimal application of variable inputs x_{ikt}^*. Moreover, in order to take into account the simultaneous bias between of y_{kt}^* and x_{ikt}^*, we instrument the variable input application by market price ratios. The addition of (i) the variable input demand functions as variable input instruments and (i) the optimum restrictions on the parameters in order to allocate the input between several outputs allows for a full integration of the optimization process of the farmer.

4. Empirical model, econometric strategy and biodiversity indicators

The aim of this section is to show how we overcome the empirical issues in order to test our theoretical model. The first part presents the measure of the levels of farmland biodiversity through the utilization of biodiversity indicators. The second part presents the empirical model that we estimate.

4.1. Biodiversity indicators

Biodiversity measures are not easily available. Thus, most of the authors have used biodiversity indicators which gave indications on the real biodiversity levels. Among the diversity of biodiversity indicators, two groups are currently distinguished: (i) direct indicators which measure presence of an indicator species in point maps (*e.g.* Gregory et al., 2005) and (ii) indirect indicators (or structural indicators) based on land-use composition and configuration (Kindlmann and Burel, 2008). This last approach is highly influenced by landscape ecology which postulate that landscape structure (defined by its composition and configuration) determine species dynamics and thus species abundance (Burel and Baudry, 2003). There exist many landscape indicators which inform on the levels of the landscape functionalities. However, as there is no institutional dataset which provide enough highly details on both the economic and geographic sides, it requires privileging one of the two dimensions. Our needs in economic data compel us to select biodiversity indicators which can be computed with limited information on landscape structure (*i.e.* only on landscape composition).

For our empirical application, we select two kinds of biodiversity habitat: arable lands (noted B_{1t}) and permanent grasslands (noted B_{2t}). In the case of arable lands, we choose to rely on a Shannon index, an indicator which has been used by several empirical microeconomic studies to measure crop diversity (Di Falco and Chavas, 2008; Di Falco and Perrings, 2003, 2005; Matsushita et al., 2016; van Rensburg and Mulugeta, 2016). Indeed, this indicator is very used for biodiversity measures because it has the advantage to correct for species abundance and is not sensitive to sample size (Keylock, 2005). Above all, it is well adapt to measure habitat diversity (Mainwaring, 2001). The Shannon index is usually write as

$$B_{1t} = \sum_{k=1}^{K} s_{kt} \ln(s_{kt})$$

where s_{kt} is the proportion of each area in the total arable land area, and where $k \in K$ is an output which grows on arable lands. Permanent grasslands or other areas (e.g. permanent cultures) do not enter in K. B_{1t} takes the value 0 when the farm presents a monoculture and B_{1t} increases with the number of farm arable land productions. In other terms, B_{1t} increases when habitat diversity increases and, as biodiversity increases when habitat diversity increases, B_{1t} increases when biodiversity increases.

Mixed farms of western France often present a diversified acreage. Indeed, most of them produce crops, maize silage and temporary grasslands[7]. We thus compute a simplified Shannon index corresponding to the acreage composition of the three main areas of mixed farms of western France:

$$B'_{1t} = \sum_{m=1}^{3} s_{mt} \ln(s_{mt})$$

where s_{mt} is the proportion of each area in the sum of the three areas.

The comparison of the productive effects of B_{1t} and B'_{1t} on crop and milk productions illustrates the importance of the “marginal” productions. Though different indicators, Smale et al. (1998) have also used several biodiversity indicators for the analysis of crop diversity productive effects.

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[7] These three outputs represent 78,2% of the total area of our sample. See section 5 for more details.

For permanent grassland biodiversity, we choose our indicator as the proportion of permanent grasslands in the the utilized agricultural area (UAA), *i.e.* $B_{2t} = s_{Gt}$ where the Gth output is permanent grassland[8]. As already said, the interest to focus on permanent grasslands share is to have a proxy of the number of permanent semi-natural landscape elements which are susceptible to have productive effects on milk and crop productions (*e.g.* hedgerows, trees, shrubs, earth banks, etc.). Indeed, analysis of the landscape composition in North-West of France has notably concluded to the positive correlation between permanent grasslands and hedgerows (Baudry et al., 2000b; Thenail, 2002). However, high share of permanent grasslands increases also landscape complexity and thus there is a "buffer" effect on biological control. Both effects (landscape complexity and semi-natural elements) will be captured on the biodiversity productive capacity.

4.2. Empirical model and econometric strategy

We present in this part the empirical model that we want to estimate. We consider two outputs in our model: crops (k=1) and milk (k=2). The two outputs are product on separated areas S_{1t} and S_{2t}. For both outputs, we estimate the production functions. The first one, a log-linear production function is estimated in order to use the associated constraints on marginal productivity (following the first order conditions (5)). For crops, we estimate:

$$F_{1t}(x_{i1t}, B_{jt}, Z_{lt}) = \log(y_{1t}) = \beta_{01} + \sum_{i=1}^{4} \beta_{i1} x_{i1t} + \sum_{j=1}^{2} \beta_{j1} B_{jt} + \sum_{l=1}^{3} \beta_{l1} z_{lt} + \varepsilon_1 \qquad (8)$$

$F_{1t}(x_{i1t}, B_{jt}, Z_{lt})$ is the crop yield function which express the quantity of crop produced by crop area. We consider four variable inputs *i*: mineral fertilizer (*i* = 1), pesticides (*i* = 2), seeds (*i* = 3) and fuel (*i* = 4). The three other fixed inputs *l* are available labor, farm capital and total farm area. They are divided by the utilized agricultural area. ε_1 is the error term of the equation (9). It captures notably the effects of the unknown variables from the econometrician. In order to limit this bias, we use also control variables.

For milk, we also estimate a log-linear production function such as:

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[8] Note that we can compute B_{1t} as: $B_{1t} = \sum_{k=1}^{K} \frac{S_{kt}}{(S_{tott} - S_{Gt})} \ln\left(\frac{S_{kt}}{(S_{tott} - S_{Gt})}\right)$ where S_{kt} is the size of the area dedicated to crop *k*, S_{Gt} is the size of the area dedicated to permanent grassland and S_{tott} is the utilized agricultural area of the farm.

$$F_{2t}(x_{i2t}, B_{jt}, Z_{lt}) = \log(y_{2t}) = \beta_{02} + \sum_{i=1}^{6} \beta_{i2} x_{i1t} + \sum_{j=1}^{2} \beta_{j2} B_{jt} + \sum_{l=1}^{3} \beta_{l2} z_{lt} + \varepsilon_2 \qquad (9)$$

Milk production $F_{2t}(x_{i2t}, B_{jt}, z_{lt})$ is expressed in kilograms of milk per hectare of main forage area (S_{2t} is equal to the total size allocated to maize silage, temporary grasslands and permanent grasslands). In addition to the four previous variable inputs which are necessitated to animal feeding (notably forage production), we add purchased feed (*i=5*) and health expenses (*i=6*). We also consider the two kinds of agricultural biodiversity and the fixed inputs z_{lt}. ε_2 is the error term of the equation (9). Similarly to (8), we also add control variable to reduce the endogenous biases.

The β_{ik} in equations (8) and (9) represent the marginal productivity of input *i* on output *k* (*i.e.* the $\frac{\partial F_{kt}}{\partial x_{ikt}}$). The final optimal condition of our theoretical model imposes that the ratios $\frac{\beta_{i1}}{\beta_{i2}}$ are equals for common variable inputs. In our model, we thus have three restrictions:

$$\frac{\beta_{11}}{\beta_{12}} = \frac{\beta_{21}}{\beta_{22}} = \frac{\beta_{31}}{\beta_{32}} = \frac{\beta_{41}}{\beta_{42}} \qquad \text{(R1)} - \text{(R3)}$$

This captures the rational short term optimization of the farmer. As we consider only the restricted profit function, these three restrictions capture the essential part of the farmer's econometric behavior. As a consequence β_{ik} measure the product of the marginal productivity of input *i* on product *k* on one hand by an input repartition factor[9] on the other hand. This last factor captures the relative input needs of crops and forage production. Thereby, the parameters β_{ik} measure two effects which are impossible to separate. However, as our interested parameters are the β_{jk}, we just have to verify that β_{ik} are consistent with theory for each input *i* and output *k*. As the input repartition factor is positive, we expect that β_{ik} are positive.

As underlined in the theoretical model section, we also add input demand functions as instruments in order to overcome the simultaneous biases. These function are written as:

$$x_{it}^{*} = \alpha_{i0} + \alpha_{i1} \frac{p_{1t-1}}{w_{it}} + \alpha_{i2} \frac{p_{2t-1}}{w_{it}} + \alpha_{ij} \frac{w_{jt}}{w_{it}} + \mu_i \qquad (10)$$

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[9] Another solution would be to use input repartition using output areas (Carpentier and Letort, 2012; Just et al., 1990). However, as we are interested in the estimation of the production function parameters, this solution would necessitate the mobilization of nonlinear econometrics. Linear econometrics does not allow for the desegregation of these two effects.

where $j \neq i$ and μ_i is the error term of equation (10). This linear specification is line with the characteristics of the demand function which should be decreasing and homogeneous of degree zero in prices. Our results suggest that the input demand functions depend more on the output price of the previous year rather than the output prices of year t. We thus consider that farmers of our sample have naïve anticipation regarding output prices (Nerlove and Bessler, 2001)[10]. Naïve anticipations are notably support for milk production by the milk quota until 2015. For input demands however, we use current prices. The utilization of previous prices for outputs and current prices for inputs is a common feature in agricultural production economics. In addition to market prices, we also add milk quota and the exogenous variable of equations (8) and (9) in (10) in order to increase the effectiveness of those regressions. We will discuss deeper the interest of these equations on the following econometric strategy part.

As underline in the theoretical part, an important economic issue in the case of multi-output farms is that these farms can benefit from joint technology. In the case of mixed farms with crop and milk productions, the cattle dejections can be used to enhance the production of crops. This is an example of quasi-joint technology where the byproduct of the production of milk is used for another production. To increase the inputs allocated to milk increase (i) the production of milk but also (ii) the production of organic fertilization. The organic fertilization can then be used for crop and forage productions in substitution to mineral fertilization. For our study, we have to take into account this specificity. Indeed, permanent grasslands are statistically linked to milk systems. As a consequence, there is a risk that a portion of B_{2t} captures the effect of organic fertilization. In order to capture this effect, we add proxies of organic application in (8) and (9). To measure the available organic fertilizer at the farm scale, we compute a formula given by Environmental and Agricultural French Ministries based on the number of animal units at the farm scale (CORPEN, 2006). We distinguish two kinds of organic manure: the one from cattle and the one from other livestock. This addition in the empirical model allows the estimation of the “true” productive effects of permanent grasslands.

A similar issue concerns the inter-consumption of crops for cattle feed. However, our data suggests that this inter-consumption represents less than 10% of animal feed. We thus assume that these inter-consumption is not a key element strategy of mixed farms.

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[10] Except for the case of the animal variable input demand function where the current prices are more effective than previous prices. This is coherent with the agronomic view. Indeed, cow feed and reproduction and health purchase can be adjusted much quicker than forage production (and thus variable input demand functions of mineral fertilizer, pesticides, seeds and fuel). We also test rational expectations of output prices but the results suggest that milk farmers have more naïve anticipations.

In addition to linear production functions, we also try, in a second step, to estimate log linear production functions with crossed terms between the B_{jt} and x_{ikt} (for $i \in [1;3]$). These crossed terms add some flexibility to the model, but, above all, they add information on the relationship between biodiversity productive capacity and variable inputs. The addition of crossed effects on the production function increases however the number of endogenous terms and increase the complexity of the parameter estimations (Chamberlain, 1987). The additional instruments are computed as the multiplication of market price ratios by B_{jt}.

We estimate the parameters of the two log-linear production functions (8) and (9) on a pooled panel data sample. In order to take into account for potential heteroscedasticity and the correlations between the error terms of the two equations[11], we estimate the model constituted of (8) and (9) with GMM. As discussed before, we thus estimate the $\hat{x}_{ikt}^{*}$ on instruments variables thanks to equation (10). We thus estimate a system of two production functions with the instrumentation of the six input thanks to variable input demand with the equations parameter restrictions (R1) - (R3). In a second step, we do the same estimation with the addition of crossed terms. We present the results of the two estimations on table 2.

For robustness check, we also estimate the second model with other methods. As a first indication, we estimate these parameters separately for each production with ordinary least squares (OLS) method. We then estimate the system constituted of equations (9) and (10) with the addition of the parameter restrictions (R1) - (R3) in a seemingly unrelated regression (SUR). optimization process of the farmer. These two first steps do not take into account for the endogenous biases linked to the simultaneous choices between y_{kt}^{*} and x_{ikt}^{*}. As a consequence, we choose to estimate a Three Stage Least Square Instrumental Variable (3SLS) estimation procedure. Finally, and in order to test for restrictions effect, we estimate model 2 with GMM but without the restrictions. Alternative estimations are presented in the annexes (table A1).

5. Data and variables description

Data were obtained from the French Farm Accountancy Data Network (FADN), a bookkeeping survey carried out each year by the French Ministry of Agriculture on a rotating panel of farms. Each country of the European Union has to conducted a similar survey. The FADN has the objective to analyse the effects of the past CAP reforms and to simulate the future ones. The

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[11] The correlations are notably linked to farm specific variables which are unknown for the econometrician.

FADN is valuable for European economists because it provides highly detailed available economic information of the European farms.

We use the FADN samples of three NUTS2 regions of North-West of France from 2002 to 2014: Brittany ("Bretagne" in French), Lower Normandy ("Basse-Normandie" in French) and Western Loire ("Pays-de-la-Loire" in French). These regions are characterized by mix farming systems and are mainly orientated towards breeding, especially for pig, poultry and milk production. As pig and poultry breeders are mainly off soil, we focus on dairy activities. Indeed, these three regions present a high concentration of the French milk production: more than the half of the French milk production in 2016 were produced on these regions (AGRESTE, 2016). Most of them have also a crop production[12]. These three regions have also a good dotation on permanent grasslands[13]. Indeed, dairy farms present the significant advantage to, contrary to other farming systems, maintain a large part of their UAA in grasslands.

Over the whole period, there are 7131 farms with a milk production on these regions which are present two years in a row[14]. In order to examine the effect of B'_{1t} (the degraded arable biodiversity indicator), we select only the farms which have area dedicated to crops, maize silage and temporary grasslands. Over the whole period, our sample contains thus 1035 farms whose presence in the survey is on average of 4,85 years, *i.e.* 70,4% of the initial milk farm sample (and 71,4 % of the initial total area). As we use naïve anticipation for our instruments, we delete information on the first year of each farm. At the end, we estimate our two models on 3984 observations.

As we used output prices of the previous year for the instrumentation of variable inputs, the year 2002 is only used to give information on milk and crop prices for the year 2003. As a consequence, the set of financial instruments from the CAP were slightly similar between the whole period. Indeed, farms from our sample face only the 2008 CAP reform. If the 2003 CAP reform has presented many changes in comparison with the previous CAP programs, the 2008 CAP reform is quite similar to the 2003-2008 reform. The most notable changes are the suppression of fallow obligations, the gradual increase of milk quotas and the generalization of the decoupling subventions. As the 2014 PAC reform has been applied in 2015, we can consider that the set of financial supports were quite homogenous during our sample period.

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[12] In our sample, 93% of the farms have a crop production. Dairy farms produce several crops which can enter in the cow alimentation or can be sold on crop markets.

[13] Lower Normandy had notably more than 700 000 Ha of permanent grasslands in 2006 (AGRESTE, 2009).

[14] For which we can compute output lagged prices.

Table 1 presents the description statistics of the variables used in the empirical analysis. Our data are mainly based on farm structure and major production inputs. We do not present other variable inputs such as energy or maintenance spending. Studied regions face an oceanic climate providing temperate temperatures and regular rainfall. Irrigation is thus not a common practice in these regions and is not considered in our analysis. As farm total purchased variable inputs are presented in value in the FADN, we obtain an index of annual index consumption using an index of price evolution. The price of each input is obtained at the regional scale each year using the French regional account for agriculture (base 100 in 2015). The summary statistics of variable inputs in Table 1 are thus not the real farm scale purchased quantities but only an index of this consumption.

Here, crops recover 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 crops in 2002. In opposition, utilized milk prices are individual ones. All the input and milk prices were deflated by inflation rates among the period[15].

Table 1: Descriptive statistics

(N = 3984)

	Mean	Median	Q1	Q3	Min	Max
Crop yield (in constant €/Ha)	534,76	542,92	416,12	654,7	3,92	2175,11
Milk yield (in tons/Ha)	64,72	63,51	47,45	79,61	2,77	209,09
log(crop yield*100)	10,799	10,902	10,636	11,089	5,971	12,29
log(milk yield*1000)	10,982	11,058	10,767	11,285	7,926	12,25
Degrated Arable Biodiversity index	0,996	1,033	0,963	1,071	0,268	1,099
Arable Biodiversity index	1,278	1,236	1,048	1,51	0,206	2,287
Grassland Biodiversity index	0,093	0,014	0	0,12	0	0,82
Total area (are)	9356	7978	5723	11461	1559	38288
Main forage area (are)	6164	5411	3822	7664	989	25820
Fertilizer (quantity index)	131,74	105,92	61,95	169,98	0	1082,39
Pesticides (quantity index)	74,12	55,77	32,63	89,28	0	860,01
Seeds (quantity index)	84,89	68,28	44,41	102,64	0	898,57
Fuel (quantity index)	60,43	49,67	32,12	76,57	0	314,55
Cow feed (quantity index)	299,29	241,26	139,39	384,02	1,7	2803,41
Health and reproduction (quantity index)	55,74	44,05	27,21	74,32	0	407,17
Available cattle fertilizer	8871,66	7456,86	5273,93	10949,31	735,81	43301,69
Other available livestock fertilizer	1872,91	0	0	0	0	95850
Capital (€)	302393	255178	159678	381575	0	3903139
Labor (annual worker unit / 100)	220,17	200	150	300	100	1188
Labor (declared total working time in hours)	3530,54	3200	2400	4800	1600	19000
Disadvantaged area (Yes = 5; No = 1)	1,147	1	1	1	1	5

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[15] We have also try to deflate with an indicator of agricultural good prices but the estimations are less effective.

On our sample, 96% of the area is dedicated either to crops, maize silage, temporary grasslands or permanent grasslands. This decomposition highlights the importance of the analysis of B'_{1t} in comparison with B_{1t}. Indeed, it seems that mixed farmers from our sample manage in priority three or four kinds of area (B'_{1t} and B_{2t}) but do not diversify much more their acreage. In the sample, 63,2% of the crop area are soft wheat. We do find that the Shannon index of the total arable land biodiversity index is on average higher than the degraded one. Coherently, we also find that the total arable land biodiversity index has a higher variance than the degraded arable land biodiversity index. Among our sample, 54% of the observations presents an area dedicated to permanent grasslands. Permanent grasslands represent 9,3% of the areas.

The majority of the mixed farms from our sample are more orientated towards milk production. Milk and crop are the two first profitable outputs of our farm sample. On average, 57.45% of the revenues come from milk production and 8.03% come from cereal production. Revenues from cereal production represent on average as much as the revenues linked to the selling of the byproducts of milk production. For example, 6.29% of the farm revenues come from selling of cull cows and 2.13% from selling of calves. Some of the farms in our sample have other breeding activities, notably pig production. If the average revenues from this activity weight 6.09% of the revenues, only 11% of the farms of our have this activity.

6. Results

Table 2 reports the estimation results of the two log-linear production functions of the estimated system with GMM and parameter restrictions (R1) – (R3) on marginal productivities. Table A1 in annexes presents the parameter estimations of the two production functions with four other different estimation methods. In complement to the estimated production function parameters of table 2, Table A2 (in annexes) summaries the parameter estimations of the variable input instrumentation of the system which is used in the GMM and 3SLS methods.

Table 2: GMM estimations of the yield equations of the complete system

	Model 1				Model 2			
	log (y_crops)		**log (y_milk)**		**log (y_crops)**		**log (y_milk)**	
	Estim.	Sign.	Estim.	Sign.	Estim.	Sign.	Estim.	Sign.
Const	10,27	***	10,70	***	9,31	***	10,64	***
	(0,09)		(0,12)		(0,51)		(0,32)	
Biodiversity								
B1	0,260	***	-0,08		1,06	**	-0,08	
	(0,054)		(0,085)		(0,39)		(0,34)	
B2	0,011		-0,57	***	1,27	**	-0,11	
	(0,008)		(0,06)		(0,48)		(0,44)	
B1 * B2					-1,19	**	-0,36	
					(0,41)		(0,36)	
Variable inputs								
Fertilizer	-21,28	***	2,94		-54,23	**	-18,82	
	(3,87)		(3,76)		(18,82)		(16,30)	
Fertilizer * B1					26,80	*	15,29	
					(12,80)		(11,84)	
Fertilizer * B2					-5,76		23,28	
					(21,09)		(17,19)	
Pesticides	48,81	***	-6,65		170,73	**	-39,08	
	(12,56)		(8,78)		(59,16)		(51,97)	
Pesticides * B1					-94,59	*	-33,19	
					(40,67)		(33,19)	
Pesticides * B2					12,37		-81,41	
					(81,73)		(64,55)	
Seeds	9,61		-1,33		56,39		56,24	
	(10,47)		(2,29)		(48,47)		(44,13)	
Seeds * B1					-37,27		-46,02	
					(35,85)		(39,93)	
Seeds * B2					25,65		28,63	
					(62,28)		(46,75)	
Fuel	6,22		-0,87		0,48		28,04	°
	(22,98)		(3,22)		(18,95)		(16,81)	
Cow feed			10,66	***			11,71	***
			(1,66)				(1,44)	
Health and reproduction			53,52	***			30,44	**
			(12,33)				(9,44)	
Organic Fertilizer proxies								
Available cattle fertilizer/total area	0,06		-0,46	***	0,02		-0,45	***
	(0,06)		(0,06)		(0,06)		(0,07)	
Other available livestock fertilizer /total area	-0,003		-0,043	*	-0,02		-0,07	**
	(0,003)		(0,019)		(0,02)		(0,02)	
Control variables								
Total area	-5,6E-06	*	-0,00002	***	-4,71E-06		-2E-05	***
	(2,23E-6)		(2,70E-6)		(2,30E-6)		(2,61E-6)	
Capital/total area	0,002	°	0,0005		0,0014	°	-0,001	
	(0,0008)		(0,0009)		(0,0007)		(0,0008)	
Labor (annual worker unit) / total area	46,97		108,72	**	5,90		61,34	*
	(35,70)		(36,68)		(36,14)		(28,55)	
Labor (declared total working time) / total area	-3,03		-6,48	**	-0,37		-3,45	°
	(2,23)		(2,29)		(2,30)		(1,78)	
Disadvantaged area	0,01		-0,009		-0,006		-0,02	
	(0,012)		(0,015)		(0,01)		(0,014)	
Restrictions								
Restriction 1	-0,047							
Restriction 2	-0,016							
Restriction 3	-0,008							
Number of observation	3984							

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

In the case of model 1 (without crossed term effects), results in Table 2 show that the variable inputs display some surprising signs. Indeed, for cereals, if we do find that pesticides increase significantly yields, as expected in theory, we also find that mineral fertilizer decrease cereal yields. This is a surprising result because, if the theoretical result should be positive, most if the empirical results have found that the fertilizer marginal productivity has thus no impact on marginal productivity on most cases. The null marginal productivity has been found in many works on mixed farms (Carpentier, 1995; Dupraz, 1996). A possible justification is that, from a certain amount of application, fertilizers are not limiting any more (Carpentier, 1995; Dupraz, 1996). With the low prices of mineral fertilizer and the availability of manure for organic fertilization, mixed farmers have a high availability of nitrogen. As a consequence, the null productivity is sometimes interpreted as a self-insurance behavior. In our SUR estimation with restrictions (table A1), we find parameters which are all significant and positive (for pesticides, seeds, fuel, cow feed and health and reproduction expenses) except in the case of fertilizer where we do not find any effect. Thus, the SUR estimation gives us the expected results. Our results in the model 1 with GMM estimation are not consistent with theory. The explanation may come from the instrumentation (see Table A2 in annexes) or also because of heterogeneity issues. Regarding the first potential issue, the R of the fertilizer instrumentation is the lowest one which indicates that we may face weak instrument problem. The second potential bias is linked to the aggregation of all the cereals into an index. The aggregation weights the nitrogen needs and, as all cereals do not require the same amount of nitrogen, it may lead to negative productivity. Results on milk yields underline that the results are much less significant, as we could have expected. Indeed, fertilizer, pesticides and seeds may impact milk yields through forage yields. However, forage constitutes only a single input in the milk production function and can moreover be a substitute to other inputs. This may explain the lack of significance of the productivity of fertilizer, pesticides and seeds. In comparison, we do find significant and positive productivities for cow feed and health and reproduction expanses. Finally, it is important to highlight that the restrictions are significant in the SUR estimation but not in the GMM one. If the restrictions are important enough to straighten the productivity to significantly positive in the SUR estimation, they do not play a sufficient role in the case of GMM estimation. Our method for input allocation is less efficient when we instrument variable input application.

Regarding biodiversity productive capacity, we do find that B_{1t} increases cereal yields. However, we do not find any effect of B_{2t} on cereal yields, suggesting that permanent grasslands and attached elements do not have any productive spillovers towards arable lands. However, it seems that share of permanent grasslands reduce milk yields, capturing tendency to extensive farming techniques, notably grazing. This interpretation is notably support by the effect of the size of the UAA on milk yield (negative and highly significant). We do not find any effect of B_{1t} on milk yield. Thus, even if B_{1t} increases forage yield, the effect is not captured in the estimation of model 1. Comparing these results with SUR estimation (table A1), we find that instrumentation degrades these effects. Results provide by this functional form does not provide additional information with regard to the existent literature.

Crossed terms introduction provides interesting results, even if some of them are still surprising. Regarding the variable inputs signs, introduction of crossed terms forces us to release the parameter restrictions (R1) – (R3). However, it gives quite similar results than model 1. We still find that the proper effect of pesticides is positive and the one of fertilizer is negative. We do not find any proper effect of seeds and fuel on milk and cereal yields. For milk, we still find a highly significant effect of cow feed and health and reproduction expenses on yields. The single difference is that we find that fuel does increase milk yield. Results with SUR and 3SLS estimations on model 2 (table A1) are much more consistent with theory. We notably find that the proper effect of fertilizer is null in both production functions. The proper effect of seeds on cereal yields is also positive and significant (table A1). Aggregation issue and the indirect linked between fertilizer, pesticides, seeds and milk yield are still captured in model 2. However, estimation of model 2 gives interesting results for other parameters.

The first one is that we find positive and significant effects of B_{1t} and B_{2t} on cereal yields. We thus find the same positive effects of arable land diversity on crop production than previous studies (Chavas and Di Falco, 2012; Di Falco and Chavas, 2008, 2009; Di Falco et al., 2010; Matsushita et al., 2016; Smale et al., 1998). The positive effects of B_{1t} capture the productive effects of crop rotation but also the effects of biological control on current year. Regarding the positive and significant proper effect of B_{2t} on cereal yields, it highlights that there are productive spillovers from permanent grassland areas to crop areas. As permanent grasslands are fixed elements, their effect is not linked to crop rotation. We can assume that their presence increase acreage complexity and thus biological control, but also, that the higher density of semi-natural elements attached to these areas increase yields (effect of biological control and wind-break). This is the first time that this result is found in empirical economics. These results are robust according to estimation method (table A1).

The second interesting result is that proper effects of both biodiversity productive capacity are not significant. This is more consistent with theory than in model 1 or in OLS and SUR estimations (table A1). Indeed, it would be surprising that permanent grasslands and other permanent landscape elements have positive productive effects on milk yield. Even if some wind-breaks effect can increase the well-being of milk cows (Kort, 1988), the decrease of available energy in forage should decrease milk yield. The potential productive effects of B_{1t} on forage yields are not captured on this estimation. The lack of significance of both biodiversity productive capacity and variable inputs underlines that it is difficult to estimate a yield expressed in quantity by area for animal outputs. The 3SLS estimation provides similar results (table A1).

The third interesting result with the addition of crossed terms is that most of crossed terms are significant and provide new insights on biodiversity productive capacity. First, it appears that the both biodiversity productive capacity are substitute for cereal yields. Thus, their proper effects on yields are positive and the crossed terms reduce these effects. These results seem to be confirmed by landscape ecology studies on the North-West of France. They find that hedgerow and permanent grasslands densities decrease pest pressure, and, interestingly, that high hedgerow density reduces the effect of crop mosaic (Puech et al., 2015 and on-going works). Second, interaction of biodiversity productive capacities is null for milk yields, confirming the lack of influence of biodiversity productive capacity on this output. These effects on interaction between B_{1t} and B_{2t} is confirmed by 3SLS estimation (table A1).

Finally, crossed terms of biodiversity productive capacity with variable inputs underline three interesting points. First, we confirm the result of Di Falco and Chavas (2006) that pesticides and B_{1t} are substitute in the case of cereal yields. This confirm the role of biological control on pest regulation which can replace chemical inputs. We find similar result with B_{2t} on milk yields in the case of 3SLS estimation (table A1). Second, we find that interaction parameter of B_{1t} with mineral fertilizer is positive in cereal yields, suggesting that B_{1t} and fertilizer are complementary inputs. This means that, with a good soil structure (linked to acreage diversity and, certainly, crop rotation), farmers may put more fertilizer in order to increase yields. Similar results has been found by Kim et al. (2000) in the long run in USA. This result is not robust in the 3SLS estimation but is replaced by the same effect on milk yield. Third, we find interesting results on the effects of interaction term of biodiversity productive capacity with seeds on both production functions. Seeds are indeed important input for forage production. The interaction of B_{1t} with seeds decrease milk yields, suggesting that arable land diversity permit to reduce the required amount of seeds. More surprisingly, it seems that B_{2t} and seeds are complementary.

We interpret this result by the role of hedgerows as wind-break. This last result is only find in the case of 3SLS estimation (table A1), suggesting the presence of heterogeneity issues.

The OLS and SUR methods display many significant parameters. The correction of endogeneity reduce the significativity of our parameters, confirming that there are some unobserved variables in the error terms which impact cereals and milk yields. Comparison of results of 3SLS (table A1) with the GMM ones (table 2) underline that the correction of heteroscedasticity modifies the significativy of some parameters. The interaction terms between biodiversity productive capacity and variable inputs are more consistent with theory in the 3SLS estimation, notably regarding the fertilizer productivitites. On the other hand, the significant parameters for seeds in the two production functions disappear when we correct for heteroscedasticity. The results are much robust on cereal yields then on milk yields. The lack of robustness on the estimation of the parameters of the milk production function may be link to (i) the estimation of the production function by unity of forage area, (ii) the repartition of the variable input on forage production even if we do not observe forage production and (iii) the less sensibility of milk production to market prices due to the milk quotas and the possible penalty in case of quota violation.

Regarding the effectiveness of our instrumentation, table A2 shows that the effects of relative market prices are not always significant in the case of input demand functions. However, when parameters of ratio of output prices (in *t-1*) on input price (in *t*) are significant at a threshold of 5% (in half cases), they are always of the right theoretically sign (*i.e.* negative). This means that, when output prices increase relatively to input prices, variable input demand decreases. The quality of adjustment is between 16% for fertilizer and 33% for cow feed and most of them are around 25%. These R are classical for variable input demand functions (*e.g.* Carpentier and Letort, 2012). Except in the case of nitrogen, these results confirm that market price ratio and milk quota are not weak instruments. Our results are thus robust to endogenous bias.

7. Discussion

7.1. Data limits

Utilization of the FADN is useful because it provides an indicative sample of French farms with enough economic details for a suitable microeconomic analysis. However, our mobilization of the database suffers from some limits which could be overcome with additional works.

The first issue is linked to the lack of information on topological and meteorological conditions. This conditions are however crucial for variable input demands and farm management. Farmer optimization process will conduct to different equilibrium according to these conditions. In particular, biodiversity levels should depend on topologic conditions, *e.g.* permanent grasslands may be situated on less productive lands (such as slope lands or wetlands). As a consequence, our biodiversity indicators may be correlate to these missing information and thus capture some of the productive effects on the estimators. Variable input demands depend also on topologic conditions (e.g. slop areas) but mainly on meteorological conditions. Crop and forage production are indeed highly dependent on climatic conditions. The farmer optimizes thus his input allocation in order to benefit or to offset the meteorological conditions. The instrumentation of our variable input demand functions would be more effective if we match these missing information because it will capture some unobserved heterogeneity[16]. This issue is inherent to the database but can be overcome with the matching of "Météo France" and the French National Geographic Institute thanks to official municipality number of the farm.

The second issue is that we have to estimate input allocations because of the lack of analytical accounting in the FADN. Other databases give however such analytical accounting, providing information on conventional input repartition (in quantity and not in value) between the farm outputs. If conventional input productive effects are not our main interested subject, additional information may ease the interpretation of the estimated parameters. For the moment, we can only verify that the estimators have the right sign.

The third issue is that we only consider market prices in the variable input demand functions. We think that our analysis may beneficiate to the addition of CAP subventions and CAP policies. Coupled subsidies should notably be added to the market prices in order to reflect the real incentives faced by farmers. Given their restricted conditions, some decoupled subsidies may also give useful information on the unobserved heterogeneity and be added in our system as control variables. A better integration of milk quota in our model can also increase the robustness of the milk production function estimation. Future econometric works will investigate these effects.

The last identified issue regarding our data is the potential presence of outliers, notably with regards to the structure of the revenues. It is highly likely that the farms with developed poultry or pig production do not manage the same way their variable and natural inputs. Future econometric works will test the presence of outliers.

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[16] Some tries have been conducted to eliminate the individual and temporal fixed effects with the panel data but are, for the moment, unsuccessful.

7.2. Critics of our biodiversity indicators

The distinction of several biodiversity is a crucial point of our study because it recognizes that areas can only provide suitable habitat for a specific kind of biodiversity. However, our biodiversity indicators suffer from several bias.

Indeed, the choice of indicator is difficult and relies highly on data availability. Mobilization of FADN database restrict our possibilities. Indeed, we can thus only compute indicators depending on farm landscape composition. In order to overcome these issues, it would necessitate to introduce information on farm landscape structure[17]. However, the FADN does not allow any construction of this kind of indicator. Giving information on both landscape configuration and composition, the selection of the Land Parcel Information system (LPIS) would be much more appropriate for the computation of landscape indicators. Based on LPIS database, Desjeux et al. (2015) have notably built an aggregated indicator at the French LAU1 scale which integrate arable land diversity and permanent grassland shares but also, afforested lands shares. Our microeconomic analysis suffers notably from the lack of afforested land information because some of biological control are related to these areas. The FADN does provide information on permanent crops but it would restrain our sample from 3984 observations to 215 ones. On the other side, mobilization of LPIS is not sufficient for our analysis because it does not provide enough information on the economic dimenson. The selection of the FADN gives thus useful information on the economic side, to the detriment of the ecological side. As a consequence, we have restricted our work for two kinds of habitat.

Another limit may come from the lack of landscape scale (Kindlmann and Burel, 2008). Indeed, we compute our indicators at the farm scale. Even if there is no reference on this criteria selection when cited authors describe the indicator selection, it appears that all cited studies that use the Shannon index are base at an aggregated scale (Di Falco and Chavas, 2008; Di Falco and Perrings, 2003, 2005; Matsushita et al., 2016). The studies computing their biodiversity indicators at the farm scale do usually not use the Shannon index but more simple indicators (Chavas and Di Falco, 2012; Di Falco and Chavas, 2009; Di Falco et al., 2010; Omer et al., 2007). However, no significant differences have been found on the productive effects of acreage diversity on crop production according to scale and indicator selection. Even if the landscape is obviously split and uncompleted when we look only on lands of single farms, we thus consider that the computation of the Shannon index at the farm scale give suitable information

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[17] Example of landscape configuration indicators is the ratio perimeter to area (van Rensburg and Mulugeta, 2016) or margins length (e.g. wheat-crop interfaces are an indicator of biological control – Bertrand et al., 2016 –).

on level of biodiversity. Matching of additional information on the configuration of landscape (e.g. thanks to the Land Parcel Information system - LPIS) would allow for a complete agricultural landscape (even if we will not have any information on the land utilisation of other economic activities). However, it would necessitate additional effort on the microeconomic modelling, notably with regard to common-pool resource and public good theories. This is thus far beyond the objective of the current paper[18].

Moreover, biodiversity indicators based on landscape structure do not take into account farmer practices. If landscapes' elements can be seen as inputs for agricultural production, their expressions depend on agricultural practices (Le Coeur et al., 2002). Biodiversity-friendly practices (e.g. low pesticide applications, reduced tillage practices) enhance biodiversity levels. These practices are in fact farmer choices which make the implicit choice to enhance natural input expression to the detriment of conventional inputs. Omer et al. (2007) have notably proposed a biodiversity indicator specification which allow introduce conventional input applications in order to take into account from their negative effects on biodiversity levels.

Additional bias is linked to farmers' CAP declaration of their permanent grassland areas. Indeed, the legislative specificities on these areas can lead some farmers to underreport their permanent grassland areas, notably reporting them as temporary grasslands. As a consequence, our biodiversity indicator B_{2t} may be biased.

Set aside the ecological issues, additional issues can from the potential biases linked to economic confounders. Indeed, there is a risk to confound ecological processes with economic ones. First potential economic confounder is that acreage diversity indicator informs on fixed input organization. As we only have partial measure of capital and labor into the economic dataset, the Shannon index could inform on the quality of capital and labor. The second potential economic confounder is that acreage decisions are endogenous to outputs. As already said, permanent grassland share is at least partially a function of milk cows. As a consequence, to introduce B_{2t} into crop production function captures the joint production of milk and crops. The computation of farm available organic fertilizer should this technology complementarity. As we find that all parameters of control variables in model 2 are coherent with theory both in both GMM and 3SLS estimations, ae can thus expect that biodiversity indicators do not capture

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[18] Some test on the dispersion of the land around the farm could however inform on the level of fragmentation of the farm landscape (Latruffe and Piet, 2014).

any economic confounders. However, potential endogeneity of our biodiversity indicators exist. We comment this potential issue in the next part.

7.3. Instrumentation of variable input demand functions: is it enough?

Most of the cited studies on biodiversity productive capacity have instrumented biodiversity indicators and considered the utilization of variable inputs are exogenous, or, as said by Di Falco and Chavas (2008), are “predetermined”. In fact, we have chosen the opposite approach. In our case, we do not have instrumented the biodiversity indicators. We have rather assumed that there were predetermined, or, as said previously, fixed in the short term. However, they are some proofs that our biodiversity indicators may be endogenous.

Indeed, multicrop microeconometric models have underlined the key role of price and policy incentives allocated areas (*e.g.* Carpentier and Letort, 2012). This would mean that we also should instrument our biodiversity indicators by market prices. In this case, the computation of instruments for the crossed terms between biodiversity productive capacity and variable inputs would have been complicated.

However, if the acreage price elasticities are high between cereals, they are quite fix between cereals and other outputs (Carpentier and Letort, 2012). These limitations are notably due to shadow costs. Indeed, as underlined by Carpentier and Letort (2014):

> « The agricultural scientists and the extension agents consulted by the authors usually assert that farmers are more reluctant to change their cropping practices than their land allocation, at least on the short run and within standard rotation patterns. »

These predetermined systems which influenced biodiversity are usually explained by specific capital needs, which leads to shadow costs. These costs are interpreted as diversification costs (Carpentier and Letort, 2012, 2014) and prevent farmers to significantly modify its acreage in the short time. They are notably higher when the capital is specific. Existence of shadow cost lets us assume that biodiversity indicators can be considered as “predetermined” variables which are not susceptible to suffer from endogenous bias[19].

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[19] There are however some proofs that farmers manage their biodiversity in the short time. For example, farmers can allocate specific outputs close to other ones in order to create a mosaic which can benefit to production through biological control enhancement. However, our biodiversity indicators are influenced by farm landscape composition and not by farm landscape structure. If farm acreage composition does not evolve through time, our indicators are fixed. As a consequence, the allocation of a specific parcel to an output or another according year does not impact our indicator.

The hypothesis of predetermined biodiversity is however less correct in the long term. In this case, we can consider biodiversity productive capacity as a quasi-fixed input which can be managed. In this case, we should instrument the biodiversity productive capacity. Based on acreage model, we could instrument biodiversity indicator with the other quasi-fixed input such as total UAA, capital and labor (Carpentier and Letort, 2012, 2014). The introduction of long-term optimization is also interesting because biodiversity productive capacity enhances current and future production (Di Falco and Chavas, 2008; Matsushita et al., 2016; Tilman et al., 2006). Famous example of dynamic ecosystem management is crop rotation. Some studies have tried to analyze the farmers' economic behavior regarding this dynamic management (Hennessy, 2006). According to data availability, most of them have focused on the dynamic rotation at the field-scale (Hendricks et al., 2014a, 2014b). However, field-scale analysis does not take into account for the farm-scale constraints, notably regarding quasi-input management. Carpentier and Gohin (2015) have proposed a theoretical approach to illustrate this issue which is difficult to estimate with the FADN. Adaptation of our model with the instrumentation of biodiversity indicators may overcome these issues.

The correction of endogenous biases in the variable input allocations is one of our contribution in this paper. Our results have notably confirmed that variable inputs parameters may suffer from endogenous bias. As the effectiveness of the selected instruments seems sufficient[20] (R between 0,16 and 0,33), variable input parameters and crossed term parameters seems unbiased. Moreover, it seems that the potential endogeneity of the biodiversity indicators should not impact our estimations. Indeed, the correction of endogeneity for acreage decisions do not modify significantly the estimated variable input allocation (Carpentier and Letort, 2012). The assumption that biodiversity indicators are exogenous should not modify the results on our variable input parameters. Thus, our results should be unbiased.

7.4. Why does farmland biodiversity decrease?

As most of European biodiversity lives on agricultural lands, we have already underlined the crucial needs of information about the impact of biodiversity into farm production. To better

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[20] Other choices may however increase the robustness of our system but it would increase the complexity of our study. For example, additional tests may be done on the anticipation process of the sample farms. Recent works have indicated that quasi-rational anticipations work well, and in the case of crops, the utilization of future prices may also success. We have tested the rational anticipations but the estimators display opposite sign with theory.

understand biodiversity productive capacity and its management is essential to improve environmental policies. Our study gives new insight on that subject.

7.4.1. Arable land biodiversity

Our approach has notably confirmed previous results on crop diversity positive effects on crop production. Instrumentation of variable inputs has suppressed the potential bias of previous studies. We have even expanded the existing results, providing interesting results on the interactions of B_{1t} with fertilizer and pesticides. Effect of arable land diversity is however much complex on milk production, notably because we do not observe forage yield. To our knowledge, it is the first time that arable land biodiversity productive capacity has been found in France. They suggest that arable land biodiversity is a productive input for crop production. However, the French LAU1 analysis of Desjeux et al. (2015) has underlined a trendy decline of crop diversity in whole France between 2007 and 2010. Even if their analysis does not benefit from a microeconomic model analysis, this could indicate that crop diversity is not profitable for most farms.

The first explanation could be that arable land biodiversity do not increase much other output productions. Our analysis confirms that arable land biodiversity effects on milk production are complex. However, this does not explain why the crop diversity decline has also been observed in crop specialized French LAU1 regions (Desjeux et al., 2015).

The second explanation could be link to arable land biodiversity management costs. Indeed, as already underline in previous part, some authors have examined the existence of diversification costs (Carpentier and Letort, 2012, 2014; Koutchade et al., 2015). They highlight the importance of scale economies in acreage management in order to decrease management costs (notably for machinery management and investment). Especially, it seems that the presence of some output in the acreage increases highly theses costs (Koutchade et al., 2015). Our findings confirm the productive importance of biodiversity but do not provide information on biodiversity costs.

Finally, we have to underline that Desjeux et al. (2015) indicator evolution is influence by market prices. Farmers’ acreage decisions depend on their anticipation price process. Market prices evolution since 2007 can explain the specialization of some farmers in a short time. However, evidences from rotation management in United States suggest that biodiversity management is simplified only for a short period (Hendricks et al., 2014a). In our case study, averaged B_{1t} are variable between 2002 and 2014. They are notably at their highest levels in 2009, when crop prices were at their lowest levels. Note that in our case study, we find that B_{1t} have increased on average by 6% between 2007 and 2010 (the median evolution displays however a decrease of 2%), which is not in line with Desjeux et al. (2015). This can be explained by the panel rotating structure and inspectors' farm choices.

For policymakers, to subsidy arable land diversity may increase yields. We may thus be surprised that farmers benefit from diversification subsidies. Our analysis should be completed with cost or profit analysis to see if diversification costs exceeds the marginal revenues linked to ΔB_{1t}.

7.4.2. Permanent grassland biodiversity

To our knowledge, this is the first time that permanent grassland biodiversity productive capacity has been investigated on both crop and milk productions. Our results suggest that there is a strong and significant positive effect of this biodiversity on crop production. To our knowledge, this is the first time that such effect has been found. Similar result was highlight by Klemick (2011) on forest fallow production externalities towards agricultural goods in Brazil[21]. Our result confirms the agronomical and ecological studies on the potential beneficial effects of permanent grasslands and related landscape elements on crop production (wind-break, erosion-brake, microclimate contribution or insect habitat for pest management). Desjeux et al. (2015) have notably found an important augmentation of grassland shares on crop specialized French LAU1 regions (notably in the Paris basin). These evolutions can reflect the adaptation of crop specialized farmers to the simplified agroecosystem and thus, the farmers wish to limit the effect of the limiting physical factor. They suggest that permanent grasslands could be profitable for crop productions even if permanent grassland shares are still very low on these regions. However, we think that the low levels of B_{2t} on these regions are related to the public good characteristics of the biodiversity productive capacity which incite farmers to behave as free-riders. Indeed, if permanent grassland biodiversity increases crop yield, the allocation of a field for grasslands instead of crops leads to some opportunity costs (without consideration of spillover productive effects, permanent grasslands are less profitable than crop production). As a consequence, it can prevent farmers to bear the whole cost of biodiversity provision.

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[21] Even if forest fallows are not permanent grasslands, they share some similarities on their role into the ecosystem functioning. Their impact on hydrological cycles and biodiversity explain their positive productive effects on crop production.

Production of permanent grassland biodiversity has notably proved to be costly for farmers in Northern Europe (Gullstrand et al., 2014).

Our results are not surprising on the case of milk production. If estimations of model 2 indicate that there is no impact of permanent grassland on milk production, model 1 suggests that permanent grassland decreases milk yield. This is not surprising because permanent grasslands depict more "extensive" farms which prefer to limit feed costs rather to increase milk yield with concentrate intakes. In model 2, biodiversity levels do not impact production. We may conclude that farmers with milk activity have no incentives to maintain permanent grasslands and attached landscape elements. Indeed, at the best, B_{2t} has no effect on milk yield. As our study does not examine intensively the cost structure, we cannot conclude on the profitable effect of permanent grassland on milk production. Desjeux et al. (2015) have though displayed that permanent grasslands have declined in our case study regions. This suggests that permanent grasslands are less profitable for milk farms than other lands and, thus, the presence of opportunity costs.

For policymakers, it seems that, contrary to B_{1t}, AEM aiming to maintain permanent grasslands are indeed required. Indeed, even with no integration of the cost dimension, we see that farmers have no incentives to maintain permanent grasslands. As permanent grasslands leads to opportunity costs and management costs (Gullstrand et al., 2014), farmers may need to be compensated from these losses. In the case of crop regions, this comment has to be nuanced as we underline it in the next part.

7.4.3. Interactions of permanent grassland biodiversity, arable land biodiversity and variable inputs

One of the most interesting result is that the two biodiversity indicators are substitute to each other. For example, regarding the dispersion of B_{1t} and the productivity parameters of B_{1t}, B_{2t} and $B_{1t} * B_{2t}$, we can compute that B_{2t} has only a productive effect on cereals yields when B_{1t} is lower than 1,07, *i.e.* in 30% of our sample. Similarly, B_{1t} has a productive effect when B_{2t} is lower than 0,9, *i.e.* in all the observation of our sample. For landscape ecologists, this substitution may be linked to the fact that both permanent grasslands and hedgerows enhances biological control. They notably found that, in landscapes with low hedgerow density, farmers need to have a high complexity of arable land mosaic to reach high level of biological control. The same level can be reached in landscapes with high hedgerow density with a lower mosaic complexity. Thus, farmers have two strategies: to enhance arable land diversity or to prefer high permanent grassland shares. This may explain why Desjeux et al. (2015) have found that arable land diversity decreases and permanent grassland shares increases[22]. As a consequence, policymakers may not have to pay farmers to maintain permanent grasslands in the case of specialized crop regions. It notably depends on the level of B_{1t}. However, as permanent grasslands lead to opportunity costs, farmers may behave as free-riders. Regulators may have to intervene anyway but, in this case, in order to increase coordination. Moreover, as the proper effect of B_{1t} always exceed the interaction term with B_{2t}, we wonder if regulators really need to subsidy crop diversification. Similar analysis on profit or costs is however required to confirm this remark.

On the case of milk, the introduction of the interaction term leads to non-significance of the biodiversity productive capacity parameters. As our analysis does not integrated any cost dimension, this may explain why Desjeux et al. (2015) have found that B_{2t} have decreased almost everywhere in our case-study regions. This also confirms that policymakers have to pay farmers to maintain their permanent grasslands and attached semi-natural landscape elements.

Finally, we want to underline that the crossed effects of B_{1t} with fertilizer and pesticides or with B_{2t} and seeds are very important for policymakers. In our case study regions, there is indeed a high issue of water quality due to high concentration of nitrates and pesticides. Thus, if policymakers want to subside farmers to maintain biodiversity in order to influence for variable input application, the optimal solution depends on these interactions. In the case of pesticides, we can assume that the cross-compliance from last CAP reform will lead to a decrease of pesticides application. Optimization of the producer program will surely lead to pesticides reduction as B_{1t} is substitute to pesticides. However, if policymakers want to reduce nitrates concentration, the subvention of arable land biodiversity only will surely lead to increase fertilizer application because of the relation of complementarity between B_{1t} and fertilizers. Even if the leaches are reduced in this case (Dinnes et al., 2002), the increase of fertilizer application may degraded water quality. In case of nitrate pollution, we recommend that the biodiversity subvention is followed by a fertilizer tax. The mix of the two instruments should reduce nitrates concentration and enhance biodiversity.

To conclude on the effect of biodiversity on farmers' production process, future research should analyze deeply the cost of using biodiversity productive capacity. Indeed, whereas most authors

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[22] This reflection does not integrated acreage costs and is only based on productivities.

considered these functionalities as free[23], the management of the biodiversity productive capacity is costly: natural input utilization has a price. These costs could be related to management complexity or implantation of environmental-friendly practices which are both labor intensive. The modification of management and agricultural practices can also impact the productivity of the other inputs such as capital (*e.g.* Lotfi et al., 2010).

8. Conclusion

Previous studies focusing on the crop diversity management have found that crop diversity reduces market and production risks but also that it increases mean crop production. Yet, the analysis needs to be extended to other outputs and other biodiversity habitats. This paper contributes to this literature by presenting an empirical analysis of the productive effects of arable land biodiversity and permanent grassland biodiversity on both milk and crop productions. Biodiversity levels are measured thanks to a Shannon index for the case of arable lands and area shares in the case of permanent grasslands. Using microeconomic FADN data of mixed farms from western France over a thirteen-year period, we examined productivity of biodiversity productive capacity. Applying GMM method for accounting the endogenous biases of variable inputs linked to farmers' simultaneous choices, we investigate how the two kinds of biodiversity impact crop and milk production. Based on producer optimization program, our estimations benefit also from an original method to take into account for the repartition of variable inputs between several outputs.

The econometric results indicate that both kinds of biodiversity are positively and significantly related to crop production. The effects on milk production are complex and not as robust. Contrary to previous studies, the correction of endogenous bias on variable input application and the treatment for organic fertilization allows a better estimation of biodiversity productive effects. With these correction, we confirm the previous results of the literature on the productive effects of arable land biodiversity on crop production. Our main result is that permanent grasslands have a productive spillover on crop production. This result stresses that maintaining permanent grasslands and/or attached landscape elements could increase the productivity of the agroecosystem in the case of crop production. Results confirm also that biodiversity productive capacity may interact with variable input applications. The relation of substitution between arable land biodiversity and pesticides found by Di Falco and Chavas (2006) is notably

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[23] The MEA defines the "ecosystem services" as "the benefits people obtain from ecosystems." These "services" are assumed to be free.

confirmed here. We also find that arable land biodiversity and fertilizer are complement and that permanent grasslands and seeds are substitute. From our knowledge, this is the first time that these results are found in the empirical economics literature. As discussed on the previous part, these interactions have deep consequences on the choices of agro-environmental measures.

However, our results are still not totally sufficient. Results of the parameter estimations of fertilizer productivity highlight that our model is still uncompleted. Future econometric estimations will benefit from additional data on topological and meteorological conditions. Regarding the differences on the parameter estimations of our fertilizer parameters with GMM and 3SLS, we will also investigate deeply the incidences of heterogeneity on the estimation of our parameters. For the moment, it seems that the correction of heterogeneity thanks to GMM is not sufficient to have the expected signs. Future estimations will thus add individual fixed effects to test the robustness of our results. Finally, new estimation will also be conducted with new biodiversity indicator computations. This would provide information on the importance of 'marginal' crops into the biodiversity productive capacity.

If these current results provide new insights for policymakers, they may not be sufficient for reorganization of public funds. Future researches should focus more on cost structure of biodiversity productive effect management in order to fully understand the effect of biodiversity on farmers' optimization process. Indeed, to not take into account the complexity of the management and the impact of biodiversity management on other practices is a major lack in the "ecosystem services" literature.

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Annexes

Table A1 : OLS, SUR, 3SLS and GMM (without restrictions) estimations of milk and crop production functions

	OLS		SUR w/ parameter restrictions		3SLS	
	log(y_crops)	log(y_milk)	log(y_crops)	log(y_milk)	log(y_crops)	log(y_milk)
Const	9,68 ***	10,08 ***	10,09 ***	10,39 ***	8,35 ***	10,64 ***
	(0,10)	(0,07)	(0,06)	(0,04)	(0,60)	(0,51)
Biodiversity						
B1	0,73 ***	0,48 ***	0,39 ***	0,13 ***	1,68 ***	-0,20
	(0,07)	(0,04)	(0,03)	(0,02)	(0,48)	(0,40)
B2	0,51 *	-0,23	-0,08 °	-0,79 ***	1,39 *	-0,53
	(0,22)	(0,14)	(0,0,05)	(0,04)	(0,58)	(0,48)
B1 * B2	-0,78 ***	-0,99 ***			-1,11 *	0,28
	(0,17)	(0,11)			(0,43)	(0,37)
Variable inputs						
Fertilizer	-14,87 **	-6,48 ***	-0,58	-0,26	-32,57	-24,77
	(4,75)	(3,07)	(0,96)	(0,37)	(21,01)	(17,93)
Fertilizer * B1	11,65 ***	2,65			18,55	23,05 °
	(3,45)	(2,22)			(14,71)	(12,75)
Fertilizer * B2	-2,18	19,24 ***			-15,62	24,26
	(7,29)	(4,70)			(22,55)	(19,11)
Pesticides	76,61 ***	16,85 *	14,99 ***	5,77 ***	175,67 **	34,80
	(10,41)	(6,73)	(2,24)	(1,20)	(62,12)	(51,27)
Pesticides * B1	-46,61 ***	8,68 °			-99,41 *	-14,81
	(7,08)	(4,57)			(37,02)	(37,32)
Pesticides * B2	60,67 **	-7,72			-84,52	-224,2 ***
	(18,6)	(12,01)			(81,98)	(67,98)
Seeds	26,32 **	38,77 ***	7,17 ***	2,76 ***	163,38 ***	37,18
	(8,90)	(5,78)	(1,78)	(0,79)	(55,21)	(51,27)
Seeds * B1	-12,90 *	-8,68 °			-98,43 *	-23,88
	(6,09)	(4,57)			(41,96)	(35,13)
Seeds * B2	1,94	-7,72			110,55 °	98,83 *
	(16,92)	(12,01)			(59,43)	(49,05)
Fuel	2,95	6,66 **	9,84 ***	3,78 **	-39,56 °	-13,11
	(3,23)	(2,10)	(2,77)	(1,22)	(23,02)	(12,94)
Cow feed		6,37 ***		6,37 ***		12,65 ***
		(0,21)		(0,21)		(1,60)
Health and reproduction		7,29 ***		7,29 ***		31,50 ***
		(0,96)		(0,96)		(10,21)
Organic Fertilizer proxies						
Available cattle fertilizer/area	-0,024	-0,27 ***	-0,03	-0,24 ***	0,02	-0,50 ***
	(0,029)	(0,02)	(0,03)	(0,02)	(0,06)	(0,07)
Other avai. liv. fertilizer/area	0,006	-0,07 ***	-0,003	-0,07 ***	0,05 °	-0,04 *
	(0,012)	(0,008)	(0,01)	(0,008)	(0,02)	(0,02)
Control variables						
Total area	-2,8E-6 °	-2E-5 ***	-5E-6 ***	-2E-05 ***	-2,33E-6	-2E-05 ***
	(1,65E-06)	(1,08E-06)	(1,65E-06)	(1,08E-06)	(2,73E-06)	(2,47E-06)
Capital/area	0,002 ***	0,004 ***	0,002 ***	0,005 ***	0,001	-0,001
	(0,0005)	(0,0003)	(0,0005)	(0,0003)	(0,0008)	(0,001)
Labor (LU) / area	42,79 °	34,17 *	40,56	35,40 *	43,58	72,14 **
	(25,62)	(16,54)	(25,89)	(16,55)	(29,23)	(24,31)
Labor (H) / area	-2,77 °	-1,63	-2,65 °	-1,71	-2,81	-4,20 **
	(1,59)	(1,03)	(1,61)	(1,03)	(1,82)	(1,51)
Disadvantaged area	-0,003	-0,01 *	0,003	-0,012 *	-0,009	-0,003
	(0,01)	(0,006)	(0,01)	(0,006)	(0,01)	(0,01)
Restrictions						
Restriction 1			0,19 °			
Restriction 2			-1,37 *			
Restriction 3			-1,21 *			
N° of observation	3984	3984	3984	3984	3984	3984
R^2	17,63	63,02	15,15	62,94		

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

Table A2: variable input instrumentation (with addition of exogenous variable in log(y_crops) and log(y_milk)) (N = 3984)

	fertlizer / tot. area	**pesticide / tot. area**	**seeds / tot. area**	**fuel / tot. area**	**cow feed / for. area**	**health & repro. / for. area**
Const	-0,05 ***	-0,003	-0,016 *	0,008 **	0,016	-0,006
	(0,01)	(0,01)	(0,007)	(0,002)	(0,013)	(0,006)
Market price ratio						
fertilizer price (t) / crop price (t-1)	-0,001 °					
	(0,0004)					
fertilizer price (t) / milk price (t-1)	-0,004					
	(0,006)					
pesticide price (t) / crop price (t-1)		-0,001 ***				
		(0,0002)				
pesticide (t) / milk price (t-1)		-0,001				
		(0,003)				
seed price (t) / crop price (t-1)			-0,0006 *			
			(0,0002)			
seed price (t) / milk price (t-1)			-0,002			
			(0,03)			
fuel price (t) / crop price (t-1)				-1,3E-06		
				(0,0002)		
fuel price (t) / milk price (t-1)				0,001		
				(0,001)		
cow feed price (t) / milk price (t)					-0,03 °	
					(0,002)	
health & repro. price (t) / milk price (t)						-0,01 **
						(0,004)
fertilizer price (t) / pesticide price (t)	-0,031 ***	0,001				
	(0,007)	(0,001)				
fertilizer price (t) / seed price (t)	0,056 ***		-0,001			
	(0,008)		(0,001)			
fertilizer price (t) / fuel price (t)	0,004 *			-0,0006		
	(0,0015)			(0,0006)		
seed price (t) / pesticide price (t)		-0,02 **	0,018 ***			
		(0,007)	(0,004)			
seed price (t) / fuel price (t)			-0,001	-0,01 ***		
			(0,001)	(0,003)		
fuel price (t) / pesticide price (t)		-0,003 *		-0,004 ***		
		(0,001)		(0,001)		
cow feed price (t) / fertilizer price (t)	0,012 ***				-0,002	
	(0,003)				(0,004)	
health & repro. price (t) / fertilizer price (t)	0,025 ***					-0,004 **
	(0,006)					(0,001)
cow feed price (t) / pesticide price (t)		0,003			0,14 ***	
		(0,002)			(0,03)	
health & repro. price (t) / pesticide price (t)		0,01 *				0,001
		(0,005)				(0,003)
cow feed price (t) / seed price (t)			0,0001		-0,15 ***	
			(0,002)		(0,03)	
health & repro. price (t) / seed price (t)			0,004			0,01
			(0,005)			(0,008)
cow feed price (t) / fuel price (t)				0,01 ***	-0,02 ***	
				(0,001)	(0,005)	
health & repro. price (t) / fuel price (t)				0,002		0,001
				(0,004)		(0,001)
Other instrument						
quota	-3,04E-07	2,27E-07	2,10E-05 ***	1,40E-06 ***	6,70E-05 ***	8,75E-06
	(9,04E-07)	(4,83E-07)	(5,44E-07)	(3,27E-07)	(3,4E-06)	(7,86E-06)
R²	15,6	28,48	26,07	26,19	33,91	18,59

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