# Biodiversity productive effects in milk farms of western 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 5654 FADN observations from 2002 to 2014 in French regions of Bretagne, Basse-Normandie and Pays-de-la-Loire. We estimate the productive effect of biodiversity taking into account for the variable input endogenous biases and joint technology specificity. Using Three Stage Least Square method, we estimate linear and quadratic of both production functions with ad-hoc addition of variable input demand functions. We measure biodiversity through the utilization of landscape metric indicators. For the first time in this literature, 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 but it seems that permanent grasslands decrease milk production. The effect of arable land biodiversity on milk production is not robust for the moment. Our results can be useful for policymakers as they bring new insights on the management of biodiversity by farmers.

## 1. Introduction

Over the last decades, humans have modified and influenced ecosystems more than ever in recent history (MEA, 2005). Many studies have pointed the influence of modern human activities, notably of agriculture, on the degradation of biodiversity (Dale and Polasky, 2007; Kleijn et al., 2009). Despite the open societal commitment to this issue, degradation of biodiversity continues, often at increasing rates (Butchart et al., 2010; Krebs et al., 1999; Robinson and Sutherland, 2002). These declines have encouraged policymakers to propose regulatory measures aiming to conserve biodiversity, notably since the Rio Biodiversity Convention (1992). In a first period, these measures have focused on biodiversity conservation of remarkable species, with, for example, Natura 2000 areas in European Union (EU) countries. However, these “land sparing” strategies have proved to be not beneficial for biological conservation in Europe (Dimitrakopoulos et al., 2004; Fischer et al., 2011; Żmihorski et al., 2016). Indeed, European biodiversity has evolved according to agricultural traditional practices, e.g. presence of semi natural landscape elements, diversified acreages or grazing of livestock (Kleijn et al., 2009). This development has forced policymakers to privilege the creation of ecological corridors in order to conserve whole food chain and favor the conservation of ordinary biodiversity (Soule and Gilpin, 1991). As a consequence, more recent policy measures have thus favoured land sharing policies through the promotion of market incentives (Fischer et al., 2011; Hart et al., 2014). In particular, the agro environmental measures (AEM) aim to encourage farmers to internalize environmental costs linked to their activity and can lead some farmers to adapt their practices towards biodiversity friendly practices. These AEM are specially designed for a purpose such as farmland biodiversity or water quality. However, AEM appear to be not effective on both biological (Kleijn and Sutherland, 2003; Kleijn et al., 2001) and economic sides (Chabé-Ferret and Subervie, 2013). The low effectiveness of AEM is notably related to (i) the low percentage of contracted AEM on territories and (ii) to the low cost opportunity of the contracted farmers which, in most cases, already made the contracted practices on their farms. This has led economists to examine alternative approaches in order to overcome these issues, *e.g.* auction mechanisms (Latacz-Lohmann and Van der Hamsvoort, 1997), coordination bonus (Parkhurst and Shogren, 2007) or payments with threshold conditionality (Dupraz et al., 2009).

If these studies bring new useful elements for policymakers, we regret that they do not enter more into the farmer optimization process. In particular, we regret that only few economic studies focus on the effect of biodiversity into the agricultural production process. The effect of the policy target output on farmers' production and profit is however a main concern. Indeed, if the target output has public good characteristics, it is provided by private agents who bore the costs but not all the benefits. Economists tend to focus on the effect of AEM on profit and the identification of opportunity costs. Some studies have for example focused on the effect of AEM on reorientation of inputs for production (Chabé-Ferret and Subervie, 2013; Lacroix and Thomas, 2011; Laukkanen and Nauges, 2014). The comparison between predicted land allocation and fertilizer use for area under AEM and area without any environmental contract is used on environmental production functions to quantify the impact of AEM on environment quality. If these studies go deeper on the analysis of the effects of environmental constraints on production process, they do not consider the effect of environmental improvement in production. In other terms, they do not consider environmental quality as a productive input. It is thus important to study deeper the link between production and biodiversity.

The analysis of biodiversity effects on production have become more and more popular, notably since the publication of the MEA (2005). The MEA recognized, as ecological economists had already said, that nature contributes to society well-being and can enhance production of human activities (Costanza et al., 1997; Haines-Young and Potschin, 2010; MEA, 2005). The influence of nature is obvious for agriculture because this activity depends heavily on ecological processes. The ecological functionalities provided by agricultural landscapes can influence positively or negatively the agricultural production process. As a consequence, the management of ecological functionalities is an essential part of the work of farmer. Taking into account a current economic context, the farmer optimizes his objective function (most of the time, his total revenues) with the allocation of inputs for a given production (Mundlak, 2001). If these inputs can be bought on markets (e.g. fertilizer, pesticides, fuel, machinery), they can also be natural. A famous example of the effect of natural inputs is the effect of fallow in agricultural production as a special case of soil management. Soil management offers many opportunities for farmers to benefit for their effects on production, e.g. tillage reduction practices (Hediger, 2003; Wu and Babcock, 1998). Other examples of environmental productive management include biological control (Thies and Tscharntke, 1999), crop rotations (Hennessy, 2006) or organic fertilization. The work of the farmer is thus to manage his production given the economic context, the available inputs and the production technology in order to maximize its total revenues.

The analysis of the management of biodiversity into the farmers' production process is essential because it allows a better understanding of the place of biodiversity for agricultural producers. A better allocation of public funds for biodiversity conservation depends heavily on the better comprehension of the link between biodiversity and production of agricultural goods. Among the important points that have been examined, the role of biodiversity on risk market reduction and production have received the most of attention. The impact of biodiversity (or crop diversity) on market risk is beneficial because it provides a portfolio of assets for farmers who face fluctuating farm prices (Chavas, 2008). This has led some authors to give an insurance value to biodiversity (Baumgärtner, 2007). If this is a crucial point on the understanding of farmers' behavior with regards to biodiversity, we rather focus on the impact of biodiversity on production. Whereas classical view in economy is that biodiversity is a joint product of agricultural production (Hart et al., 2014; Wossink and Swinton, 2007), recent studies have try to better understand the links between this production joint process (Chavas, 2009; Omer et al., 2010). The originality of these studies is that they consider biodiversity as a productive input. To study biodiversity as a natural input necessitates to examine classical economic production issues, notably on the production technology. The role of the production technology is essential because it determines which inputs are substitute or complementary with other inputs. The substitutability between conventional inputs (e.g. mineral fertilizer, pesticides, etc.) and natural inputs is an issue of increasing importance in a context where conventional input prices are suspected to become higher (notably through their taxation – (Femenia and Letort, 2016) –) and farmers face increasing output price fluctuation. The relative comparison of productive effects of biodiversity with other conventional inputs is an important step in the comprehension of the role of biodiversity into the production process.

Several studies have examined empirically the effect of biodiversity on agricultural production through the econometric estimation of a primal production function (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). Most of them study a crop oriented agroecosystem and underline the positive effect of crop diversity on production[1]. Similar studies have analyzed the effect of habitat diversity on profit (Di Falco and Perrings, 2005; van Rensburg and Mulugeta, 2016). They find a positive profitable effect of biodiversity. To our knowledge, only one study has examined the effect of biodiversity on production within grassland agroecosystems (van Rensburg and Mulugeta, 2016) but it seems that the effect of biodiversity on the production of these systems is also positive.

If these studies give interesting results for the understanding of management of biodiversity by farmers, they present some issues, notably with the hypothesis of optimizer behavior of the farmer. Indeed, these studies estimate a primal production function (or system) where biodiversity is an explicative variable. Other explicative variables usually introduce elements on climate, soil, farm structure but also on other conventional inputs (labor, capital, variable inputs – *e.g.* fertilizers –). Most of these studies have instrumented the biodiversity variable in order to take into account for simultaneity of choices between biodiversity management and objective production levels. However, they do not apply the same econometric treatment for the other inputs, notably variable inputs. This assume that the farmer optimizes his biodiversity level but not his other inputs, which seems highly unlikely. Moreover, neither of these studies have integrated the economic context on their analysis. We will discuss in more details this issue later.

On this study we propose to investigate the effect of two kind of biodiversity on the production of a sample of mixed farms (orientated towards milk production) from western France. Contrary to other parts of the world, mixed farms are relatively well implanted in

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[1] 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).

Europe. In particular, there are many mixed farms with milk production in France and Great-Brittany. The evolution of these systems through time have notably influenced the species structure of these regions and partly explains why land sharing policy strategies are more adapted to European landscapes. Among the managed areas, permanent grasslands provide a suitable habitat for many remarkable species but also to more common species. However, the number of permanent grasslands decreases for several decades (Peyraud et al., 2012)[2]. If they still represent 30% of the total agricultural area of France, they crystallize tensions among stakeholders. On one hand, they are valorized by society because they are a large resource of biodiversity. On the other hand, some of them can be more profitable for farmers if they are turn into arable land. The destruction of permanent grasslands contributes also to the removal of other permanent landscape elements which were traditionally linked to those areas. Indeed, many butches and hedgerows have been removed in Europe, notably during the 1980s (Calvo-Iglesias et al., 2009; Haines-Young et al., 2000). These declines tend to slow down, notably with the transformation of land consolidation policies and promulgation of conservation ones[3]. However, according to agronomical studies, hedgerows provide several valuable functions for farmers (Baudry et al., 2000a). These productive effects are however not known precisely. More studies on these effects are crucial because it can contribute to understand the trendy decline of permanent grasslands. Our study aims partly to overcome these deficiencies.

Indeed, the two interested biodiversity of our study are the one on arable lands (almost similar to crop diversity) and the one on permanent grasslands. The distinction of two kinds of biodiversity is supported both by ecological theories enhancing the preference of species to one habitat and methodological choices. Indeed, we measure the biodiversity levels with indicators based on dedicated areas. The utilization of biodiversity indicators supposes that one specific area is a suitable habitat for some species but not for some others. As a consequence, we can consider that the two kinds of interested farmland biodiversity are different and independent from each other (Desjeux et al., 2015). Thanks to the

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[2] We estimate that we loss more than 30% of the amount of permanent grasslands since 1960. 740 000 km of hedgerows were lost in France during the between 1970 and 2000 (Le Coeur et al., 2002).

[3] The evolution of the CAP with the conditionality contributes also to their maintain on European landscapes.

introduction of these indicators in both production function equations, we explain their effects on production of crops and milk. Contrary to previous cited studies, this allow examining the cross-effect of biodiversity between productions. Indeed, other studies have examined the effect of biodiversity supported by specific areas on the production of these areas. In other words, they focus on the effect of diversity of a single finished system on the production of this system. Here, we have two distinguished systems (arable lands and grasslands) but which are managed by a single agent. From our knowledge, this is the first time that someone studies the effects of two kinds of biodiversity on the production of a multi-output farm.

The issue of the form of the technology is stressed in the case of a multi-output farm. Indeed, if previous studies have underlined the productive effects of biodiversity in the case of a single output, how does biodiversity impact several outputs? What is the impact of biodiversity on milk and forage productions? Considering the hypothesis of independent biodiversity, are there any productive spillovers between arable land productions and forage production under permanent grasslands? Are the two kinds of biodiversity a source of complementarity at the farm scale? These questions need to be addressed in order to better understand the impact of biodiversity on the diversity of the farm systems and not exclusively on farms specialized in cash crop production. This is notably the first time that the productive effects of biodiversity are analysed with a milk production case study. This allows an examination of the productive effects of permanent grasslands. The analysis of their productive effects on crop and milk productions gives new insights to understand their steady decline.

On this study, we thus examine the productive effects of two independent kinds of biodiversity on the case of a multi-output farms of western France. The next section provides a critical review of the literature on the subject, notably on the lack of optimization considerations in the previous studies. We present the theoretical model on the third section. The fourth section presents the empirical model, the econometric strategy and the used biodiversity indicators. The fifth section presents the data and the sixth section presents the results. We then discussed the results before to conclude and give 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 (Costanza et al., 1997; Zhang et al., 2007). This introduction is partly due to previous works in ecology and agronomy where it was found that biodiversity has positive effects on landscape functionalities.

#### 2.1.1. Agronomical and ecological literature

Since the first hypothesis of diversity-stability (Elton, 1958; MacArthur, 1955), the ecological literature has examined intensively the effect of diversity on the functionalities of an ecosystem. Several empirical studies have underlined the complementary role of species on ecosystem resilience (Holling, 1973; Hooper et al., 2005). The complementary role of species has also been examined through the analysis of ecosystem production. Some studies have notably proved that biodiversity increases the ecosystem production, especially on net primary production (Costanza et al., 2007; Tilman et al., 1996, 1997). They thus confirm the hypothesis of the over-yielding effect (Hector et al., 2002; Hooper et al., 2005; Tilman et al., 1996, 2005).

The agronomical literature has also tried to benefit from the functionalities provide by biodiversity in order to increase 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 (i) the biological protection against pest, disease and weeds (ii) the nutrient stock available for the following production and (iii) the soil structure through the effect of the different root systems which allow a better root penetration of the following production (Hennessy, 2006). Other famous practices which enhance natural input productive effects 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.

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 permanent grassland systems.

In western France, permanent grasslands constitute an important part of the landscape composition (Baudry et al., 2000a). They constitute, with the presence of many hedgerows, a traditional landscape which is called “Bocage” (Baudry et al., 2000a). With the decline of hedgerow networks in northern Europe, some authors have examined the ecological functionalities link with those landscapes elements (Batáry et al., 2010; Baudry et al., 2000a). If hedgerows provide several functions which are valorised by society (e.g. water filtration – (Mérot et al., 1999) –, flood prevention or biodiversity habitat for mammalian carnivores, birds and insects – (Gehring and Swihart, 2003) –), they can also benefit to farmers. Indeed, agronomic works have focused on the positive effects of hedgerows on agricultural production. 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 insect habitat which can improve pest management (Aviron et al., 2005; Baudry et al., 2000a; Lewis, 1969). The clearing of hedgerows during the second part of the XX$^{st}$ century have notably conducted to a decrease of bee populations (Buchmann and Ascher, 2005). However, these functionalities are not easily valorised by farmers, notably because they are substitute with other inputs such as capital. High hedgerow density does increase complexity of capital management which can explain why some farmers have tended to enlarge their fields and so to remove hedgerows (Lotfi et al., 2010). As a consequence, it is today complex to find the effect of hedgerow on production. For example, (Thenail, 2002) found that dense hedgerow landscapes were associated with smaller farms which have less machinery and lower milk productivity. Scale economies coupled with substitutability between capital and natural input increase the complexity of statistic identification of the productive effect of hedgerows.

### 2.1.2. Economic literature

The analysis of positive effects of biodiversity on agriculture has recently benefited from a growing empirical literature in economics, especially regarding biodiversity productivity and profitability. These researches estimate through statistical methods the marginal effects of biodiversity in production function 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 like the Shannon index (Chavas and Di Falco, 2012; Di Falco and Chavas, 2008, 2009; Di Falco and Perrings, 2005; Smale et al., 1998). They found that biodiversity is a productive input of agricultural outputs which enhances mean yields and reduce variance yields (Chavas and Di Falco, 2012; Di Falco and Chavas, 2008; Di Falco et al., 2010; Ofori-Bah and Asafu-Adjaye, 2011; Smale et al., 1998). Thus, in addition to reduce risk market through a portfolio-like strategy (Chavas, 2008), biodiversity also decreases risk production and enhances production (Di Falco and Chavas, 2008, 2009).

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). Moreover, there are some evidences from developing countries that agrochemical inputs and biodiversity are substitute inputs (Di

Falco and Chavas, 2006). However, these relations are not well understood in developed countries, especially because of the high levels of agrochemical input utilization.

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). Crops are indeed a suitable habitat for many species of which the quality enhances as diversity increases (Bertrand et al., 2016). 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, 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; Yachi and Loreau, 1999).

### 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) whereas they consider several kind of product on the diversity index. 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 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. 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 increases *(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. On the other hand, ecological and agronomical literature on permanent grasslands and attached landscape elements underline the possible productive effects of these elements on crop and forage (maize silage and temporary grasslands) productions. We believe that more researches deserve to be conducted on these crossed effects in order to better understand farmers' economic behavior regarding the management of semi-natural landscape elements such as grasslands, forests or hedgerows.

Third, most of the cited studies use a primal approach to measure the effect of biodiversity on production. However, they fail to capture farmers' economic 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). If farmers can dedicate more areas to the output whom price increases[4], they can also increase output yield[5] (Carpentier and Letort, 2012). 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

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[4] We say that producer increase their production at the extensive margin.

[5] We say that producer increase their production at the intensive margin.

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 natural inputs (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 profit only through the management of natural and conventional inputs. It is thus not right to only focus on biodiversity management and not the management of variable inputs[6]. 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 natural inputs (Chavas and Di Falco, 2012). 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.

Our study aims to overcome these three issues. In response to the two 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.

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[6] 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.

## 3. Theoretical Model

We consider that a farmer maximizes each year *t* his restricted profit function $\Pi_t$ 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 (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 applies on his farm (noted $X_{it}$, $i \in I$). He buys these inputs at the market price (noted $w_{it}$, $i \in I$). 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:

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

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 constraining the farmer.

We consider that the farmer produces *K* products on its farm for which he produces $Y_{kt}$ for the k^th^ output. Each of the *K* outputs are sell 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, we can write (1) as:

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

where $\pi_{kt}$ is the margin of each production and $\pi_{kt}^*$ is its optimum (in order to maximize $\Pi_t$). $\mathrm{T}_k$ 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.

We can write $\pi_{kt}$ as:

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

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

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

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 and $x_{ikt}$ is the by area amount of input *i* allocated to each output. 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 $\mathrm{T}_k$ regroups the production function of each production $F_{kt}(x_{ikt}, Z_{kt})$. Taking into account the constant return to acreage assumption, $F_{kt}(x_{ikt}, Z_{kt})$ represents the yield of output *k* in year *t*. It is assumed that $F_{kt}(x_{ikt}, Z_{kt})$ verifies for each input *i* and output *k* that $\frac{\partial F_{kt}(x_{ikt}, Z_{kt})}{\partial x_{ikt}} > 0$.

In the case of multi-output firm, a joint technology allows for scope economies. Assuming two production, we can write that $F_1(x_{i2t}, B_{jt}, Z_{lt}, Y_2 | Y_2 > 0) \geq F_1(x_{i2t}, B_{jt}, Z_{lt}, Y_2 | Y_2 = 0)$. The production of the first input increases when there is a specific second production. Our model take into account for these specifities.

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

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

Considering the economic context and his fixed input dotation, the farmer optimizes in the same time $Y_{kt}^*$ and $X_{ikt}^*$. When the farmer sows his production, he has thus already chose the optimal levels $F_{kt}^{*}$ and $x_{ikt}^{*}$ given the anticipated economic context and his fixed input dotation. The choice of $F_{kt}^{*}$ is simultaneous with the choice of $x_{ikt}^{*}$. For the econometric estimation of the production function parameters, this led to endogenous biases.

Without surprise, the equation (5) means that the marginal productivity in value is equal to the cost of the last unity of input. As a multi-output producer, the farmer will optimize these conditions on each output, leading to:

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

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)*[7], we thus reach the optimal condition:

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

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. Contrary to previous studies, this imposes a constraint on the production function parameters which include the farmer's economic behavior.

In our empirical model, we estimate production functions $F_{kt}(\cdot)$ of milk and crops on a sample of mixed farms of western France. The estimation of the parameters of the two functions use the parameter constraints (7) on the optimal application of variable inputs $x_{ikt}^{*}$. In order to overcome the endogenous biases linked to the simultaneous choices of $F_{kt}^{*}$ and $x_{ikt}^{*}$, we also add for each variable inputs an ad-hoc demand function depending on market prices ratio (Carpentier and Letort, 2012). We can thus write $x_{ikt}^{*}$ as:

$$x_{ikt}^{*} = D_i\left(\frac{E(p_{kt})}{E(w_{it})};\frac{E(w_{jt})}{E(w_{it})}\right)\ ;\ \forall\ j \neq i \qquad (8)$$

---

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

$D_i$ is the demand function for input $i$. It is decreasing and homogeneous of degree zero in prices. $x^*_{ikt}$ increases when output prices increases relatively to the price of input $i$. The addition of both the demand functions and the optimum constraints on the parameters allows 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. Most of the authors have thus utilized 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 (Gregory et al., 2005) and (ii) indirect indicators (or structural indicators) based on land-use composition and structure (Kindlmann and Burel, 2008). This last approach is highly influenced by landscape ecology which postulate that landscape structure (defined by both its composition and configuration) determine species dynamics and thus biodiversity abundance (Burel and Baudry, 2003). There exist many landscape indicators which inform on the levels of the landscape functionalities (Haines-Young and Potschin, 2010). However, as there is no institutional dataset which provide enough highly detailed data 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. Indeed, even if economic dataset does not usually inform on landscape configuration, they provide at least useful information on landscape composition.

The mobilization of landscape ecology in economics is scarce but there are more and more works using landscape metrics indicators for monetary valuation of landscape attributes (Tagliafierro et al., 2013). Early utilization of these indicators are notably used for theoretical and empirical estimations of biodiversity effects on agricultural productivity and stability (Di Falco and Chavas, 2008; Heisey et al., 1997; Smale et al., 1998; Weitzman, 2000).

For our empirical application, we select two kinds of biodiversity habitat: arable lands (noted $B_{1t}$) and permanent grasslands (noted $B_{2t}$). The distinction of several biodiversity is a crucial point of our study. The distinction of several biodiversity habitat recognizes that areas can only provide suitable habitat for a specific kind of biodiversity (Duflot et al., 2014). The distinction of different habitat is notably used in studies based on high nature value indicators which try to integrate the different kinds of biodiversity habitat (Baldock et al., 1993; Desjeux et al., 2015). Desjeux et al. (2015) have notably integrate the whole diversity of farmland biodiversity habitats for the studying of CAP reforms on farmland biodiversity[8]. However, we do not have sufficient detailed information to compute a high nature value indicator at the farm scale based on FADN data. As a consequence, we restrict our work for two kinds of habitat.

In the case of arable lands, we choose to rely on a Shannon index. 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[9] (Keylock, 2005). If the Shannon index was first developed to study species diversity, it is also well adapt for habitat diversity (Mainwaring, 2001). It was particularly used by several empirical microeconomic studies to measure crop diversity (Chavas and Di Falco, 2012; Di Falco and Chavas, 2008, 2009; Di Falco and Perrings, 2005; Smale et al., 1998). The Shannon index is usually write as

$$H = -\sum_{s=1}^{S} p_s \ln(p_s)$$

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[8] However, Desjeux et al. (2015) do not present any microeconomic model which could allow a decomposition of the CAP reform effects on the producer optimization program.

[9] This is in line with the constant return to acreage assumption.

where $p_s$ is the proportion of each species (or habitat) in the sample. In our case, we can write:

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

where $s_{kt}$ is the proportion of each area in the utilized agricultural area (UAA), 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, *i.e.* when arable land biodiversity increases. The utilization of Shannon index in studies on biodiversity productive and risk spreading effects is widely used. Indeed, most of the cited studies have used this indicator (or a derived one) for the measure of farmland (or crop land) biodiversity (Di Falco and Chavas, 2008, 2009, Di Falco and Perrings, 2003, 2005; Matsushita et al., 2016; van Rensburg and Mulugeta, 2016; Smale et al., 1998).

Mixed farms of western France often present a diversified acreage. Indeed, most of them produce crops, maize silage and temporary grasslands[10]. We thus compute a simplified Shannon index corresponding to the acreage composition of the three main areas of mixed farms of western France:

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

The comparison of the productive effects of $B_{1t}$ (the full arable land biodiversity indicator) and $B'_{1t}$ (the degraded arable land biodiversity indicator) on crop and milk productions illustrates the importance of the “marginal” productions. Though different indicators,

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

(Smale et al., 1998) have also used several biodiversity indicators for the analysis of crop diversity productive effects.

For permanent grassland biodiversity, we choose our indicator as the proportion of permanent grasslands in the UAA, *i.e.* $B_{2t} = s_{Gt}$ where the G$^{\text{th}}$ output is permanent grassland. 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 western France has notably concluded to the positive correlation between permanent grasslands and hedgerows (Baudry et al., 2000b; Thenail, 2002). For example, (Baudry et al., 2000b) found in a small area of Brittany (France) that cash crop farms contain 40% less hedgerows than milk and meat cattle farms.

## 4.2. Empirical model and econometric strategy

### 4.2.1. Empirical model

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 two production function. The first one, a 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:

$$F_{1t}(x_{i1t}, B_{jt}, Z_{lt}) = \beta_{01} + \sum_{i=1}^{4} \beta_{i1} x_{i1t} + \sum_{j=1}^{2} \beta_{j1} B_{jt} + \sum_{l=1}^{3} \beta_{l1} Z_{lt} + \varepsilon_1 \tag{9}$$

$F_{1t}(x_{i1t}, B_{jt}, Z_{lt})$ 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). We consider two kinds of agricultural biodiversity: arable land biodiversity and permanent grassland biodiversity. The three other fixed inputs $Z_{lt}$ are available labor, farm capital and total farm area. $\varepsilon_1$ 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 linear production function such as:

$$F_{2t}(x_{i2t}, B_{jt}, Z_{lt}) = \beta_{02} + \sum_{i=1}^{6} \beta_{i2} x_{i1t} + \sum_{j=1}^{2} \beta_{j2} B_{jt} + \sum_{l=1}^{3} \beta_{l2} Z_{lt} + \varepsilon_2 \qquad (10)$$

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 $Z_{lt}$. $\varepsilon_2$ is the error term of the equation (10). Similarly to (9), we also add control variable to reduce the endogenous biases.

The $\beta_{ik}$ in equations (9) and (10) 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 constraints:

$$\frac{\beta_{11}}{\beta_{12}} = \frac{\beta_{21}}{\beta_{22}} \qquad (C1)$$

$$\frac{\beta_{21}}{\beta_{22}} = \frac{\beta_{31}}{\beta_{32}} \qquad (C2)$$

$$\frac{\beta_{31}}{\beta_{32}} = \frac{\beta_{41}}{\beta_{42}} \qquad (C3)$$

This captures the rational short term optimization of the farmer. As we consider only the restricted profit function, these three constraints capture the essential part of the farmer's econometric behavior.

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

$$x_{ikt}^{*} = \alpha_0 - \alpha_1 \frac{p_{1t-1}}{w_{it}} - \alpha_2 \frac{p_{2t-1}}{w_{it}} - \alpha_j \frac{w_{jt}}{w_{it}} + \mu_i \tag{11}$$

where $j \neq i$ and $\mu_i$ is the error term of equation (11). This linear specification is line with the characteristics of the demand function $D_i$. 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)[11]. 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 (Carpentier and Letort, 2012). In addition to market prices, we also add the exogenous variable of equations (9) and (10) in (11) 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 (9) and (10). As manure production is a function of total farm milk and the number of cattle on the farm, we add the number of cattle unit and

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

the farm quota[12]. Indeed, these two variables can be considered as exogenous in the short term. Milk quota is strictly exogenous because it depends on historical regional production levels. Cattle units are endogenous in the long term but are more exogenous in the short term[13]. Addition of farm available manure proxies in the empirical model brings new information which released the interception of the organic fertilization productive effect in the parameters of $B_{2t}$. This addition allows the estimation of the "true" productive effects of permanent grasslands. In order to take into account the whole farm available organic nutrient, we also add proxy[14] of the manure from other farm livestock (e.g. pigs, poultry, sheep, *etc.*).

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.

Another important issue in our empirical model is that the $x_{ikt}$ are not available for each $k \in K$. Indeed, we use French data from the Farm Accountancy Data Network (FADN) for our econometric estimation. However, the FADN does not provide sufficient analytical account and induces a lack of information on the utilization of farmers' purchased inputs. Indeed, the FADN only provides information on the total amount of purchased input at the farm scale $X_{it}$ (in Euros). The lack of activity-specific data is a commonly encountered problem when analyzing production structure of multiproduct farms (Carpentier and Letort, 2012). In order to overcome this issue, we compute $x_{it}$ as $X_{it}/S_t$, *i.e.* the average application of input *i* at the farm scale. As a consequence $\beta_{ik}$ measure the product of the marginal productivity of input *i* on product *k* by an input repartition factor[15]. This last factor captures the relative input needs of crops and forage production. Thereby, the parameters

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[12] Farm quota for milk production is used as proxy for available cattle manure only in the case of the crop production function. The addition of milk quota in the estimation of milk yield will probably capture historical production effect rather than the productive effect of organic fertilization on forage production.

[13] We will come back to this point on the discussion section.

[14] The number of livestock unit other than cattle.

[15] 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.

$\beta_{ik}$ measure two effects which are impossible to separate. However, as our interested parameters are the $\beta_{jk}$, we just verify that $\beta_{ik}$ are positive for each input *i* and output *k*.

In addition to linear production functions, we also try, in a second step, to estimate quadratic production functions in order to allow for the maximum of flexibility. For crops, we have:

$$F_{1t}(x_{i1t}, B_{jt}, z_{lt}) = \beta_{10} + \sum_{i=1}^{4} \beta_{i1} x_{i1t} + \sum_{j=1}^{2} \beta_{j1} B_{jt} + \frac{1}{2} \sum_{i=1}^{4} \sum_{i=1}^{4} \beta_{i1k} x_{i1t} x_{i1t} + \frac{1}{2} \sum_{j=1}^{2} \sum_{j=1}^{2} \beta_{jj1} B_{jt} B_{jt} + \frac{1}{2} \sum_{i=1}^{4} \sum_{j=1}^{2} \beta_{ij1} x_{i1t} B_{jt} + \sum_{l=1}^{3} \beta_l z_{lt} + \varepsilon_1^q \tag{12}$$

where $\varepsilon_1^q$ is the error term of the equation. The quadratic functional form authorizes for non-linear effects for all the inputs. Indeed, we use simple and squared terms in order to count for decreasing marginal effects. We also add crossed effect terms between biodiversity and variable inputs. This enables us to examine more deeply the form of the agricultural technology, notably for the substitutability and complementarity effects between natural (biodiversity) and chemical inputs.

The milk production function has a similar form:

$$F_{2t}(x_{i2t}, B_{jt}, z_{lt}) = \beta_{20} + \sum_{i=5}^{6} \beta_{i2} x_{it} + \sum_{j=1}^{2} \beta_{j2} B_{jt} + \frac{1}{2} \sum_{i=1}^{4} \sum_{i=1}^{4} \beta_{ii2} x_{i2t} x_{i2t} + \frac{1}{2} \sum_{i=5}^{6} \sum_{i=5}^{6} \beta_{ii2} x_{it} x_{it} + \frac{1}{2} \sum_{j=1}^{2} \sum_{j=1}^{2} \beta_{jj2} B_{jt} B_{jt} + \frac{1}{2} \sum_{i=1}^{4} \sum_{j=1}^{2} \beta_{ij2} x_{i2t} B_{jt} + \frac{1}{2} \sum_{i=5}^{6} \sum_{j=1}^{2} \beta_{ij2} x_{it} B_{jt} + \sum_{l=1}^{3} \beta_l z_{lt} + \varepsilon_2^q \tag{13}$$

The addition of squared and crossed effects on the production function increases however the number of endogenous terms and increase the complexity of the parameter estimations (Chamberlain, 1987).

### 4.2.2. Econometric identification strategy

We estimate the parameters of the two linear production functions (9) and (10) on a pooled panel data sample. As a first indication, we estimate these parameters separately for each production with ordinary least squares (OLS) method. For comparison, we then estimate the system constituted of equations (9) and (10) with the addition of the parameter constraints (C1) - (C3) in a seemingly unrelated regression (SUR). This second step corrects the variance of the estimated parameters taking into account for the correlations between the error terms of the two equations[16]. The parameter constraints allow to take into account for the 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. The appropriate implementation of the estimated parameters requires that the selected instrumental variables are correlated with the endogenous variable but not with the error terms. As discussed before, we thus estimate the $\hat{x}_{ikt}^{*}$ on exogenous variables thanks to equation (11). The selected exogenous variables are the prices market (the ones from the current year for inputs and previous year prices for outputs)[17] and the other exogenous variables of the system (e.g. capital, labor, UAA)[18]. We thus estimate a system of two production functions and six input demand equations. In order to take into account for the optimization constraints, we compute this system with and without the parameter constraints (C1) - (C3). We present the result of the 3SLS estimation with parameter constraints on table 2. Other estimations are presented in the annexes.

The correction of endogenous biases in the variable input allocations is one of our contribution in this paper. Contrary to previous work, we however choose to not correct for endogenous bias on the biodiversity indicators. Indeed, we make the assumption that farmers do not manage easily their biodiversity levels in the short term. If this assumption is relatively naïve for $B_{1t}$ and $B'_{1t}$, management of permanent grasslands is more in the long term. Some authors have however underlined that farmers face adjustment costs (Lansink and Stefanou, 2001) or diversification costs (Carpentier and Letort, 2012, 2014)

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

[17] As market prices are shared by farmers, there are not contained on the error terms of (9) and (10) (i.e. $\varepsilon_1$ and $\varepsilon_2$).

[18] In the future, we want to add some variables on typological and meteorological conditions. Indeed, the farmer application of variable inputs depends on his topological conditions (during all his carrier) and the annual meteorological conditions. This will capture some of the individual and temporal variations.

which tend to confirm our assumption of short term quasi-fixity of the farm biodiversity levels[19].

Similarly, the quadratic functions are estimate using OLS, SUR and 3SLS but without any constraints on parameters. Indeed, the addition of non-linear terms on the function modify the constraints (C1) – (C3) which could not been implement in the system estimation. For the moment, we add squared effects[20] but we only instrument the linear-term of the input applications. Instrumentation of a product of an endogenous variable is however suggested by (Chamberlain, 1987)[21]. The result of the first estimation of this simplified system are available in the annexes of this paper.

## 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 FADN is valuable for European economists because it provides highly detailed available economic information of the European farms. On the geographic side, the FADN provide information on farms' acreages which allow computation of our biodiversity indicators[22].

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

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[19] Further estimations will released this assumption, at least for $B_{1t}$ and $B'_{1t}$.

[20] We plan to add crossed effect in the future in order to understand deeply the substitute/complementary relationships between biodiversity and conventional inputs.

[21] First estimations have complicated the estimation of the interested parameters. More tries are needed in order to find more instrumental variables and suppress collinearity issues of the whole system.

[22] FADN does not provided any information on both landscape configuration and non-agricultural activities (which also influence biodiversity levels). As a consequence, we select which are based only on landscape composition, which mean in our case, on acreage composition.

and milk production. As pig and poultry breeders are mainly off soil, we focus on dairy farming. Indeed, these three regions because they 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). However, most of them have also a crop production[23]. These three regions have also a good dotation on permanent grasslands. Lower Normandy had notably more than 700 000 Ha of permanent grasslands in 2006 (AGRESTE, 2009). 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[24]. 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 5654 observations, i.e. 79,3% of the initial milk farm sample (and 80,4 % of the initial total area). The rotating sample is constituted of 1035 farms whose presence in the survey is on average of 5,46 years. All the selected farms have at least a year an activity in milk and crop productions.

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. Adopted for the 2010 campaign, the most notable changes are the suppression of fallow obligations, the gradual increase of milk quotas (1% per year) 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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[23] 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.

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

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.

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. All the input and output prices were deflated by inflation rates among the period[25].

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

**Table 1:** Descriptive statistics on the variables used in the regressions

| | **Mean** | **Median** | **Q1** | **Q3** | **Min** | **Max** |
|---|---|---|---|---|---|---|
| Crop yield (in quintal/acres) | 0,66 | 0,68 | 0,58 | 0,75 | 0,02 | 1,32 |
| Milk yield (in tons/Ha) | 63,15 | 61,97 | 45,21 | 78,48 | 14,87 | 209,1 |
| Degrated Arable Biodiversity index | 0,96 | 1 | 0,91 | 1,05 | 0,03 | 1,1 |
| Arable Biodiversity index | 1,19 | 1,14 | 0,97 | 1,44 | 0,12 | 2,22 |
| Grassland Biodiversity index | 0,1 | 0,02 | 0 | 0,14 | 0 | 0,92 |
| Fertilizer (quantity index) | 124 | 99 | 56,9 | 161,6 | 0 | 1082 |
| Pesticides (quantity index) | 66,18 | 48,9 | 27,01 | 80,92 | 0 | 860 |
| Seeds (quantity index) | 77,97 | 62,62 | 40,1 | 95 | 0 | 898,6 |
| Fuel (quantity index) | 56,54 | 46,79 | 30,37 | 71,78 | 0 | 314,5 |
| Cow feed (quantity index) | 279,4 | 219,5 | 128,7 | 362,8 | 0,72 | 2803 |
| Health and reproduction (quantity index) | 52,81 | 41,99 | 25,39 | 66,98 | 0 | 407,1 |
| Cattle livestock unit/total area (/Ha) | 1,22 | 1,16 | 0,92 | 1,45 | 0,07 | 8,12 |
| Other livestock unit/total area (/Ha) | 1,12 | 0 | 0 | 0,94 | 0 | 70,37 |
| Milk quota/total area (tons/acres) | 0,042 | 0,04 | 0,03 | 0,051 | 0 | 0,14 |
| Total area (acres) | 8877 | 7626 | 5394 | 10870 | 695 | 38290 |
| Capital/total area (€/acres) | 33,13 | 30,22 | 20,92 | 41,06 | 0 | 134,6 |
| Labor (annual worker unit / 100) | 216,2 | 200 | 150 | 267 | 80 | 1281 |
| Labor (declared total working time in hours) | 3467 | 3200 | 2400 | 4280 | 1280 | 20500 |
| Cow/total area (tenth of head / acres) | 0,063 | 0,061 | 0,047 | 0,077 | 0,002 | 0,201 |

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. Milk production is present in all the sample observations and crop production is missing for only 58 observations (1% of the observation).

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. Whereas the computation of the degraded arable land biodiversity index integrates the proportion of crop category, the arable land biodiversity index includes all the diversity of crops. 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 10% of the areas.

## 6. Results

Table 2 reports the estimation results of the two linear production functions of the estimated system. The used method is the Three Stages Least Squares with parameter constraints (C1) – (C3) on marginal productivities. Table A1 in annexes presents the parameter estimations of the two production functions with three other different estimation methods: Ordinary Least Squares, Seemingly Unrelated Regressions and Three Stages Least Squares without parameter constraints. 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 estimated with the Three Stages Least Squares with parameter constraints method. Table A3 in annexes presents the preliminary results of the estimation results of the two quadratic production functions.

**Table 2:** 3SLS estimations of the yield equations of the complete system

| | y_crops | | y_milk | |
|---|---|---|---|---|
| | Estim. | Sign. | Estim. | Sign. |
| **Const** | -0,24 | *** | -238,9 | *** |
| | (0,05) | | (25,6) | |
| **Biodiversity** | | | | |
| Degraded Arable Biodiversity index | -0,05 | | 407,3 | *** |
| | (0,042) | | (57,6) | |
| (Degraded Arable Biodiversity index)² | | | -205,9 | *** |
| | | | (32,9) | |
| Arable Biodiversity index | 0,047 | * | -83,3 | ** |
| | (0,023) | | (21,65) | |
| (Arable Biodiversity index)² | | | 22,6 | ** |
| | | | (8,05) | |
| Grassland Biodiversity index | 0,204 | *** | -56,62 | |
| | (0,034) | | (71,1) | |
| **Variable inputs** | | | | |
| Fertilizer / total area | 0,03 | | 1,7 | |
| | ( 2,01) | | (131,1) | |
| Pesticides / total area | 7,88 | ** | 515,7 | * |
| | (2,92) | | (211,5) | |
| Seeds / total area | 22,77 | *** | 1491,2 | *** |
| | (5,74) | | (466,1) | |
| Fuel / total area | 88.14 | *** | 5770,3 | *** |
| | (11,94) | | (1321,8) | |
| Cow feed / main forage area | | | 3355,6 | *** |
| | | | (119,3) | |
| Health and reproduction / main forage area | | | -436,02 | |
| | | | (258,2) | |
| **Organic Fertilizer proxies** | | | | |
| Cattle livestock unit/total area | 0,052 | ** | 10,3 | ** |
| | (0,016) | | (3,12) | |
| Other livestock unit/total area | -0,002 | | 0,49 | |
| | (0,002) | | (0,44) | |
| Milk quota/total area | 2,19 | *** | | |
| | (0,49) | | | |
| **Control variables** | | | | |
| Total area | 2,31E-6 | | -0,0009 | * |
| | (1,56E-6) | | (0,0004) | |
| Capital/total area | -0,001 | * | -0,0011 | |
| | (0,0005) | | (0,092) | |
| Labor (annual worker unit) | -0,002 | | -0,41 | |
| | (0,002) | | (0,33) | |
| Labor (declared total working time) | 0,0001 | | 0,025 | |
| | (0,0001) | | (0,02) | |
| Cow/total area | | | -704,6 | *** |
| | | | (93,99) | |
| Number of observation | 2479 | | | |

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

The results in Table 2 show that the variable inputs display the expected signs on both production functions, excepted in the case of health and reproduction spending but the parameter is not significant. All other parameters of variable inputs are significant at a threshold of 5% (most of them are significant at a threshold of 0,1%) excepted in the case of mineral fertilizer where the estimated parameters of both production functions are non-significant. This is not a surprised because, with the low prices of mineral fertilizer and the availability of manure for organic fertilization, farmers from our sample have a high availability of fertilizers. The application of the additional unity of fertilizer has thus no impact on marginal productivity on most cases. This result 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). Results from Table A1 suggest that variable inputs are indeed endogenous. Whereas OLS method provides consistent estimation of the variable input marginal productivities on crop production (mineral fertilizer has a positive and significant effect), their effects on milk production are not theoretically consistent in the case of seeds and mineral fertilizer. SUR estimation with parameter constraints do not correct from these biases. The estimation through the Three Stages Least Squares without parameter constraints method gives interesting results. Whereas we find comparable variable input productive effects with the previous Three Stages Least Squares estimation (with parameter constraints) in the case of crop production, their productive effects on milk production are negative and significant in the case of pesticides, seeds and fuel. The addition of parameter constraints allows obtaining the theoretical effect of variable input on milk production[26]. We can explain this sensitivity by the dependence of milk production on forage production. The effects of variable inputs such as fertilizer, pesticides, seeds and fuel impact milk production through their impacts on forage production. Results on crop production are much more robust. Table A2 shows however 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. To conclude on variable inputs, we do find non-negative productive effects on both productions in the case of Three Stages

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[26] Note that the addition of parameter constraints on the 3SLS method was coupled with the non-instrumentation of pesticide demand. The addition of constraints (C1) and (C2) coupled with pesticide price addition in other variable demand functions allow capturing the farmer optimization process.

Least Squares estimation with parameter constraints. The signs of the demand function are quite consistent with theory and the comparison between SUR and OLS estimation confirms the endogenous biases of simultaneous choices.

Fertilization decisions are a critical point of mixed farm management as fertilization can be bought on market our produced on the farms through the mobilization of others inputs. Whereas we do not find any productive effects of mineral fertilization on both production functions, organic fertilization increases production of both milk (and thus forage) and crops. The proxies of available cattle manure have positive and significant effects in both production functions. Available organic manure from other livestock has no productive impact on both production functions. This result has also been found in other works on mixed farms orientated towards pig production (Dupraz, 1996). A given justification of the productive differential effects is that milk farms do manage fertilization for productive purpose (similar to fertilization demand) but pig and poultry farms manage fertilization only for legislative purposes (demand for land for manure spreading).

Regarding the productive effects of our interested variables (the biodiversity indicators), the estimated parameters in Table 2 display the effects are different between the indicators and the productions. On a first hand, the crop production increases when both the arable land biodiversity and the permanent grassland biodiversity indexes increase. The degraded arable land biodiversity $B'_{1t}$ has however no significant effect on crop production. The positive effect of $B_{1t}$ on crop production suggests that the whole arable land diversity is important, not only the three main areas. In fact, $B_{1t}$ benefits from the desegregation of crop area in all the 13 categories of the FADN crops. As a consequence, in addition to take into account other marginal production, $B_{1t}$ captures the whole crop diversity. $B'_{1t}$ does not measure crop diversity but more the area management of the main outputs. We thus find the same positive effects of arable land diversity on crop production than previous studies on the analysis of crop diversity productive effects on crop production (Chavas and Di Falco, 2012; Di Falco and Chavas, 2008, 2009; Di Falco et al., 2010; Matsushita et al., 2016; Smale et al., 1998). However, other studies which integrate other habitats than only crop diversity have also found a positive effect on crop production (Omer et al., 2007; van

Rensburg and Mulugeta, 2016). Our analysis does not allow to know if crop biodiversity is the most important part of arable land biodiversity. An interesting point of our study is that permanent grassland biodiversity index $B_{2t}$ does increase crop yield. This tend to confirm first results of ecological and agronomical studies on the productive effects of permanent grasslands and related permanent landscape elements. Similar results on profit were also found by (van Rensburg and Mulugeta, 2016) on the case of upland livestock farms in Ireland. They found that the ratio perimeter to area decreases the profit, i.e. that the number of field margins increases profit. As the number of field margins is correlated with the number of permanent landscape elements (Baudry et al., 2000b; Thenail, 2002), we tend to find similar results though we rather focus on production and use a different indicator. There is thus a productive spillover from permanent grassland areas to crop areas. Other econometric methods give similar results on the effects of our three biodiversity indicators. The only marginal difference is that $B'_{1t}$ has a positive productive effect on crop production in the case of OLS and SUR estimations which disappears when input demand function are instrumented.

On the other hand, in the case of milk production, the effect of biodiversity is much more complex. The Table 2 display that $B'_{1t}$ has a positive effect (with decreasing rate though[27]) on milk production. $B_{1t}$ has however a negative effect (with increasing rate) on milk production. The comparison of the level of the effects tend to underline the higher marginal productive importance of $B'_{1t}$ rather than $B_{1t}$. As $B'_{1t}$ measures the entropy of the restricted system composed of crop, corn silage and temporary grasslands, we can consider, in this case, that $B'_{1t}$ is a proxy of forage diversity. An increase of $B'_{1t}$ corresponds to a higher diversity of the main areas and thus to forage areas. This could explain the higher levels of estimated parameters. Indeed, agronomical studies tend to underline the role of forage diversity and portion diversity on milk yield (Huneau et al., 2013). It is however difficult to confirm this effect as milk yield depends more classically on nutrient and energy intakes.

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[27] We also try to add squared effects of $B_{1t}$ and $B'_{1t}$ in the crop yield estimation but the effect were non-significant and even degrade the significance of the effect of the linear terms.

We may thus also assume that $B'_{1t}$ increases forage production (or quality) and thus increase milk production. Indeed, farmers can increase nutrient and energy intakes through the augmentation of forage and concentrates quantity or quality. These effects are notably illustrated by the productive effects of cow feed purchases. Another explanation is given by (Delaby and Peyraud, 2009) or (Peyraud et al., 2009) which suggest that when the main forage is more specialized, the production decreases because (i) if the main forage area is orientated towards grasslands then the farmer does not choose to reach the highest milk potential of cows or (ii) if the main forage area is orientated towards corn, then the farmer choose to have a purest corn ration which is risky because it increases disease risks. However, the estimated parameters are not robust as we can see with the comparison of the other estimation method, notably the case of the Three Stages Least Squares estimation without parameter constraints. In this last case, the effect on $B'_{1t}$ are not significant whereas $B_{1t}$ has a productive and significant effect (at the threshold of 5%). Similarly, we find in the Three Stages Least Squares estimation with parameter constraints that the permanent grassland biodiversity index $B_{2t}$ has no effect on milk production whereas all other estimations display significant and negative effect on milk production. Similarly to the arable land biodiversity index, the results are less robust in the case of milk production function. However, 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 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.

In addition to the linear production function estimations, preliminary results on the quadratic production function estimations are available in annexes (table A3). Indeed, despite the remarks of (Chamberlain, 1987) on endogenous variable, we had time to only instrument linear term of variable input for the moment. If we only add squared effect of variable inputs (and organic fertilization proxies), the results seem however to confirm initial results. We find the right theoretically productive effects of variable and biodiversity inputs in most cases. Indeed, most of the productive effects are positive with decreasing rates. The introduction of squared terms is notably important for fixed input productive effect estimation. In the case of capital, this correct the squared effect correct the linear one on the crop production function. Future works will require to instrument the additional suspected endogenous variables, i.e. at least the squared terms of the variable inputs.

## 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[28]. This issue is inherent to the database but can be overcome with the matching of "Météo France" and the French National Geographic Institute (IGN) thanks to official municipality number of the farm headquarter.

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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[28] 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

Our biodiversity indicators suffer from several bias, notably according their construction. 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. Landscape ecology have however stressed the importance of (i) landscape configuration and (ii) landscape scale (Kindlmann and Burel, 2008). Our biodiversity measures suffer from both biases. In order to overcome these issues, it would necessitate to introduce information on farm landscape structure. Example of landscape configuration indicators is the ratio perimeter to area used by (van Rensburg and Mulugeta, 2016) or the length of an interested interface between two outputs (e.g. the wheat-crop interface for an indicator of biological control by carabid beetles – (Bertrand et al., 2016) –). However, the FADN does not allow any construction of this kind of indicator. In addition, none information is available on landscape composition or configuration of neighbor farmers. The construction of biodiversity indicators at the farm scale does not allow a well understanding of biodiversity management by a farmer. Indeed, biodiversity productive effects have public good characteristics. A farmer can thus behave as a free-rider in order to benefice from biodiversity productive effects without assume biodiversity management costs. The selection of the Land Parcel Information system (LPIS) would be much more appropriate for the computation of landscape indicators because we would have agricultural landscape composition and configuration of all CAP subsided French farms. 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, complementary information on afforested lands through LPIS database. Our microeconomic analysis suffers notably from the lack of afforested land information. The FADN does provide information on permanent crops but it would restrain our sample from 5654 observations to 215 ones. However, mobilization of LPIS is not sufficient for our analysis because it does not provide enough information on the economic side. The selection of the FADN gives thus useful information on the economic side, to the detriment of the ecological side.

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.

A future work will also consist to test a different specification in the computation of the Shannon index. Indeed, our two indicators ($B_{1t}$ and $B_{2t}$) are linked by the share of permanent grassland area $s_{Gt}$. Indeed, when permanent grassland share increases, shares of $s_{kt}$ are mechanically modified. This implies that our two kinds of biodiversity are not independent in our empirical results. We will thus test the following alternative specification:

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

This last formula correct arable land shares from permanent grassland shares. Independent biodiversity assumption holds strictly in that case. First econometric results with this specification do not change heavily estimated results. The effects do not change on the crop production function but modify the effect of biodiversity on milk production function. More model specification is however needed in order to increase robustness of the estimations.

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

One of the originality of our paper is that we instrument variable input application with the addition of ad-hoc input demand functions. Indeed, all other cited papers does not correct for the simultaneous choices between input allocation and objective output whereas this is a common issue in agricultural economics. The instrumentation has provided coherent parameters and the effectiveness of the selected instruments seems sufficient ($R^2$ comprise between 0,5 and 0,7). Additional testing may however increase the robustness of our system[29]. The interesting point is that the endogenous biases do not change the conclusions of the previous studies. Biodiversity is a productive input in the case of crop production.

However, these estimations are not complete for the moment. Indeed, some of the explicative variables are suspected to be endogenous. This is especially the case of the variable measuring the cattle livestock unit. Indeed, cattle livestock unit and number of cows are managed by the farmer according to market prices. If the milk activity is less profitable, the farmer could sell some cows (maybe sell sooner cull cows) in order to restore some of the margin. Due to the lack of time, we did not success to instrument correctly these activities. However, we have tested two alternative model specifications. In the first one, we have used lag variables. In the second, we have compute and instrument an indicator of organic fertilization thanks to the CORPEN (a service of the French Agricultural Ministry). The first one gives similar result for crop production but first analysis modifies the effect of estimated parameters on milk production. This is quite logical and confirms the potential endogenous bias. Additional tries have however give interesting results even if there are not robust for the moment. The second solution has the benefice to construct a single organic fertilizer variable. However, despite its instrumentation, there is no effect on both production function. Additional tries will be done in the future, notably with the creation of a cattle organic fertilizer variable and another for the other livestock.

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[29] Additional tests should be done on the anticipation process of the sample farms. We have tested the rational anticipations but the estimators display opposite sign with theory. Recent works have indicated that quasi-rational anticipations work, and in the case of crops, the utilization of future prices may also success.

Most of the cited studies on the productive effects of biodiversity 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.

It is nevertheless probable that our biodiversity indicators are an endogenous choice for farmers. Indeed, there are measured thanks to acreage decisions which depend on the economic context. Our assumptions on the effect of $B'_{1t}$ on the productive effect of milk yields illustrate these possible economic decisions. The extensive margins decisions are however limited 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 linked to specific output production. Indeed, the management of capital introduce shadow costs linked to the associated constraints which prevent the farmer to change his system. These costs are notably higher when the capital is specific (*e.g.* resale of specific machinery on second hand markets). These costs are interpreted as diversification costs (Carpentier and Letort, 2012, 2014) and prevent the management of the biodiversity in the short time. We thus estimate that our biodiversity indicators can be considered as "predetermined" variables which are not susceptible to suffer from endogenous bias.

There are however some proofs that farmers manage their biodiversity. 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, this does not contradict the previous point because our indicators are not sensible to structural modifications. Indeed, $B_{1t}$ , $B'_{1t}$ and $B_{2t}$ are all indicators which are influenced by farm landscape composition and not by farm landscape structure. If the farm output dedicated areas do 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. Indeed, management of biodiversity is more susceptible to be realized in the long term, where quasi-fixed input can be managed. Some studies have underlined that biodiversity enhances current and future production (Brock and Xepapadeas, 2003; Di Falco and Chavas, 2008; Matsushita et al., 2016). These results are notably consistent with natural science studies (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. They notably regret that field-scale analyses do not model acreage choices. Acreage choices are indeed constrained by the multi-output technology and farm dotation in quasi-fixed inputs.

If our model capture implicitly the acreage decisions through our variable input parameter restriction, our model does not integrate explicitly for acreage management. Indeed, our purpose on this paper was not to examine an acreage model but only to focus on the productive effects of biodiversity taking into account for variable input allocation. As these allocations depend on the relative output allocated areas, we constrain the input allocation to the acreage choices. In addition to the difficulty to analyze the variable input parameters in the production functions, our model may suffer from a lack of flexibility on the input allocation.

On future researches, we will release this assumption with the addition of a dynamic acreage decisions in the model. Recent works have indeed succeeded to model in the same time (i) production function, (ii) variable input demand function and (iii) acreage function (Carpentier and Letort, 2012). The addition of the acreage model part will authorize to endogenize biodiversity management. Indeed, as our biodiversity indicators depend on acreage shares, we could model the farmers' economic behavior regarding biodiversity at the farm scale. The dynamic dimension will illustrate the farm scale intertemporal management of the farmer between current on future periods. Indeed, expected market prices influence acreage choices for several years (Carpentier and Gohin, 2015). On a first hand, they incite farmers to maximize their extensive margins. On the other hand, farmers can also enhance intensive margins through a suitable dynamic acreage management. Adding the acreage part in the model will authorize (i) more flexibility into the variable input allocation, (ii) the estimation of the real variable input productivity, (iii) to endogenize biodiversity indicators and thus (iv) to measure the costs of biodiversity management.

## 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. Better understanding of biodiversity 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 the previous studied. We have even expanded the result with the underlying of the import role of other marginal productions on crop production. 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 the arable land productive effects have 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 other output productions. Our analysis confirms that arable land biodiversity effects on milk production are complex and certainly variables. However, this does not explain why the crop diversity decline has also been observed in crop specialized French LAU1 regions.

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). These costs can notably be linked to the adjustment cost theory (Lansink and Stefanou, 2001). All these works agree to underline the importance of scale economies in acreage management in order to decrease management costs (notably for machinery management and investment). It seems that the presence of some output in the acreage increases highly theses costs (Koutchade et al., 2015). Specialization tend however to increase pesticide utilization (Lansink and Stefanou, 2001). This reflect the need for a minimum of biodiversity which can be a substitute for crop health management. Our findings confirm the productive importance of biodiversity but do not provide information on biodiversity costs. Our future researches will examine this dimension.

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 $B_{1t}$ and $B'_{1t}$ 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.

### 7.4.2. Permanent grassland biodiversity

To our knowledge, this is the first time that permanent grassland biodiversity productive effects has been investigated on both crop and milk productions. Surprisingly, 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[30]. 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). This suggests that permanent grasslands could be profitable for crop productions even if permanent grassland shares are still very low on these regions. We think that the public good characteristics of the biodiversity productive functionalities incite farmers to behave as free-riders. Indeed, if permanent grassland biodiversity increase 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 the natural input provision. (Klemick, 2011) has notably underlined that forest fallow productive effects are more important for upstream fallows rather than on-farm fallows. Future researches should investigate these effects on the case of permanent grasslands. Moreover, early land consolidation policies on these regions have tend to eliminate permanent landscape elements. Recent increases on grassland shares 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.

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[30] 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 are stressed to explain their positive productive effects on crop production.

Our results are however less surprising on the case of milk production. If our last estimation indicates that there is no impact of permanent grassland on milk production, all other estimations suggest 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. As previously underline, our study does not examine intensively the cost structure. We can thus do not 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.

To conclude on the effect of biodiversity on farmers' production process, future research should analyze deeply the cost of using natural inputs. Indeed, whereas most authors considered these functionalities as free[31], the management of the ecosystem inputs 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 variable ones or capital. The possible negative effects of these practices on the productivity of other inputs lead to opportunity costs. Future estimations on the quadratic production functions may give new insights on the substitutability/complementarity relationship between natural inputs and conventional ones and thus give indications on the levels of the opportunity costs.

## 8. Conclusion

Previous studies focusing on the crop diversity management have found that crop diversity reduces market risk and production risk but increase 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

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

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 natural inputs. Applying Three Stage Least Square 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.

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 robust. The different results obtained through several model specification and econometric method estimation tend to underline the thin productive effect of arable land biodiversity and a negative productive effect for permanent grassland biodiversity. 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. As we observe a progressive decline of permanent grasslands in Europe, this suggest though that these areas are not profitable for crop specialized farmers. However, recent increases of grassland areas on French specialized regions may indicate that some farmers have tried to overcome this issue of limiting physical factor. In other words, some farmers have tried to increase environmental quality in order to increase crop production. However, the public good characteristics of the biodiversity productive effects incite specialized crop farmers to behave as free riders which could limit this augmentation. We could imagine that policies should help more farmers on these regions to face the costs of landscape reorganization.

Future econometric estimations will benefit from additional data on topological and meteorological conditions. We will also try new method for organic fertilization management in order to overcome potential endogenous biases. New estimation will also be conducted with new biodiversity indicator computations. Estimation of quadratic production function parameters will also continue, with especially the instrumentation of variable input squared terms.  In order to improve the robustness of milk production estimation, we will also try to estimate a dual production function.

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 (scale and scope economies) of biodiversity productive effect management in order to fully understand the effect of biodiversity on farmers' optimization process. Indeed, the analysis of productive effects provides useful information but not taking into account the complexity of the management and the impact of natural input management on other practices is a major lack in the "ecosystem services" literature.

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# Annexes

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

| | OLS | | SUR with parameter constraints | | 3SLS without parameter constraints | |
|---|---|---|---|---|---|---|
| | y_crops | y_milk | y_crops | y_milk | y_crops | y_milk |
| **Const** | 0,297 *** | 16,63 *** | 0,302 *** | 24,49 *** | -0,27 *** | 190,9 *** |
| | (0,018) | (3,96) | (0,018) | (4,48) | (0,05) | (49,3) |
| **Biodiversity** | | | | | | |
| Degrated Arable Biodiversity index | 0,03 | -27,19 * | 0,038 * | -50,93 *** | -0,071 | 131,02 |
| | (0,017) | (9,52) | (0,017) | (10,65) | (0,047) | (109,61) |
| (Degrated Arable Biodiversity index)² | | 13,06 * | | 24,97 *** | | -52,02 |
| | | (5,47) | | (6,08) | | (63,93) |
| Arable Biodiversity index | 0,114 *** | 1,261 | 0,112 *** | 0,022 | 0,073 ** | 114,54 * |
| | (0,007) | (3,724) | (0,007) | (3,701) | (0,033) | (47,56) |
| (Arable Biodiversity index)² | | 8,19 *** | | 8,67 *** | | 11,53 |
| | | (1,41) | | (1,4) | | (20,95) |
| Grassland Biodiversity index | 0,083 *** | -16,47 *** | 0,08 *** | -16,96 *** | 0,183 *** | -93,79 *** |
| | (0,013) | (1,14) | (0,012) | (1,15) | (0,037) | (23,28) |
| **Variable inputs** | | | | | | |
| Fertilizer | 1,447 *** | -102,46 *** | 0,27 | 23,8 | 0,32 | 5256 *** |
| | (0,261) | (23,65) | (0,19) | (16,94) | ( 2,13) | (1308) |
| Pesticides | 7,572 *** | 897,66 *** | 8,86 *** | 769,1 | 6,97 | -12574 *** |
| | (0,59) | (55,76) | (0,56) | (52,427) | (4,30) | (2434) |
| Seeds | -0,723 | -106,16 * | -1,03 * | -90,18 ** | 18,01 ** | -11131 * |
| | (0,493) | (44,97) | (0,37) | (32,16) | (6,61) | (5223) |
| Fuel | 3,051 *** | 57,8 | 1,49 *** | 129,71 ** | 102,99 *** | -55171 *** |
| | (0,757) | (68,96) | (0,57) | (50,14) | (14,32) | (9418) |
| Cow feed | | 328,71 *** | | 325,85 *** | | 2970 *** |
| | | (7,42) | | (7,218) | | (303,9) |
| Health and reproduction | | 322,8 *** | | 299,95 *** | | 129,3 |
| | | (31,92) | | (31,68) | | (464,6) |
| **Organic Fertilizer proxies** | | | | | | |
| Cattle livestock unit/total area | 0,037 *** | -8,37 *** | 0,038 *** | -9,08 *** | 0,046 * | -0,36 |
| | (0,0043) | (0,4) | (0,004) | (0,4) | (0,018) | (11,4) |
| Other livestock unit/total area | 0,0023 *** | 0,03 | 0,0016 * | -0,036 | -0,003 | 4,81 ** |
| | (0,0006) | (0,056) | (0,0006) | (0,056) | (0,003) | (1,56) |
| Milk quota/total area | 1,164 *** | | 0,91 *** | | 2,37 *** | |
| | (0,141) | | (0,141) | | (0,51) | |
| **Control variables** | | | | | | |
| Total area | 3,04E-7 | -0,001 *** | 1,23E-6 * | -0,0006 *** | -3,2E-8 | -4,61E-05 |
| | (6,193E-7) | (0,00006) | (5,08E-7) | (0,00004) | (1,64E-6) | (9,9E-5) |
| Capital/total area | 0,0006 *** | 0,13 *** | 0,0006 *** | 0,13 *** | -0,0018 ** | 1,52 *** |
| | (0,0001) | (0,011) | (0,0001) | (0,012) | (0,0006) | (0,3) |
| Labor (annual worker unit) | -0,0007 | 0,139 * | -0,0007 | 0,148 ** | -0,003 | 1,1 |
| | (0,0006) | (0,055) | (0,0006) | (0,054) | (0,002) | (1,01) |
| Labor (declared total working time) | 0,00004 | -0,008 * | 0,00004 | -0,008 * | 0,0002 | -0,06 |
| | (0,00004) | (0,003) | (0,00004) | (0,003) | (0,0001) | (0,06) |
| Cow/total area | | 587,58 *** | | 590,38 *** | | -1208 *** |
| | | (9,49) | | (9,54) | | (162,4) |
| Restrictions | | | | | | |
| Restriction 1 | | | -452,37 *** | | | |
| Restriction 2 | | | 146,4 | | | |
| Restriction 3 | | | 362,34 ** | | | |
| Number of observation | 5596 | 5654 | 5596 | 5596 | 2479 | 2479 |
| R² | 0,21 | 0,8019 | 0,2091 | 0,8046 | | |

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

Table A2: variable input instrumentation in the 3SLS model with parameter constrains

| | **fertlizer / total area** | **seeds / total area** | **fuel / total area** | **cow feed / forage area** |
|---|---|---|---|---|
| **Const** | 0,02 *** | -0,008 ** | 0,006 *** | 0,02 **** |
| | (0,001) | (0,002) | (0,0002) | (0,004) |
| **Market price ratio** | | | | |
| fertilizer price (t) / crop price (t-1) | 0,005 ** | | | |
| | (0,001) | | | |
| fertilizer price (t) / milk price (t-1) | 0,019 * | | | |
| | (0,008) | | | |
| seed price (t) / crop price (t-1) | | 0,0001 | | |
| | | (0,0001) | | |
| seed price (t) / milk price (t-1) | | (0,002) | | |
| | | (0,004) | | |
| fuel price (t) / crop price (t-1) | | | -0,0001 | |
| | | | (0,0002) | |
| fuel price (t) / milk price (t-1) | | | 0,002 *** | |
| | | | (0,0005) | |
| cow feed price (t) / milk price (t) | | | | -0,016 |
| | | | | (0,009) |
| fertilizer price (t) / pesticide price (t) | 0,018 ** | | | |
| | (0,006) | | | |
| fertilizer price (t) / seed price (t) | -0,015 * | | | |
| | (0,006) | | | |
| fertilizer price (t) / fuel price (t) | 0,003 * | | | |
| | (0,0015) | | | |
| seed price (t) / pesticide price (t) | | -0,014 *** | | |
| | | (0,003) | | |
| seed price (t) / fuel price (t) | | 0,001 | | |
| | | (0,0006) | | |
| cow feed price (t) / fertilizer price (t) | | | | 0,004 |
| | | | | (0,002) |
| **Exogenous variables in y_crops and y_milk** | | | | |
| Arable Biodiversity index | 0,004 *** | 0,004 *** | | |
| | (0,0004) | (0,0002) | | |
| Grassland Biodiversity index | | -0,004 *** | | |
| | | (0,0005) | | |
| Cattle livestock unit/total area | | 0,001 *** | | |
| | | (0,0002) | | |
| Cattle livestock unit | | -1,72E-07 *** | | |
| | | (1,46E-08) | | |
| Other livestock unit/total area | -0,0006 *** | -0,00001 | | |
| | (0,00006) | (0,00004) | | |
| Labor (annual worker unit) | | 5,86E-06 *** | 0,00004 *** | |
| | | (7,85E-7) | (0,0001) | |
| Labor (declared total working time) | | | -2,26E-06 ** | |
| | | | (7,08E-07) | |
| Capital | | | 1,09E-09 *** | |
| | | | (1,85E-10) | |
| Cow/forage area | | | | 0,311 *** |
| | | | | (0,013) |
| Number of observation | 2479 | | | |
| R² | 57,08 | 64,77 | 65,1 | 51,59 |

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

Table A3: 3SLS estimations of the quadratic yield equations

| | y_crops | y_milk | | y_crops | y_milk |
|---|---|---|---|---|---|
| **Const** | 0,28 *** | -1,21 | | | |
| | (0,078) | (7,21) | | | |
| **Biodiversity** | | | **Organic Fertilizer proxies** | | |
| Degrated Arable Biodiversity index | -0,09 | 15,12 | Cattle livestock unit/total area | 0,059 *** | -24,01 *** |
| | (0,17) | (15,91) | | (0,016) | (1,59) |
| (Degrated Arable Biodiversity index)² | 0,03 | -6,9 | (Cattle livestock unit/total area) ² | -0,008 * | 3,9 *** |
| | (0,10) | (8,9) | | (0,003) | (0,33) |
| Arable Biodiversity index | 0,24 *** | -1,4 | Other livestock unit/total area | 0,005 * | -0,09 |
| | (0,06) | (5,4) | | (0,002) | (0,18) |
| (Arable Biodiversity index)² | -0,05 * | 7,11 *** | (Other livestock unit/total area) ² | -0,0002 * | 0,00002 |
| | (0,02) | (2,04) | | (0,0001) | (0,008) |
| Grassland Biodiversity index | 0,13 ** | -27,4 *** | Milk quota/total area | -0,34 | |
| | (0,04) | (4,1) | | (0,69) | |
| Grassland Biodiversity index ² | -0,11 | 24,7 *** | (Milk quota/total area) ² | 13,49 * | |
| | (0,08) | (7,3) | | (6,85) | |
| **Variable inputs** | | | **Control variables** | | |
| Fertilizer / total area | 1,21 | 203 | Total area | -2,29E-08 | -0,001 *** |
| | (1,18) | (106) | | (2,29E-6) | (0,0001) |
| (Fertilizer/total area) ² | -30,9 | -9494 ** | Total area ² | -4,98E-11 | |
| | (33,54) | (2995) | | (6,67E-11) | |
| Pesticides/ total area | 12,36 *** | 488 * | Capital/total area | 8,73E-08 ** | 6,90E-06 ** |
| | (2,23) | (200,8) | | (2,87E-8) | (2,5E-06) |
| (Pesticides/ total area) ² | -311,4 ** | 16775 | (Capital/total area) ² | -2,84E-14 * | 4,50E-12 *** |
| | (102,7) | (9186) | | (1,29E-14) | (1,1E-12) |
| Seeds/ total area | 1,8 | -204 | Labor (annual worker unit) | -0,0006 | 0,07 |
| | (1,42) | (127) | | (0,0008) | (0,08) |
| (Seeds/ total area) ² | -45,8 | -6111 | Labor (declared total working time) | 0,00004 | -0,003 |
| | (39,6) | (3527) | | (0,0008) | (0,004) |
| Fuel/ total area | 11,3 ** | 783 * | Cow/total area | | 571,4 *** |
| | (3,63) | (325) | | | (59,8) |
| (Fuel/ total area) ² | -496 * | -33630 | (Cow/total area) ² | | -181,7 |
| | (228) | (20415) | | | (396) |
| Cow feed/ main forage area | | 682,9 *** | | | |
| | | (23,5) | | | |
| (Cow feed/main forage area) ² | | -1120,5 *** | | | |
| | | (131) | | | |
| Health and reproduction /main forage area | | 434,5 *** | | | |
| | | (77,3) | | | |
| (Health and reproduction/main forage area) ² | | -2672 | | | |
| | | (1646) | | | |
| Number of observation | 2479 | | | | |

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