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How do farmers manage crop biodiversity?

A dynamic acreage model with productive feedback

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Abstract:

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

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1 Introduction

It is widely recognized that human activities, especially modern agriculture, have negative impacts on biodiversity (MEA, 2005). The simplification of habitats from natural areas to arable lands (and monoculture) has decreased biodiversity levels. Because biodiversity greatly contributes to the functioning of the ecosystem, this loss threatens the provision of valuable ecological functionalities. Biodiversity is a crucial issue not only for our society but also for the sustainability of agriculture. Indeed, these functionalities support the provision of ecosystem services that provide suitable agricultural production conditions (MEA, 2005). Few authors have emphasized the productive value of biodiversity for crop farms (see Di Falco, 2012 for a review). These authors have usually estimated the effects of crop biodiversity using primal production functions or reduced form profit functions. Because measures of species density on point maps are often unavailable in databases, biodiversity is generally approximated by indicators based on land use, such as the Shannon index to measure crop diversity (e.g., Donfouet et al., 2017). In this paper, like most agricultural economists, we focus on crop diversity to approximate the level of biodiversity at the farm level. [1] This approach is highly influenced by landscape ecology, which postulates that landscape structure, defined by both its composition and configuration, determines species dynamics and, hence, species density (Burel and Baudry, 2003). In particular, crop diversity increases the likelihood of species diversity (Di Falco, 2012). It also improves several ecosystem services such as the nutrient stock, the soil structure (Mäder et al., 2002), pollination (Kennedy et al., 2013) and biological control (Letourneau et al., 2011). Of course, crop diversity is only an indirect indicator and does not reflect the complexity of the notion of biodiversity.

From our point of view, the economic literature on crop biodiversity emphasizes two main empirical results. First, crop diversity increases the mean yield and reduces the variance yield. This finding has led authors to consider both a productive value of biodiversity (Chavas, 2009) and an insurance value of biodiversity (Baumgärtner, 2007). Second, crop diversity of the previous year increases current production (Di Falco and Chavas, 2008). This result suggests that the productive effects of biodiversity persist over time.

Because biodiversity levels depend on land use, the current productive capacity of biodiversity depends on current and past acreage decisions. In this case, a dynamic model is necessary to represent production and acreage decisions. Here, we propose a dynamic acreage model

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[1] We use the terms “crop biodiversity” and “crop diversity” interchangeably.

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considering that farmers manage their biodiversity as capital. Similar to how firms make certain investment decisions to benefit from the productive capacity of capital, we assume that farmers make cropland decisions to benefit from the productive capacity of crop biodiversity. Thus, our objective is to confirm that farmers make cropland decisions with the aim of maintaining their current and future productive capacities. Therefore, we compile literatures on the productivity of crop diversity and acreage choices (e.g., Chambers and Just, 1989). Compared to other studies on biodiversity productivity, we extend this analysis to land allocation and variable input applications. These choices partly explain farmers' behaviours regarding the productive capacity of biodiversity. This concept may be relevant, especially for impact analyses of the economic incentives associated with biodiversity management and for evaluations of agro-environmental measures designed to maintain and promote biodiversity. We consider only the mean effect of biodiversity on the yield and input use, but the literature indicates that biodiversity reduces also the probability of a low yield (Di Falco and Chavas, 2009). It is theoretically possible to consider risk aversion and the impact of biodiversity on production variability in our model. Nevertheless, in practice, this inclusion would complicate the model notably with regard to the number of parameters to be estimated. We focus on the estimation of dynamic effects, which is already a more complicated approach than the standard multicrop model of crop allocation.

To our knowledge, few papers have considered the dynamics of acreage allocation within a dynamic theoretical farm-level model. One exception is the work of Orazem and Miranowski (1994), who built a dynamic model of acreage allocation. They assumed that farmers' acreage allocation decisions are conditional on their current stock of soil capital, which depends on past acreage allocations. Orazem and Miranowski considered that some crops increase future soil quality and thus have positive productivity effects. The main idea of their paper is similar to that of ours. Nevertheless, there are several key differences. First, their soil indicator is defined by crops, while our biodiversity indicator is implemented at the farm level. Their assumption technically suggests that the soil indicator of a crop depends on the past acreage of all crops and on only the current acreage of the considered crop. Orazem and Miranowski used this assumption to represent crop rotation effects. Our biodiversity indicator depends on the current and past acreages of all crops. Our specification expresses that crop yields depend not only on past crop diversity but also on current crop diversity, which agrees with Di Falco and Chavas (2008). This dependence complicates the derivation of acreage equations but better represents farmers' behaviour. Second, Orazem and Miranowski (1994) did not consider the potential

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effects of soil quality on input use, such as fertilizer application. This issue requires the imposition of identifying restrictions and leads to a less efficient estimation of parameters associated with the productive effects of soil quality. Here, we propose to estimate together acreage, input application and output supply equations.

Another interesting paper is that of Thomas (2003), who presented a dynamic model of nitrogen management at the farm level considering root crops and fertilizer as the two sources of nitrogen. He measured farmers' fertilizer application decisions considering that farmers account for nitrogen accumulation, i.e., the nitrogen stock available for the next period as a result of current production decisions. Similar to Orazem and Miranowski (1994), Thomas (2003) provided a framework to explain crop rotation decisions with a temporal lag in acreage decisions. Although his dynamic optimization programme is quite similar to ours, his theoretical model differs in three main respects. First, he focused on the effect of the nitrogen stock on fertilizer decisions and did not consider the other productive effects of crop rotations, such as biological control. Second, his state variable, the carry-over nitrogen, is a function of past nitrogen levels in plots and does not depend on current acreage decisions. Third, he assumed that farmers can instantaneously adjust their land allocation, while Oude Lansink and Stefanou (2001) found that area adjustments are quite slow.

Indeed, Oude Lansink and Stefanou (2001) proposed a dynamic model of acreage allocation to derive dynamic measures of scope and scale economies. Contrary to Orazem and Miranowski (1994) and Thomas (2003), they estimated reduced-form equations rather than a structural model. The originality of their acreage model is associated with the use of adjustment costs. They consider that output-specific areas evolve over time and that these area adjustments are costly. These costs are associated with the underutilization of fixed inputs or the reorganization of the farm operation. Adjustment costs have already been used in investment and employment literature. The adjustment cost function captures the fact that the productivity effects of quasi-fixed inputs are not instantaneous because producers incur additional costs in adjusting their stocks of capital and labour. Carpentier and Letort (2012, 2014) and Kaminski et al. (2013) used a similar cost function within a static multioutput acreage allocation model. In these cases, these costs were interpreted as the implicit costs linked to the management of both crop rotation constraints and quasi-fixed input constraints.

Our work is also based on the concept of adjustment costs for land allocation, but our modelling is different in one important way. In Oude Lansink and Stefanou (2001), the long-term productive effects of crop diversity are captured by a cost function. Their dual approach does not allow them to differentiate these productive effects from the adjustment costs associated with adjusting areas. Similarly, the utilization of an implicit cost function in the static acreage literature does not allow for the examination of the beneficial effects of crop diversification because it captures both the costs of fixed input management for a multioutput firm and the "negative costs" (i.e., the benefits) of crop diversity linked to the productive capacity of crop biodiversity. Our framework allows for the disassociation of the benefits and costs of crop diversification. Another interesting feature of our model is that we use an explicit representation of production technology. The explicit representation of the technology is useful for testing various adjustment cost functions within a dynamic investment model (e.g., Gardebroek 2004) and for studying environmental problems within a static land allocation model (e.g., Femenia and Letort, 2016). In our model, the specification of production technology allows us to explicitly analyse the impacts of the productive capacity of crop biodiversity on output yields and variable input savings.

The next section presents the theoretical model and a discussion of the economic interpretation. In the third section, we propose an empirical counterpart to this theoretical framework. Output supply and input demand equations, as well as first-order conditions regarding acreage choices, are estimated for a sample of French farms between 2007 and 2012. The fourth section presents the results, and the final section concludes the paper.

2 The dynamic model of acreage decisions

In this paper, we consider the productive capacity of crop biodiversity as a quasi-fixed input. Inspired by the investment literature, we develop a model that combines a multioutput farm model with a specific representation of the production technology and the specific dynamics of quasi-fixed inputs. This multi-output farm model is presented in the first part of this section. The dynamic framework is described in the second part.

2.1.The multioutput model of acreage decisions

Our modelling framework relies on models that are derived from a profit maximization problem with land as an allocable fixed input. These models are well-known in the agricultural economics literature (see, e.g., Chambers and Just 1989, Moore and Negri 1992, Wu and Segerson 1995, Oude Lansink and Peerlings 1996, Fezzi and Bateman 2011, Carpentier and Letort 2012). In our approach, price-taker farmers produce multiple outputs for which they choose the optimal quantity of variable inputs and the optimal allocation of land given the amount of fixed inputs applied based on price and production expectations.

The total restricted profit function Π_t of year t is defined as the sum of the gross margins per hectare π_{kt} of each output k ($k \in [1, K]$) multiplied by the acreage S_{kt} minus the acreage management costs defined by the function $H(\mathbf{S}_t)$:

$$\Pi_t\left(\mathbf{x}_t, B_t, \mathbf{S}_t; \mathbf{z}_t\right) = \sum_{k=1}^{K} S_{kt}\pi_{kt}\left(\mathbf{x}_{kt}, B_t; \mathbf{z}_t\right) - H\left(\mathbf{S}_t\right) \tag{1}$$

The function $H(\mathbf{S}_t)$ is assumed to be convex in $\mathbf{S}_t$. The gross margin per hectare π_{kt} of output k depends on the vector of variable input quantities $\mathbf{x}_{kt}$, the biodiversity indicator B_t and the vector of fixed input quantities $\mathbf{z}_t$. We consider that the gross margins for each output k do not depend explicitly on $\mathbf{S}_t$ (i.e. present constant return to acreage), but do depend indirectly on $\mathbf{S}_t$ thanks to B_t (see the discussion on the model assumptions below and section 3.1. on the construction of the biodiversity indicator). In a static framework, farmers choose their acreage according to the following optimization problem:

$$\max_{\mathbf{S}_t} \Pi_t\left(\mathbf{x}_t, B_t, \mathbf{S}_t; \mathbf{z}_t\right) \text{ s.t. } \sum_{k=1}^{K} S_{kt} = L_t \tag{2}$$

where L_t is the total land quantity for crops $k = 1, ..., K$. The gross margin π_{kt} is derived from the following optimization problem:

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

where y_{kt} is the yield of the output k per hectare at time t and x_{ikt} ($i \in [1, I]$) is the quantity of variable input i applied to output k per unit of land at time t. $F_{kt}\left(\mathbf{x}_{kt}, B_t; \mathbf{z}_t\right)$ is the production function, which is non-decreasing in $\mathbf{x}_{kt}$ and strictly concave in $\mathbf{x}_{kt}$.

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Our modelling framework differs from that of other models that treat land as an allocable fixed input based on three main points. These specific features are partly shared with the model proposed by Carpentier and Letort (2012, 2014). First, it relies on an explicit representation of crop production technology. Standard dual models are almost exclusively used to model farmers' behaviours regarding the explicit allocation of fixed factors. However, they are based on reduced-form functions and implicit production technology, which are not always well suited for analyses of environmental problems, such as the impact of input reduction policies (Femenia and Letort, 2016). In our model, the specification of production technology allows us to analyse the productive effects of crop biodiversity.

The second interesting feature is the utilization of the function $H(\mathbf{S}_t)$ in the total restricted profit function. This type of function has already been used in the investment and employment literature. The authors interpret this function as the adjustment costs linked to quasi-fixed input management and capture the non-instantaneous nature of the profitable effects of quasi-fixed inputs. Adjustment costs due to land allocation have previously been considered. For example, Oude Lansink and Stefanou (2001) found that although Dutch farmers have incentives for specialization, high adjustment costs prevent them from specializing. Carpentier and Letort (2012, 2014) and Kaminski et al. (2013) used a function similar to $H(\mathbf{S}_t)$ within a static multioutput acreage allocation model. They interpreted the function as the implicit costs linked to crop rotation management and quasi-fixed input constraints. Here, we use the same interpretation of the function. However, because we capture some crop rotation effects in the production functions, our cost function should mainly represent the farmers' fixed input constraints. An interesting consequence is that we capture the benefits of crop diversification on each of the gross margin π_{kt} and the costs of crop diversification (i.e., the management costs of quasi-fixed inputs) in the implicit cost function $H(\mathbf{S}_t)$. In addition, the adjustment cost model offers a methodological advantage: it provides a simple dynamic theoretical framework (which is presented in the next part).

Third, the modelling framework generally used by agricultural economists to represent farmers' acreage decisions considers one or two motives of crop diversification. The main motives of crop diversification are decreasing returns to scale (or more generally scale economies), risk spreading, crop rotation effects, and constraints associated with allocated quasi-fixed factors (other than land). Most multicrop econometric models that consider land as fixed but allocable focus on decreasing marginal returns to crop acreage (e.g., Chambers and Just 1989, Moore and

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Negri 1992) or on market risk spreading (e.g., Chavas and Holt 1990) as the motives for crop diversification. Crop rotation effects are more rarely considered in multicrop econometric models, likely due to the complexity of dynamic choice modelling (e.g., Orazem and Miranowski 1994, Thomas 2003). The constraints associated with allocated quasi-fixed factors are used as motives for crop diversification in some multicrop econometric models (e.g., Oude Lansink and Stefanou 2001, Carpentier and Letort 2012, 2014, Kaminski et al. 2013) and in some positive mathematical programming models (e.g., Howitt 1995). In our model, the motives of crop diversification are represented by the implicit cost function $H(\mathbf{S}_t)$, which approximates the constraints associated with the limiting quantities of quasi-fixed inputs, and the productivity effects of crop diversity captured in each of the gross margin π_{kt}. Consequently, our model relies on two main assumptions. The first one is farmers' risk neutrality. Although it appears restrictive, it is imposed in all multicrop model not considering risk issues.[2] The second is the assumption of constant returns to acreage as stated in the definition of the gross margins (3).[3] This assumption is used as a simplifying assumption in multicrop econometric models considering risk spreading or constraints associated with allocated quasi-fixed factors as motives for crop diversification.[4]

2.2.The dynamic framework

Although the productivity of crop biodiversity can be assessed within a static model, crop biodiversity levels will be misjudged because land-use dynamics are not considered. Indeed, acreage decisions affect biodiversity dynamics and, in turn, affects productive capacity of crop biodiversity in the future (Di Falco and Chavas, 2008). Therefore, we must consider that farmers maximize their acreage decisions taking into account that their acreage decisions influence current and future levels of the productive capacity of biodiversity. Accordingly, we assume that farmers maximize the expected value of future discounted profits over the entire period $[1;T]$:

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[2] The examination of farmers' risk-reducing strategies in the context of crop biodiversity management should be a promising area of research. Indeed, crop biodiversity reduces the probability of low yield realization as well as the magnitude of the yield shortfall under stress (e.g. Di Falco and Chavas, 2008). Here, we only consider the mean effects of crop biodiversity on yields and ignore the potential implications of crop biodiversity properties for risk-averse farmers.

[3] Note, however, that gross margins depend indirectly on acreage thanks to the biodiversity indicator.

[4] Nevertheless, our model can be easily adapted for non-constant returns to crop acreage and allow scale effects in a simple way; therefore, the parameters of the production functions can be defined as linear functions of crop acreage (Carpentier and Letort, 2010).

$$\max_{\mathbf{S}_t} E_t \left\{ \sum_{t=1}^{T} \left(\frac{1}{1+r} \right)^{t-1} \Pi_t(\mathbf{x}_t, B_t, \mathbf{S}_t; \mathbf{z}_t) \right\}$$

(4)

where *r* is the interest rate. The productive capacity of biodiversity evolves according to:

$$B_t = (1-\delta_t)B_{t-1} + g(\mathbf{S}_t)$$

(5)

and

$$\sum_{k=1}^{K} S_{kt} = L_t \, .$$

(6)

We propose a dynamic form for the biodiversity equation. The productive capacity of biodiversity in *t* depends on the current acreages in *t* and past acreages (years before *t*). The $g(\mathbf{S}_t)$ function is the biodiversity indicator that depends on $\mathbf{S}_t$. Farmers can manage this function each year. Based on the investment literature, $g(\mathbf{S}_t)$ can be considered as an investment in the productive capacity of biodiversity. The term $(1-\delta_t)B_{t-1}$ represents the inherited portion of the productive capacity of biodiversity from years before *t*. Farmers cannot manage this factor in *t* because it depends on past acreage decisions. This representation agrees with those in the literature. Indeed, previous studies have noted that the beneficial effects of crop biodiversity on production can last more than two years, even if these effects decrease over time (Hennessy 2006, Di Falco and Chavas 2008). Theoretically, this parameter depends on the natural conditions, notably climatic variations (e.g. Di Falco and Chavas, 2008) or soil and moisture conditions, as these factors may influence species dynamics. Nevertheless, for empirical purposes, we consider a single parameter δ in the following, meaning that we implicitly assume that δ_t is fixed over time.

Below, we examine the implications of the different values of the parameter δ, which is a key parameter in the estimation. When $\delta = 1$, the productive capacity of crop biodiversity depends only on current acreage decisions; past acreage decisions have no effect on current production. When $\delta = 0$, the productive capacity of crop biodiversity equally depends on past and current acreage decisions. When $\delta < 0$, the past productive capacity of biodiversity has a greater effect than current acreage decisions, meaning that the benefits of biodiversity are irreversible and can

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accumulate over time. Finally, when $\delta > 1$, the past productive capacity of biodiversity has a negative impact on the current capacity. These last two cases are difficult to justify from an ecological point of view. Thus, this parameter should range between 0 and 1. In this case, the productive capacity of biodiversity increases every year, but this increase becomes increasingly less important. After an acreage change damages biodiversity (monoculture is an example), the productive capacity of biodiversity decreases, but not instantaneously. Overall, a δ value between 0 and 1 suggests that the past productive effects of crop biodiversity still have positive impacts on production, but these effects decrease over time (Hennessy 2006, Di Falco and Chavas 2008). These potential cases are illustrated in Appendix A (available in the online supplementary data).

From a technical perspective, we propose another way of interpreting this equation. As biological protection and net primary production depend on the current acreage composition and configuration (Burel and Baudry, 2003), the productive effects of the current acreage can be interpreted as a spatial choice. In contrast, because crop rotation effects depend on the preceding crops (Hennessy, 2006), the productive effects of past acreage may be perceived as a temporal choice. Here, because equation (5) assumes that farmers manage their acreages to benefit from current and future productive effects at the same time, we consider acreage choices to be spatiotemporal choices. In this case, the δ parameter reflects the importance of the farmers' temporal acreage management versus the farmers' spatial acreage management.

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

$$V_t(B_t) = \max_{\mathbf{s}_t} E\left\{\Pi_t + \frac{1}{1+r}\left[V_{t+1}(B_{t+1})\right]\right\}. \tag{7}$$

Equation (7) illustrates the inter-temporal problem faced by farmers. Assuming an interior solution, the first-order conditions associated with the maximization of $V_t(B_t)$ according to x_{ikt} for $i \in [1; I]$ and $k \in [1; K]$ are defined by the following formula:

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$$p_{kt}\frac{\partial F_{kt}}{\partial x_{ikt}} - w_{it} = 0$$

(8)

Given optimal levels of B_t, farmers apply variable inputs such that the marginal cost of the last applied input unity equals its marginal benefit. The calculation of first-order conditions for acreage decisions are more complex. Farmers must optimize $\mathbf{S}_t$ according to $\mathbf{S}_{t-1}$ while anticipating the marginal effect of those choices on $V_{t+1}(B_{t+1})$. For a sake of simplification, we do not integrate the binding land constraint in this section but we present the derivation of the empirical model with the binding land constraint in Appendix B (available in the online supplementary data). Without the binding land constraint, the first-order conditions for acreage are defined by:

$$\frac{\partial V_t}{\partial S_{kt}} = \frac{\partial \Pi_t}{\partial S_{kt}} + \frac{1}{1+r} E\left[\frac{\partial V_{t+1}}{\partial B_{t+1}}\frac{\partial B_{t+1}}{\partial S_{kt}}\right] = 0$$

(9)

with $E\left[\frac{\partial V_{t+1}}{\partial B_{t+1}}\frac{\partial B_{t+1}}{\partial S_{kt}}\right] = \frac{\partial \Pi_{t+1}}{\partial B_{t+1}}\frac{\partial B_{t+1}}{\partial S_{kt}} + \frac{1}{(1+r)} E_t\left[\frac{\partial V_{t+2}}{\partial B_{t+2}}\frac{\partial B_{t+2}}{\partial B_{t+1}}\frac{\partial B_{t+1}}{\partial S_{kt}}\right]$

(10)

Noting that $\frac{\partial B_t}{\partial S_{kt-1}} = (1-\delta)\frac{\partial g(\mathbf{S}_{t-1})}{\partial S_{kt-1}} = (1-\delta)\frac{\partial B_t}{\partial S_{kt}}$, and following recursive reasoning, we have:

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

(11)

The first-order condition for acreage choice S_{kt} is then defined by:

$$\pi_{kt} + \sum_{j=1}^{K} S_{jt}\frac{\partial \pi_{jt}}{\partial B_t}\frac{\partial B_t}{\partial S_{kt}} - \frac{\partial H}{\partial S_{kt}} + \sum_{i=1}^{\infty}\frac{(1-\delta)^i}{(1+r)^i} E\left[\sum_{j=1}^{K} S_{jt+i}\frac{\partial \pi_{jt+i}}{\partial B_{t+i}}\frac{\partial B_{t+i}}{\partial S_{kt+i}}\right] = 0$$

(12)

To interpret equation (12), let us compare the first-order conditions of acreage in different models. In a static framework, as reported by Letort and Carpentier (2012, 2014), the conditions become:

$$\pi_{kt} = \frac{\partial H}{\partial S_{kt}} \tag{13}$$

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

In a static framework considering the productive effect of crop biodiversity, as defined by Di Falco and Perrings (2005) or Di Falco and Chavas (2006 and 2009), we have the following condition:

$$\pi_{kt} + \sum_{j=1}^{K} S_{jt} \frac{\partial \pi_{jt}}{\partial B_t} \frac{\partial B_t}{\partial S_{kt}} = \frac{\partial H}{\partial S_{kt}} \tag{14}$$

In this case, the marginal benefit of one additional unit of area devoted to crop *k* is defined as the gross margin of *k* plus the marginal profitability of the productive capacity of biodiversity on the other outputs linked to the reorganization of the total acreage. These effects include the productivity of crop biodiversity (i.e., $p_{kt}\, \partial F_{kt} / \partial B_t$) and the variable input savings due to the productive capacity of biodiversity (i.e., $w_{it}\, \partial x_{ikt} / \partial B_t$). These marginal benefits should be equal to the marginal cost of adjustment. Comparing our approach with the acreage literature (e.g., Carpentier and Letort, 2012), equation (14) illustrates the separation of the beneficial effects of crop diversity from the implicit cost function. Comparing our approach with the literature on the productive value of biodiversity, equation (14) also illustrates the importance of the effects of adjustment costs in explaining biodiversity levels at the farm scale.

In our dynamic framework, the conditions are defined by the following equation (considering an optimization problem with two periods):

$$\pi_{kt} + \sum_{j=1}^{K} S_{jt} \frac{\partial \pi_{jt}}{\partial B_t} \frac{\partial B_t}{\partial S_{kt}} + \frac{(1-\delta)}{(1+r)} E\left[\sum_{j=1}^{K} S_{jt+1} \frac{\partial \pi_{jt+1}}{\partial B_{t+1}} \frac{\partial B_{t+1}}{\partial S_{kt+1}} \right] = \frac{\partial H}{\partial S_{kt}} \tag{15}$$

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These conditions state that the marginal revenue per hectare of crop *k* at time *t* should be equal to the marginal adjustment cost due to marginal change in area *k*. The marginal revenue is defined by the gross margin of crop *k* plus the marginal profitability of the productive capacity of biodiversity for all crops plus the discounted expected marginal value of the crop biodiversity gain at time *t+1*. In other words, farmers consider the future productive effects of crop biodiversity when making their current acreage decisions. Considering the discounted expected marginal value of the crop biodiversity gain at time *t+1* as the future benefits of the current productive capacity of biodiversity, equation (15) can be interpreted as the equality between the adjustment costs due to the current acreage and the sum of the current and future benefits due to the current acreage. Equation (15) illustrates that price expectations affect the current acreage choices. The influence of price expectations is more important when the future impacts of the productive capacity of biodiversity are high, i.e., when δ is low. Our empirical model aims to estimate the magnitude of the effects of the productive capacity of biodiversity and to estimate the value of δ.

3 The empirical model

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

3.1.Data and variables

We use a dataset from a sample of farms located in the French territorial division of *La Meuse* observed between 2007 and 2012. The dataset comes from a local accounting agency and provides information on acreage, yields, and output prices. Contrary to most alternative French economic databases, it provides the variable input quantities applied per crop. Femenia and Letort (2016) used this database to estimate a static acreage model and simulate pesticide taxation policies. Because we consider the dynamics of the acreage choices, we select farms that have been identified for at least two consecutive years. We explain farmers' choices regarding the three main crops of the region, i.e., wheat (26% of the total acreage), winter barley (14% of the total acreage) and rapeseed (17% of the total acreage).[5] To avoid corner solutions

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[5] We assume that the other land uses are exogenous. The evolution of permanent grasslands, which represent 28% of the total acreage on average, relies on medium- to long-term strategies. The acreage of fodder crops relies on

in the model, we select farms with these three outputs, which yields a sample of 771 observations and represents more than 80% of the initial farm sample.

Similar to several cited studies, we measure crop diversity $g(\mathbf{S}_t)$ using the Shannon index,[6] i.e., an entropy measure based on land shares. This indicator corrects for species abundance and sample size and is well suited for measuring habitat diversity (Mainwaring, 2001). We compute $g(\mathbf{S}_t)$ as follows:

$$g(\mathbf{S}_t) = -\sum_{n=1}^{N} s_{nt} \ln(s_{nt}) \qquad (16)$$

where s_{nt} is the share of the land areas devoted to crops n ($n \epsilon [1, N]$). The n indexes refers to the endogenous crops (wheat, winter barley and rapeseed) plus all other land uses considered exogenous in the model (spring barley, peas, sunflower, forage maize, sugar beets, potatoes, permanent grasslands and other crops used as biofuels). The share s_{nt} is defined as S_{nt}/TL_t, with S_{nt} being the land devoted to output n and TL_t being the total agricultural area of the farm at time t. TL_t is the sum of L_t plus all the areas devoted to other exogenous land uses. We consider TL_t as fixed and exogenous. $g(\mathbf{S}_t)$ increases when habitat diversity increases, which reflects the augmentation of crop biodiversity (Burel and Baudry, 2003).

Table 1 presents the descriptive statistics of the variables used in the empirical analysis. We have deflated prices based on the national consumption price index. In addition, we use regional input price indexes from the French Department of Agriculture and monthly climatic variables at the municipality level obtained from the *Météo France* database.[7] To account for soil heterogeneity, we use a soil condition index at the municipal level obtained from the *Chambre d'Agriculture de Lorraine* (Hance, 2007).

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livestock production decisions and is thus based on different decision-making criteria. Some crops such as sugar beets and potatoes can easily be considered exogenous because they are produced under quotas or contracts.

[6] We also calculate the Simpson Index, as defined by $g(\mathbf{S}_t) = \sum_{n=1}^{N} \left(s_{nt}^2 - (1/N)\right) / \left(1-(1/N)\right)$. This index increases when crop diversity decreases. The estimation results are consistent with those obtained with the Shannon index, but the estimated parameters are overall less statistically significant. The results are available from the authors upon request.

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

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[Table 1 about here]

3.2.Empirical model and econometric strategies

We explain supply, input application and acreage choices for three outputs: soft wheat, winter barley and rapeseed. We consider two variable inputs: fertilizers and pesticides. The specification of our model requires assumptions about functional forms for the production functions and the adjustment cost function. We use the same forms as those employed by Carpentier and Letort (2012) and Femenia and Letort (2016). For each output *k*, we use a quadratic production function:

$$F_{kt}(\mathbf{x}_t, B_t; \mathbf{z}_t) = \alpha_{kt}(B_t; \mathbf{z}_t) - \sum_{i=1}^{I}\sum_{j=1}^{I} \gamma_{ijk} \left(\mu_{ikt}(B_t; \mathbf{z}_t) - x_{ikt}\right)\left(\mu_{jkt}(B_t; \mathbf{z}_t) - x_{jkt}\right) \tag{17}$$

The advantage of this functional form is the simple interpretation of its parameters. Parameter α_k represents the maximum yield of output *k*, and the vector of parameters $\boldsymbol{\mu}_{kt} = (\mu_{1kt}, \mu_{2kt})$ corresponds to the required level of fertilizers and pesticides to reach the maximum yield of crop *k*. These parameters are defined as functions of the productive capacity of biodiversity B_t and some pedo-climatic characteristics $\mathbf{z}_t$ such that:[8]

$$\alpha_{kt}(B_t; \mathbf{z}_t) = \alpha_{0k} + \alpha_{1k} B_t + \boldsymbol{\alpha}_{2k}\mathbf{z}_t \tag{18}$$

$$\boldsymbol{\mu}_{kt}(B_t; \mathbf{z}_t) = \boldsymbol{\mu}_{0k} + \boldsymbol{\mu}_{1k} B_t + \boldsymbol{\mu}_{2k}\mathbf{z}_t \tag{19}$$

where the parameter α_{1k} is the productivity of crop biodiversity on output *k*, and the parameter $\boldsymbol{\mu}_{1k}$ is the vector of the input savings on output *k* due to crop biodiversity. All these parameters are estimated. In particular, crop biodiversity affects production in several ways, namely, sampling, complementarity and facilitation effects (Hooper et al., 2005). The sampling effect implies that the likelihood of the presence of species with a large impact on ecosystem performance increases with crop biodiversity. The complementarity effect refers to the more efficient allocation of resources over time between species that need resources in different periods. The facilitation effect refers to the positive interactions among species that benefit from them. The complementarity and facilitation effects lead to the so-called overyielding effect, i.e., the additional yield of a species when grown with other species compared to its yield in a

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[8] $\mathbf{z}_t$ could also depend on other variables, such as capital and labor (which are not included here).

monoculture. These effects can also lead to marketed input savings if the associated ecological processes are substitute with chemical inputs (Hennessy, 2006). The matrix $\mathbf{\Gamma}_k \equiv [\gamma_{ijk}]$ determines the curvature of the function. A positive definite matrix guarantees the concavity of the production function.

The adjustment cost function is approximated using the following quadratic form:

$$H\left(\mathbf{S}_t\right) = \varphi + \sum_{k=1}^{K} \varphi_{0k} S_{kt} + 0.5 \sum_{k=1}^{K} \sum_{m=1}^{K} \varphi_{km} S_{kt} S_{mt} \qquad (20)$$

where φ, φ_{0k} and φ_{km} are parameters to be estimated. The parameter φ_{0k} depends on the farm characteristics, such as capital, machinery and labour endowment, and the matrix $\mathbf{J}_k \equiv \left[\varphi_{km}\right]$ is symmetric. The adjustment cost function corresponds to the cost associated with the reorganization of the farms' fixed inputs.

Following Lucas' critique and similar to Gardebroek (2004), we assume rational price expectations for input and output prices in $t+1$,[9] i.e., that farmers know the underlying formation price mechanisms. The assumption of rational expectations allows for the replacement of the unobserved expected prices in t+1 with their realized counterparts and the addition of an expectation error term $\boldsymbol{\varepsilon}_{t+1}$. We thus write $E(\mathbf{p}_{t+1}) = \mathbf{p}_{t+1} + \boldsymbol{\varepsilon}_{t+1}$ and $E\left(\mathbf{w}_{t+1}\right) = \mathbf{w}_{t+1} + \boldsymbol{\upsilon}_{t+1}$ and assume that $E(\boldsymbol{\varepsilon}_{t+1}) = 0$ and $E\left(\boldsymbol{\upsilon}_{t+1}\right) = 0$. We also assume that $\boldsymbol{\varepsilon}_{t+1}$ and $\boldsymbol{\upsilon}_{t+1}$ are uncorrelated with any information in *t*. The properties of the error terms suggest that farmers anticipate the realized prices in each period on average.

Solving the farmer's optimization problem leads to $\left(K \times I\right)$ input demand and K output supply equations in matrix notation as follows:

$$\mathbf{x}_{kt} = \boldsymbol{\mu}_{0k} + \boldsymbol{\mu}_{1k} B_t + \boldsymbol{\mu}_{2k} \mathbf{z}_t - p_{kt}^{-1} \mathbf{\Gamma}_k^{-1} \mathbf{w}_t + v_{kt}^{x} \qquad (21)$$

$$y_k = \alpha_{0k} + \alpha_{1k} B_t + \boldsymbol{\alpha}_{2k} \mathbf{z}_t - p_{kt}^{-2}\, \mathbf{w}_t{}' \mathbf{\Gamma}_k^{-1} \mathbf{w}_t + v_{kt}^{y} \qquad (22)$$

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[9] Alternative forms of price expectation do not change the signs of the parameter but modify the amplitude of the effects.

Additionally, $\left(K-1\right)$ first-order conditions for acreage choices can be established assuming an interior solution. These first-order conditions include the binding land constraint (with K the reference crop) as follows (see appendix B for the details of the derivation):

$$\begin{aligned}
&\left(\pi_{kt}-\pi_{Kt}\right)-\left(\varphi_{0k}-\varphi_{0K}\right)-\left(\varphi_{kK}L_t-\varphi_{KK}L_t\right)-\sum_{m=1}^{K-1}S_{mt}\left(\varphi_{km}-\varphi_{kK}-\varphi_{Km}+\varphi_{KK}\right)\\
&-\left(\ln s_{kt}-\ln s_{Kt}\right)\left[\sum_{j=1}^{K-1}s_{jt}\left(p_{jt}\alpha_{1j}-p_{Kt}\alpha_{1K}-\mathbf{w}_t\boldsymbol{\mu}_{1j}+\mathbf{w}_t\boldsymbol{\mu}_{1K}\right)+l_t\left(p_{Kt}\alpha_{1K}-\mathbf{w}_t\boldsymbol{\mu}_{1K}\right)\right]\\
&-\frac{\left(1-\delta\right)}{\left(1+r\right)}\left(\ln s_{kt+1}-\ln s_{Kt+1}\right)\left[\begin{array}{c}\sum_{j=1}^{K-1}s_{jt+1}\left(p_{jt+1}\alpha_{1j}-p_{Kt+1}\alpha_{1K}-\mathbf{w}_{t+1}\boldsymbol{\mu}_{1j}+\mathbf{w}_{t+1}\boldsymbol{\mu}_{1K}\right)\\+l_{t+1}\left(p_{Kt+1}\alpha_{1K}-\mathbf{w}_{t+1}\boldsymbol{\mu}_{1K}\right)\end{array}\right]+\nu_{kt}^{s}=0
\end{aligned}$$

(23)

where ν_{kt}^{x}, ν_{kt}^{y} and ν_{kt}^{s} are random terms accounting for unobservable heterogeneity among farmers and stochastic events that can impact production. Based on Oude Lansink and Stefanou (2001), we fix r at 0.04. The economic model composed of equations (21), (22) and (23) fully explains farmers' short-term production decisions. For output k, the marginal costs (the derivation of the adjustment cost function) of area k equal its marginal benefits (the gross margin plus the current and future marginal benefits due to the modification of productive capacity of biodiversity). Production decision equations and Euler equations are typically estimated using the Generalized Method of Moments (GMM, see Hansen and Sargent, 1980). We thus estimate equations (21), (22) and (23) with the GMM using SAS software. Note that some parameters are common to several equations and that equation (23) integrates the binding land constraint (6). Rapeseed is chosen as the reference crop, and thus, first-order conditions for acreage are estimated for wheat and barley with respect to rapeseed. A consequence is that the parameters φ_{0k}, φ_{0K}, φ_{km}, φ_{KK}, φ_{kK} and φ_{Km} can not be identified separately.

Our model has the advantage of being structural, meaning that we explicitly explain all the production decisions. This feature allows us to address the standard endogeneity problem between production decisions and acreage choices, defining explicitly the structure of the underlying endogeneity.[10] The single issue regarding endogeneity concerns the crop diversity index calculated from acreage areas and present in the output and input equations. To address

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[10] Input uses and output productions are generally considered endogenous in acreage equations because of the unobserved heterogeneity of farms, which may affect both production decisions and acreage choices. In our model, all production decisions are explicitly explained, meaning that acreage allocations depend only on the deterministic part of the production process.

this problem, we proceed in two steps. In the first step, we regress the acreages of wheat, barley and rapeseed based on all exogenous explanatory variables. We recalculate the diversity index using the predicted acreages of these three crops, still considering the other crops to be exogenous. In the second step, we estimate the complete model with the GMM technique using the predicted diversity index as an instrument in the equations of the output supply and variable input demand. The other instrumental variables, as defined by the equation, correspond to the exogenous explanatory variables.

Our empirical model has two main potential limitations. First, we do not consider the possibility of corner solutions. All farms produce the three outputs considered in the application. In addition to the standard potential problem of selection bias, this assumption limits the results concerning crop biodiversity. Indeed, the diversity index varies according to the number of crops produced and the uniform repartition of crops over the total area. Given that the number of crops is fixed and cannot change over time, the variation in the biodiversity index is only due to a change in the allocation of land between crops. Second, the crop diversity index is not simultaneously estimated with the production and acreage decisions. We are not able to express the crop diversity index as a function of acreage predicted by the complete model because the model is composed of the first-order conditions for acreage and not the analytical solution of acreage choices.

4 Results and discussion

The estimation results are presented in Table 2. The R² criteria are rather low for the yield and input demand equations. This issue has been highlighted by Carpentier and Letort (2012) and reflects heterogeneity among farmers' production conditions. The term α_k corresponds to the potential yield value for crop *k*. The terms μ_{1k} and μ_{2k} represent the quantities of fertilizer (*i=1*) and pesticide (*i=2*) required to achieve the potential yield of crop *k*. A linear combination of control variables is introduced in these terms, and the parameters α_{0k}, μ_{01k} and μ_{02k} correspond to their average values. Due to space limitations, the estimated parameters of these control variables are reported in appendix C (available in the online supplementary data). The parameters α_{1k}, μ_{11k} and μ_{12k} are the parameters associated with the crop diversity indicator for additional yields, for fertilizer savings and pesticide savings of output *k*, respectively.

Almost all estimated parameters are significantly different from zero at the 0.05 level. The parameter estimates satisfy the restrictions imposed by the concavity of crop production

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functions (γ_{1k} and γ_{2k} are positive, and $\gamma_{1k}\gamma_{2k}-\gamma_{12k}^{2}>0$ for the three crops). Similar to Femenia and Letort (2016), we find that fertilizers and pesticides are substitute inputs (the γ_{12k} is negative for the three crops). The average potential yield value α_{k}, expressed in quintals per hectare, corresponds to the average value observed in the region. This value is 72.8 quintal per hectare for wheat,[11] 65.8 for winter barley and 34.5 for rapeseed (see Table 1). The estimated values of $\boldsymbol{\mu}_{k}$ reflect the fact that cropping rapeseed requires larger quantities of fertilizers and pesticides compared with barley and wheat. These results are consistent with agronomic considerations and other results obtained from French data (Carpentier and Letort 2012, Femenia and Letort 2016).

With respect to the effects of the productive capacity of biodiversity on the average potential yield and average required use of pesticides, our model provides useful insights. First, we find that crop diversity increases yields of wheat and winter barley ($\alpha_{1\mathrm{k}}>0$). We do not find any significant effect of the productive capacity of biodiversity on the rapeseed yield. To our knowledge, this is the first time that crop diversity has been found to increase winter barley yields. This finding confirms that crop diversity increases cereal yields. However, this finding also stresses the need to carefully interpret the results of empirical applications that determine aggregate crop yields based on crop diversity, as some crops are sensitive to crop diversity, whereas others not.

[Table 2 about here]

Second, we find that the productive capacity of biodiversity leads to pesticide savings ($\mu_{12k}<0$). Di Falco and Chavas (2006) found a beneficial effect of the productive capacity of biodiversity on pesticide application based on the estimation of the variance of cereal yields and concluded that the productive capacity of biodiversity reduces production risk. Here, we extend their results by confirming that the productive capacity of biodiversity is a substitute for pesticides. The impact of the productive capacity of biodiversity on fertilizer application is only significant for wheat (at the 10% statistical level). The estimation of our structural model suggests that farmers manage the productive capacity of biodiversity to increase average yields and reduce variable input applications. The productive capacity of biodiversity increases the

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[11] It corresponds to $\left(\alpha_{01}+\alpha_{11}\bar{B}\right)=\left(70.54+1.49\times 1.53\right)=72.8$.

gross margins of the three outputs, illustrating that farmers have incentives to diversify their acreage.

All the estimated parameters of the acreage equations are significantly different from 0 at the 5% statistical level. The parameter $(\varphi_{0k} - \varphi_{0K})$, which measures the difference in fixed costs between wheat and rapeseed, is positive. This means that wheat incurs more costs for fixed inputs than does rapeseed. We find a negative value for winter barley, meaning that winter barley incurs more costs for fixed inputs than does rapeseed. As the determinant of $\mathbf{J}_k \equiv [\varphi_{km}]$ is positive, the concavity of the profit function is verified. Concerning the parameter sets $(\varphi_{km} - \varphi_{kK} - \varphi_{Km} + \varphi_{KK})$, we estimate one per acreage equation (for $k = m$) plus one parameter set that is common between the two acreage equations (for $k \neq m$, see equation 23). If we do not include the impacts of crop biodiversity in the model,[12] the sign of the common estimated parameter set is opposite to the one presented in Table 2. In this case, the implicit cost function captures all effects associated with acreage management, i.e., the beneficial effect of crop diversity and the management costs of quasi-fixed inputs. In explicitly considering the productive effect of crop diversity, we have separated the benefits and the costs of diversification. Our results agree with those of Oude Lansink and Stefanou (2001) and Chavas and Di Falco (2012), who observed opposite strengths between diversification and specialization, albeit based on different motives. However, the interpretation of the estimated parameters from our adjustment cost function is subject to limitations because the estimated parameters capture the difference between the true parameters of wheat and barley and those of rapeseed.

Finally, these results provide information regarding the management of the productive effects of crop biodiversity. The parameter δ associated with the dynamic effect of the productive capacity of biodiversity is equal to 0.70 (significantly different from 0 at the 0.1% level). This result reflects two important points.

First, similar to Di Falco and Chavas (2008), the estimation of our model indicates that farmers manage their acreage to benefit from the productive effects of past acreage but that the effects of the productive capacity on crop diversity in past years are lower than those in the current year. We confirm that the inherited portion of the productive capacity of crop biodiversity is

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[12] We have estimated the model developed by Femenia and Letort (2016), which relies on implicit cost function but does not include the effects of biodiversity on margins (see equation (13)). The results obtained with this model are available from the authors upon request.

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low, i.e., that the productive capacity of crop biodiversity is primarily managed through current acreage decisions. This result may surprise agricultural economists. Indeed, the effects of the productive capacity of biodiversity are mainly considered dynamic due to crop rotation. A high value of δ does not mean that farmers do not use crop rotations. Indeed, we do not observe acreage spatial choices. Thus, we have to assume that farmers optimize their crop rotation between two periods. Because δ is less than one, the increase in acreage diversity in one period increases yields and variable input savings in future periods, which can be interpreted as more suitable possibilities for crop rotation.

Second, this result shows that the current levels of the productive capacity of biodiversity do not considerably influence farmers' choices over more than two periods. This result agrees with the research of Di Falco and Chavas (2008) and results of Hennessy (2006). Indeed, 30% of the effect of productive capacity of biodiversity on yields and input applications is from acreage choices in $t-1$, and only 9% is from acreage choices in $t-2$ (see Figures 1 and 2 in Appendix B for a graphic representation of the dynamic effect of biodiversity with δ being equal to 0.70).[13] Our results are robust to different levels of discount rates,[14] and different forms of price expectations.[15] Some precautions are required for interpretation, as the estimated parameter may capture some preference parameters due to price expectations that are not present in our risk-neutral agent model.

Four empirical limits may affect the estimation of δ. First, the crop diversity indicator does not substantially vary between the two periods and may bias and overvalue the estimation of δ. Second, only the acreage choices of three outputs are estimated. However, the sample is composed of heterogeneous farmers, and some of them present a high degree of specialization for wheat, while others demonstrate a high level of diversification. Accordingly, the existence of a corner solution limits the accuracy of our estimations and impacts the estimation of δ. Third, we estimate a single δ for the three crops, while Hennessy (2006) provided evidences that the dynamics of crop rotations are different between crops. Fourth, we have estimated a single δ for the entire period. Di Falco and Chavas (2008) emphasized that the current productive capacity of biodiversity and the rainfall over past year interact negatively interact in crop production, i.e., the dynamic effect of the productive capacity of biodiversity depends on

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[13] $B_t = 0.30\,B_{t-1} + g(\mathbf{S}_t)$, and $B_t = (1-0.70)^2\,B_{t-2} + (1-0.70)\,g(\mathbf{S}_{t-1}) + g(\mathbf{S}_t)$

[14] δ remains between 0.69 and 0.71.

[15] δ remains between 0.70 and 0.83.

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climatic conditions. Future estimations of our model could integrate these information when estimating δ_t.

Some lessons regarding public policies can be drawn from the model and the results presented here. For example, this paper demonstrates that public policies aiming to reduce a pollutant input through pesticide taxation have a double positive impact on the environment: (i) a direct impact that is associated with input reduction (Femenia and Letort, 2016) and (ii) an indirect impact associated with increased marginal productivity of crop biodiversity. In fact, according to the theoretical model and the results, we obtain $\frac{\partial y_{kt}}{\partial B_t \partial x_{ikt}} = \sum_{j=1}^{I} \gamma_{ijk} \frac{\partial \mu_{jk}}{\partial B_t} < 0$ for each input *i* and each crop *k*. An input reduction leads to an increase in the marginal productivity of crop biodiversity. After implementing the policy, farmers are then encouraged to diversify their crops since the effects of the productive capacity of crop biodiversity on crop margins are higher.

Conversely, public policies that encourage crop diversity as proposed in agro-environmental contracts may allow for a reduction in the utilization of variable inputs. Farmers who adopt some agro-environmental measures (AEMs) by integrating a wide diversity of crops into their rotational cropping receive some payments in compensation for revenue loss. If the total impact of biodiversity on production decisions is not considered, these payments are likely misevaluated, especially in the long term.

5 Conclusion

Our structural microeconomic model allows for the simultaneous estimation of supply, variable input demand and acreage functions. Inspired by multicrop microeconometric and investment literature, our approach considers (i) the productive effects of crop biodiversity, (ii) the dynamics of the productive capacity of crop biodiversity and (iii) the adjustment costs associated with fixed input management. We find that high levels of crop diversity lead to the augmentation of yields and to input savings. Compared to the research of Femenia and Letort (2016), the introduction of crop biodiversity effects inside gross margins allows the capture of only the acreage management costs inside the implicit cost function. The separation of the benefits and costs of diversification is supported by the results. To our knowledge, this is the first time that the costs and incomes associated with the productive capacity of biodiversity have been simultaneously considered. Previous studies have typically focused on a single dimension of the productive capacity of biodiversity or on a dual restricted profit function,

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neither of which allows for a full understanding of the economic and ecosystem mechanisms. Hence, the addition of the dynamic framework provides new insights into the intertemporal management of crop biodiversity. Our model allows for a generalization of the management models of the productive capacity of biodiversity that are proposed in the economic literature.

A potential limit of our framework is that it ignores the effects of crop biodiversity on variance yields. Indeed, the literature on crop diversity has stated that crop diversity reduces the probability of low yield realization and, thus, decreases production risk. Crop diversity also decreases market risk, as crop diversity can be considered as a portfolio strategy (Di Falco and Perrings, 2005). In addition to provide more flexibility for the analysis of crop biodiversity productivity, the consideration of the effects of crop biodiversity on variance yields has an impact on risk-averse farmers. Consequently, the presented results definitely underestimate the potential beneficial effects of crop biodiversity on farmers' profit. Additional gains can notably emerge from substitution between financial insurance and crop diversity. To our knowledge, if Baumgärtner (2007) has already theoretically dealt with this issue, no study has ever measured such substitution in an empirical study. Regarding the amount of subsided crop insurance in the world (not in France though), such measurement would be a great contribution to the literature and a valuable information for policymakers.

Because we rely on investment literature, our model offers substantial possibilities for extensions; e.g., we can introduce heterogeneous adjustment costs or threshold effects into the biodiversity dynamics. Future studies could also consider several dynamic parameters as well as the impacts of climatic conditions or the heterogeneity of dynamic effects on output yields and input savings. Our model can also provide new insights on the effectiveness of AEMs because it expresses the evolution of acreage diversity management based on market fluctuations. Furthermore, our results may benefit the design of suitable AEMs and could lead to a win-win situation in which both biodiversity and agricultural profitability increase. This need has already been stressed by Omer et al. (2007) in a study based on a stochastic production function with the introduction of a biodiversity indicator. However, an analysis based on a production function is not sufficient for evaluating the relevant incentives (Omer et al., 2007). We contend that our model can provide this type of information because it expresses farmers' responses to economic incentives and the associated effects in crop biodiversity management. We do not address this issue because the analysis of current AEM effectiveness requires the mobilization of special econometric methods to overcome the sample selection bias. However, the approach developed in this paper serves as a good basis for future work in this area.

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Supplementary data

Supplementary data are available at ERAE online.

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Appendices

Appendix A. Temporal evolution of the productive capacity of biodiversity B_t according to the potential values of δ.

As explained in the empirical section, we estimate the single parameter δ instead of several δ_t values. Thus, the dynamics equation of crop biodiversity is defined by $B_t = (1-\delta)B_{t-1} + g(\mathbf{S}_t)$.

We assume that $B_0 = 0$ and that farmers cultivate 3 crops (wheat, bailey and rapeseed). We compare two situations. First, the farmer equally allocates his land among these 3 crops (Figure 1). The $g(\mathbf{S}_t)$ term is maximal, illustrating the positive effects of crop diversity on the yield and variable input savings. Second, he equally allocates his land between these 3 crops from $t=1$ to 3 and decides to cultivate only one crop from $t=4$ to 6 (Figure 2). The $g(\mathbf{S}_t)$ term changes from its maximal value to its minimal value. In each case, we compare the evolution of the productive capacity of biodiversity B_t according to different values of the δ term. As presented in Table 2, the estimated value of the δ term is 0.83. The estimated evolution of B_t is represented by the solid line. The dotted lines correspond to the different potential values of δ (described on page 8).

[Figure 1 about here]

In Figure 1, we observe three different evolutions.[16] First, when $\delta = 1$, B_t remains constant because it only depends on $g(\mathbf{S}_t)$, which remains constant. Second, when $\delta \in]0,1[$, B_t increases, but this increase is less significant over time. Third, when $\delta \leq 0$, B_t increases with a constant or increasing slope.

[Figure 2 about here]

---

[16] We do not consider the case in which $\delta > 1$ because it leads to an uninterpretable evolution. For example, if $\delta = 2$, the productive capacity of biodiversity ranges between 0 and 1 from year to year, without any changes in acreage.

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Figure 2 presents the case in which a farmer simplifies his crop rotation by cultivating only one crop in year $t = 4$. From an ecological point of view, this decision has an adverse effect on biodiversity because of the reduction in habitat diversity. However, benefits of past practices may still influence the productive capacity of crop biodiversity B_t. Compared to these ecological considerations, some potential values of δ lead to the inadequate evolution of B_t. When $\delta \leq 0$, the benefits of past acreages never decrease and can further increase in spite of the monoculture. When $\delta = 1$, the benefits of past acreages are null, and B_t is thus null. The more realistic situations correspond to the cases in which $\delta \in \left]0,1\right[$. B_t decreases at a variable rate, depending on the value of δ. The acreage decisions of the past year have a longer lasting effect as δ approaches 0.

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Appendix B. First-order conditions for acreage choices with integration of land constraint

The Lagrangian function associated to our maximization problem is defined by:

$$L\left(\mathbf{S}_t,\lambda\right)=\sum_{t=1}^{T}\left(\frac{1}{1+r}\right)^{t-1}\Pi_t\left(\mathbf{x}_t,B_t,\mathbf{S}_t;\mathbf{z}_t\right)-\lambda\left(\sum_{k=1}^{K}S_{kt}-L_t\right) \tag{A.1}$$

with λ being the Lagrangian multiplier associated with the land constraint. Considering an optimization problem with two periods, it leads to the following first-order conditions for crop $k\ (k\neq K)$ and for the reference crop K:

$$\frac{\partial L}{\partial S_{kt}}=\pi_{kt}+\sum_{j=1}^{K}S_{jt}\frac{\partial\pi_{jt}}{\partial B_t}\frac{\partial B_t}{\partial S_{kt}}-\frac{\partial H}{\partial S_{kt}}+\frac{(1-\delta)}{(1+r)}E\left[\sum_{j=1}^{K}S_{jt+1}\frac{\partial\pi_{jt+1}}{\partial B_{t+1}}\frac{\partial B_{t+1}}{\partial S_{kt+1}}\right]=\lambda \tag{A.2}$$

$$\frac{\partial L}{\partial S_{Kt}}=\pi_{Kt}+\sum_{j=1}^{K}S_{jt}\frac{\partial\pi_{jt}}{\partial B_t}\frac{\partial B_t}{\partial S_{Kt}}-\frac{\partial H}{\partial S_{Kt}}+\frac{(1-\delta)}{(1+r)}E\left[\sum_{j=1}^{K}S_{jt+1}\frac{\partial\pi_{jt+1}}{\partial B_{t+1}}\frac{\partial B_{t+1}}{\partial S_{Kt+1}}\right]=\lambda \tag{A.3}$$

$$S_{Kt}=L_t-\sum_{g=1}^{K-1}S_{gt} \tag{A.4}$$

Given that $\frac{\partial\pi_{kt}}{\partial B_t}=p_{kt}\alpha_{1k}-\mathbf{w}_t\boldsymbol{\mu}_{1k}$, $\frac{\partial B_t}{\partial S_{kt}}=-TL_t^{-1}\left(\ln s_{kt}+1\right)$ and $\frac{\partial H}{\partial S_{kt}}=\varphi_{0k}+\sum_{m=1}^{K}\varphi_{km}S_{mt}$, we obtain the following system of first-order conditions:

$$\begin{aligned}\frac{\partial L}{\partial S_{kt}}=\pi_{kt}-\sum_{j=1}^{K}s_{jt}\left(\ln s_{kt}+1\right)\left(p_{jt}\alpha_{1j}-\mathbf{w}_t\boldsymbol{\mu}_{1j}\right)-\left(\varphi_{0k}+\sum_{m=1}^{K}\varphi_{km}S_{mt}\right)\\-\frac{(1-\delta)}{(1+r)}\left[\sum_{j=1}^{K}s_{jt+1}\left(\ln s_{kt+1}+1\right)\left(p_{jt+1}\alpha_{1j}-\mathbf{w}_{t+1}\boldsymbol{\mu}_{1j}\right)\right]=\lambda\end{aligned} \tag{A.5}$$

$$\begin{aligned}\frac{\partial L}{\partial S_{Kt}}=\pi_{Kt}-\sum_{j=1}^{K}s_{jt}\left(\ln s_{Kt}+1\right)\left(p_{jt}\alpha_{1j}-\mathbf{w}_t\boldsymbol{\mu}_{1j}\right)-\left(\varphi_{0K}+\sum_{m=1}^{K}\varphi_{Km}S_{mt}\right)\\-\frac{(1-\delta)}{(1+r)}\left[\sum_{j=1}^{K}s_{jt+1}\left(\ln s_{Kt+1}+1\right)\left(p_{jt+1}\alpha_{1j}-\mathbf{w}_{t+1}\boldsymbol{\mu}_{1j}\right)\right]=\lambda\end{aligned} \tag{A.6}$$

$$S_{Kt}=L_t-\sum_{g=1}^{K-1}S_{gt} \tag{A.7}$$

Equation (A.5) minus equation (A.6) leads to:

$$\begin{aligned}\left(\pi_{kt}-\pi_{Kt}\right)-\sum_{j=1}^{K}s_{jt}\left(\ln s_{kt}-\ln s_{Kt}\right)\left(p_{jt}\alpha_{1j}-\mathbf{w}_t\boldsymbol{\mu}_{1j}\right)-\left(\varphi_{0k}-\varphi_{0K}+\sum_{m=1}^{K}\left(\varphi_{km}-\varphi_{Km}\right)S_{mt}\right)\\-\frac{(1-\delta)}{(1+r)}\left[\sum_{j=1}^{K}s_{jt+1}\left(\ln s_{kt+1}-\ln s_{Kt+1}\right)\left(p_{jt+1}\alpha_{1j}-\mathbf{w}_{t+1}\boldsymbol{\mu}_{1j}\right)\right]=0\end{aligned} \tag{A.8}$$

The inclusion of (A.7) in (A.8) leads to the following first-order condition for acreage choice of crop k $(k \neq K)$:

$$
\begin{aligned}
&(\pi_{kt}-\pi_{Kt})-(\varphi_{0k}-\varphi_{0K})-\sum_{m=1}^{K-1} S_{mt}(\varphi_{km}-\varphi_{kK}-\varphi_{Km}+\varphi_{KK})-(\varphi_{kK}L_t-\varphi_{KK}L_t) \\
&-(\ln s_{kt}-\ln s_{Kt})\left[\sum_{j=1}^{K-1} s_{jt}\left(p_{jt}\alpha_{1j}-p_{Kt}\alpha_{1K}-\mathbf{w}_t\boldsymbol{\mu}_{1j}+\mathbf{w}_t\boldsymbol{\mu}_{1K}\right)+l_t\left(p_{Kt}\alpha_{1K}-\mathbf{w}_t\boldsymbol{\mu}_{1K}\right)\right] \qquad \text{(A.9)} \\
&-\frac{(1-\delta)}{(1+r)}(\ln s_{kt+1}-\ln s_{Kt+1})\left[\begin{array}{c}\displaystyle\sum_{j=1}^{K-1} s_{jt+1}\left(p_{jt+1}\alpha_{1j}-p_{Kt+1}\alpha_{1K}-\mathbf{w}_{t+1}\boldsymbol{\mu}_{1j}+\mathbf{w}_{t+1}\boldsymbol{\mu}_{1K}\right)\\ +l_{t+1}\left(p_{Kt+1}\alpha_{1K}-\mathbf{w}_{t+1}\boldsymbol{\mu}_{1K}\right)\end{array}\right]=0
\end{aligned}
$$

With $l_t = L_t / TL_t$ being the total acreage share of all endogenous crops on total agricultural area.

Appendix C. results of GMM estimation for all estimated parameters

[Table 3 about here]

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Tables

Table 1: Descriptive statistics (N=771)

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

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Table 2: Results of GMM estimation (N=771)

	Wheat	Winter barley	Rapeseed
Yield supply			
Average potential yield			
Average value α_{0k}	70.54 ***	60.86 ***	34.14 ***
	(4.46)	(5.29)	(2.90)
Crop biodiversity index α_{1k}	1.49 °	3.20 **	0.21
	(0.88)	(1.15)	(0.34)
Curvature parameters			
γ_{1k}	833.58 ***	525.48 ***	1947.04 ***
	(72.97)	(63.93)	(221.90)
γ_{2k}	1065.45 ***	672.03 ***	2583.69 ***
	(144.00)	(150.20)	(507.70)
γ_{12k}	-884.15 ***	-576.50 ***	-1862.01 ***
	(89.02)	(65.10)	(244.50)
R²	*0.207*	*0.261*	*0.199*
Fertilizer demand			
Average required use			
Average value μ_{01k}	140.09 ***	116.26 ***	142.01 ***
	(23.17)	(18.98)	(23.54)
Crop biodiversity index μ_{11k}	-6.32 °	-3.87	-3.96
	(3.46)	(3.34)	(4.82)
R²	*0.673*	*0.602*	*0.574*
Pesticides demand			
Average required use			
Average value μ_{02k}	210.21 ***	176.49 ***	316.76 ***
	(16.93)	(13.32)	(16.80)
Crop biodiversity index μ_{12k}	-29.71 **	-13.86	-56.89 ***
	(9.86)	(10.46)	(11.04)
R²	*0.062*	*0.052*	*0.090*
Acreage			
$(\varphi_{0k}-\varphi_{0K})$	76.29 °	-392.90 ***	*(Ref)*
	(46.46)	(78.16)	
$(\varphi_{kK}-\varphi_{KK})L_t$	-36.97 *	-40.71 *	*(Ref)*
	(16.62)	(19.52)	
$(\varphi_{kk}-\varphi_{kK}-\varphi_{Kk}+\varphi_{KK})$	60.98 *	84.11 *	*(Ref)*
	(29.57)	(40.71)	
$(\varphi_{km}-\varphi_{kK}-\varphi_{Km}+\varphi_{KK})$	46.21 *		*(Ref)*
	(20.40)		
Biodiversity dynamics			
δ	0.70 ***		
	(0.13)		

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

Table 3. Detailed results of GMM estimation (N=771)

	Wheat	Winter barley	Rapeseed
Yield supply			
Average potential yield			
Constant	56.38 ***	43.94 **	30.16 **
	(15.79)	(16.60)	(10.69)
Rain in March	0.04	0.05	0.03
	(0.04)	(0.04)	(0.03)
Rain in April	0.04	0.01	-0.03
	(0.05)	(0.06)	(0.03)
Rain in May	-0.02	-0.07 *	-0.09 ***
	(0.03)	(0.03)	(0.02)
Rain in June	-0.10 **	-0.12 ***	-0.07 **
	(0.03)	(0.04)	(0.02)
Frost in May	-3.07 °	-0.56	-0.25
	(1.83)	(1.93)	(1.44)
EVT in May	0.19	-0.14	-0.03
	(0.17)	(0.20)	(0.12)
EVT in June	0.35 ***	0.45 ***	0.20 ***
	(0.09)	(0.11)	(0.06)
EVT in July	-0.09	-0.04	-0.09
	(0.08)	(0.09)	(0.06)
Temperature in February	3.79 **	3.96 **	0.85
	(1.19)	(1.42)	(0.88)
Temperature in Mars	1.33 *	-0.13	0.95 *
	(0.56)	(0.60)	(0.40)
Temperature in April	2.92 ***	1.70 *	1.96 ***
	(0.68)	(0.67)	(0.41)
Temperature in May	0.22	0.86	0.67
	(0.96)	(1.07)	(0.71)
Temperature in June	-6.67 ***	-3.73 *	-2.45 *
	(1.44)	(1.49)	(1.04)
Soil index	22.41 ***	10.61 °	10.52 *
	(6.10)	(6.01)	(4.14)
Crop biodiversity index	1.49 °	3.20 **	0.21
	(0.88)	(1.15)	(0.34)
Curvature parameters			
γ_{1k}	833.58 ***	525.48 ***	1947.04 ***
	(72.97)	(63.93)	(221.90)
γ_{2k}	1065.45 ***	672.03 ***	2583.69 ***
	(144.00)	(150.20)	(507.70)
γ_{12k}	-884.15 ***	-576.50 ***	-1862.01 ***
	(89.02)	(65.10)	(244.50)
R^2	*0.207*	*0.261*	*0.199*
Fertilizer demand			
Average required use			
Constant	115.85 ***	52.47 °	125.47 ***
	(28.46)	(30.13)	(38.15)
Rain in April	0.99 ***	0.84 ***	0.97 ***
	(0.05)	(0.05)	(0.06)
Rain in May	0.13 ***	0.08 ***	0.10 **
	(0.02)	(0.02)	(0.03)

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EVT in June	0.66 ***	0.74 ***	0.65 ***
	(0.15)	(0.13)	(0.18)
Temperature in April	10.05 ***	9.15 ***	10.13 ***
	(0.59)	(0.51)	(0.75)
Temperature in June	-11.77 ***	-8.32 ***	-11.83 ***
	(1.92)	(2.14)	(2.29)
Soil index	-16.97	-24.98 °	-19.09
	(13.38)	(13.11)	(15.63)
Crop biodiversity index	-6.32 °	-3.87	-3.96
	(3.46)	(3.34)	(4.81)
R²	*0.673*	*0.602*	*0.574*
Pesticides demand			
Average required use			
Constant	-69.51	-151.06 °	67.91
	(77.69)	(84.06)	(96.22)
Rain in April	1.12 ***	0.94 ***	0.85 ***
	(0.16)	(0.19)	(0.21)
Rain in May	0.25 **	0.14	-0.05
	(0.09)	(0.09)	(0.10)
Rain in June	-0.22	0.19	-0.24
	(0.14)	(0.15)	(0.18)
EVT in April	0.12	-0.12	-0.17
	(0.51)	(0.53)	(0.56)
EVT in May	-0.11	0.33	0.43
	(0.34)	(0.35)	(0.42)
EVT in June	1.44 ***	1.48 ***	0.60
	(0.30)	(0.29)	(0.40)
Temperature in April	13.05 ***	10.11 ***	12.87 ***
	(2.23)	(2.68)	(2.70)
Temperature in May	-2.29	-6.46	-12.94 **
	(3.70)	(4.22)	(4.67)
Temperature in June	2.75	6.25	15.29 *
	(4.70)	(5.66)	(6.55)
Soil index	-98.56 **	-61.42 *	-69.20
	(33.11)	(30.50)	(43.16)
Crop biodiversity index	-29.71 **	-13.86	-81.76 °
	(9.85)	(10.47)	(44.97)
R²	*0.062*	*0.052*	*0.090*
Acreage			
$(\varphi_{0k} - \varphi_{0K})$	76.29 °	-392.90 ***	*(Ref)*
	(46.46)	(78.16)	
$(\varphi_{kK} - \varphi_{KK}) L_t$	-36.97 *	-40.71 *	*(Ref)*
	(16.62)	(19.52)	
$(\varphi_{km} - \varphi_{kK} - \varphi_{Km} + \varphi_{KK})$	60.98 *	84.11 *	*(Ref)*
	(29.57)	(40.71)	
$(\varphi_{km} - \varphi_{kK} - \varphi_{Km} + \varphi_{KK})$	46.21 *		*(Ref)*
	(20.40)		
Biodiversity dynamics			
δ	0.70 ***		
	(0.13)		

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

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Figures

Figure 1. Evolution of the productive capacity of crop biodiversity

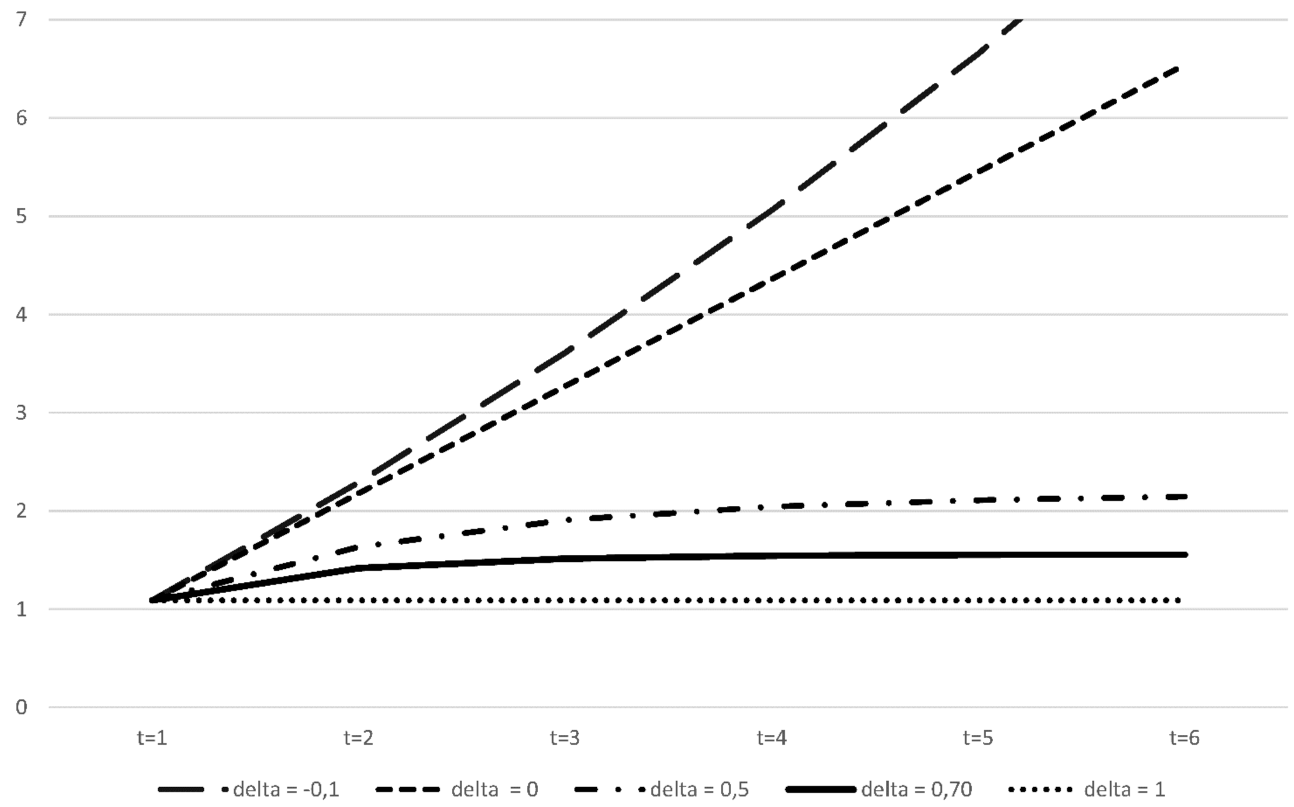
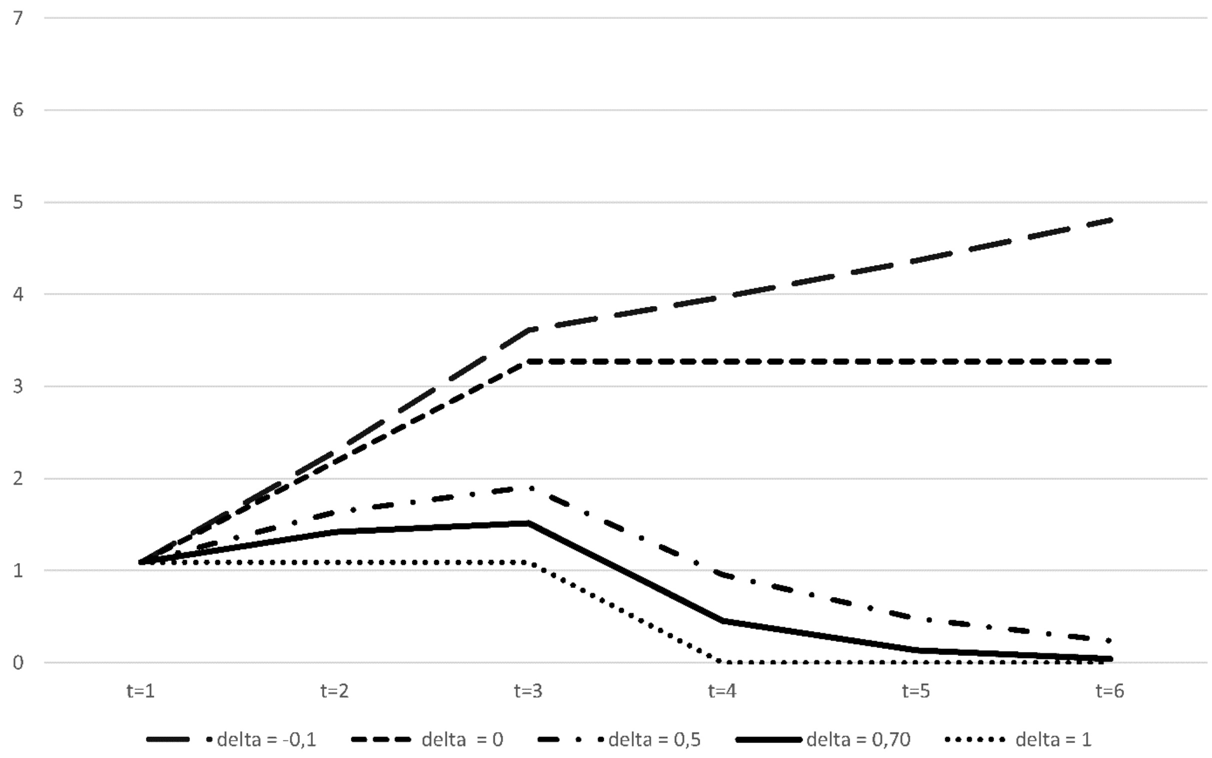


Figure 2. Evolution of the productive capacity of crop biodiversity with a change in acreage in $t = 4$



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