Balancing profitability, plant protein production and pesticide reduction in arable farming

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Abstract

Based on a panel of 458 arable farms observed over 27 years in an agricultural French region (the Meuse district), we evaluate the implications of three contrasting strategies: maximizing profitability, enhancing protein supply, and reducing pesticide use. We apply a farm activity model to assess the impacts of these strategies on margin, focusing on cost savings and revenue increases through yield/pricing adjustments. These impacts are measured by first comparing the optimal situation to the observed situation within each strategy, thereby identifying potential pathways for improvement. Subsequently, we compare the three optimal scenarios along the efficiency frontier to evaluate the potential opportunity costs for farmers when selecting a specific strategy relative to the profitability maximization strategy, which serves as the reference. This analysis indicates that the opportunity cost associated with maximizing protein supply is relatively higher than that of reducing pesticide use. This finding suggests that policies aimed at decreasing pesticide use could be economically feasible, offering fewer financial drawbacks and clearly enhanced environmental benefits, compared to strategies that focus on increasing protein production.

Keywords: sustainable agriculture; pesticide reduction; protein supply; profitability maximization; crop arable farms; activity analysis.

JEL codes: D24; C61; Q12; Q56

1. Introduction

The evolution of European agriculture, shaped by both internal and external influences since the 1960s, has been characterized by the adoption of new production techniques such as industrialization, extensive use of pesticides and fertilizers, and specialized crop cultivation (Ballot et al., 2023; Schaak et al., 2023; Tilman et al., 2002). Initially focused on boosting food supply, governments promoted industrial agricultural methods, leading to a 149.8% increase in cereal production from 1961 to 2021 (FAO, 2023). However, this growth came at the expense of natural resources, resulting in environmental degradation (Campbell et al., 2017; Millennium Ecosystem Assessment, 2005; Pimentel et al., 1997; Travisi & Nijkamp, 2008). The shift towards cereal specialization has also created a deficit in protein-rich crops, prompting imports and raising questions about food sovereignty (Magrini et al., 2016). Addressing this, some advocate for integrating legumes and oilseeds into crop rotations to diversify and potentially enhance farm profitability, though challenges like pesticide dependency and economic feasibility remain (Guinet et al., 2023; Nilsson et al., 2022).

Recognizing that farmers target maximizing profits (or profitability), integrating either protein sovereignty concerns and/or environmental considerations presents a challenge to agricultural practices. Our work explores strategies to balance farmer profitability with environmental preservation and food supply goals, analyzing three performance scenarios: maximizing profitability, optimizing protein supply, and minimizing pesticide intensity.

The determinants of farmers' profitability across different regions and farming categories has been frequently addressed in agricultural economics literature (Blank et al., 2004; Browne et al., 2013; Davidova et al., 2003; Kryszak et al., 2021; Mishra et al., 2012). For example, Blank et al. (2004) highlighted the importance of farm size and productivity, while Kryszak et al. (2021) found that smaller farms tend to achieve higher profitability per farm due to their lower specialization and associated costs.

Pesticides have played a crucial role in mitigating yield losses from weeds, pests, and diseases, thereby safeguarding farm incomes (Cooper & Dobson, 2007). However, concerns about their adverse effects on the environment, biodiversity, and human health (Beketov et al., 2013; Nicolopoulou-Stamati et al., 2016; Tang et al., 2021) have led to calls for reducing their usage in agriculture (Dasgupta et al., 2007; Frisvold, 2019; Pimentel et al., 1997; Skevas et al., 2012; Travisi & Nijkamp, 2008; Wilson & Tisdell, 2001).The potential for reducing pesticide use in France and its impact on productivity and profitability has been also widely studied (Boussemart et al., 2011; Jacquet et al., 2011; Kahindo & Blancard, 2022; Lechenet et al., 2017).

Addressing these concerns, researchers have suggested that a reduction in pesticide usage is feasible without compromising productivity or profitability. For instance, studies focusing on France have indicated that significant reductions in pesticide use are achievable without negative implications for agricultural production or costs (Boussemart et al., 2016; Jacquet et al., 2011; Kahindo & Blancard, 2022; Lechenet et al., 2017). However, there may be trade-offs to consider, as reducing pesticide use could entail additional costs or lead to changes in both the nature of crops grown and crop yields.

Nevertheless, previous studies mainly focused on a comparison between the observed situation and the optimal one achieved by eliminating different forms of inefficiencies regarding agricultural practices. Our research extends these previous studies to an opportunity cost analysis between the optimal states reached when each of the three objectives are met. Our findings highlight the trade-offs between the natural objective of profitability maximization and alternatives goals such as either protein production maximization or pesticide use minimization and provide insights into how to balance profitability with environmental preservation in farming systems.

The remainder of this paper is organized as follows: Section 2 outlines our materials and methodology, including the models used. Section 3 presents and discusses our research findings, and Section 4 draws our conclusions.

2. Material and methods

2.1. Data and variables

We sourced farm data from the Meuse Department, an administrative division in eastern France, through the Centre d'Economie Rurale et de Gestion de la Meuse.[1] Agriculture in Meuse is primarily centered on the production of cereals (44%), milk (19%), and beef cattle farming (13%), collectively constituting the majority of the total output value.[2] The cultivated area spans approximately 343,000 hectares (ha), with field crops (including cereals, maize, oilseed, and protein crops) occupying 57% of the arable land (AL).[3]

Our analysis is based on a panel of 458 farms for which field crops account for more than two-thirds of total revenue excluding subsidies. These farms were observed over 27 years from 1991 to 2017, resulting in a total of 2,900 observations (see Table A in the Appendix).

Our analysis relies on two key outputs: revenue from crops and revenue from other activities. These outputs are produced by five inputs: arable land, other surfaces, labor, fixed capital, and intermediate consumption. The farms in our sample are relatively large, with an average size of 175.8 ha, compared to the reported average arable land size in Meuse for 2020 (144.4 ha, Agreste-RA 2020).[4] Given the potential variations in land quality within our small geographical area, we adjusted land measurements by incorporating a yield index specific to each Meuse district, reflecting their distinct pedological conditions. Labor resources encompass both hired and family labor, quantified in annual full-time equivalents. On average, our database indicates a workforce of 1.7 annual full-time equivalents per farm, ranging from 0.2 to 6.3 (refer to Table 1). Fixed capital is approximated by depreciation costs associated with buildings, equipment, and agricultural service providers expressed in euros. Intermediate consumption encompasses expenditures mainly linked to crop activities, including fertilizers, seeds, pesticides, fuel, electricity and water expenses among others. For our specific study, intermediate consumption

[1] This is an audit and control organism specialized in farming activities.
[2] https://meuse.chambre-agriculture.fr/enregistrements-locaux/interface/menus/menu-acces-pratique/lagriculture-en-meuse/
[3] Idem.
[4] Idem.

further decomposes into intermediate consumption without pesticides (ICWP) and pesticide costs (P). Descriptive statistics of these variables are detailed in Table 1.

To facilitate cross-year comparisons, all monetary values have been deflated by the global consumer price index and standardized to constant euros for 2010 (€$_{2010}$). This standardization ensures consistency and accuracy in assessing changes over time.

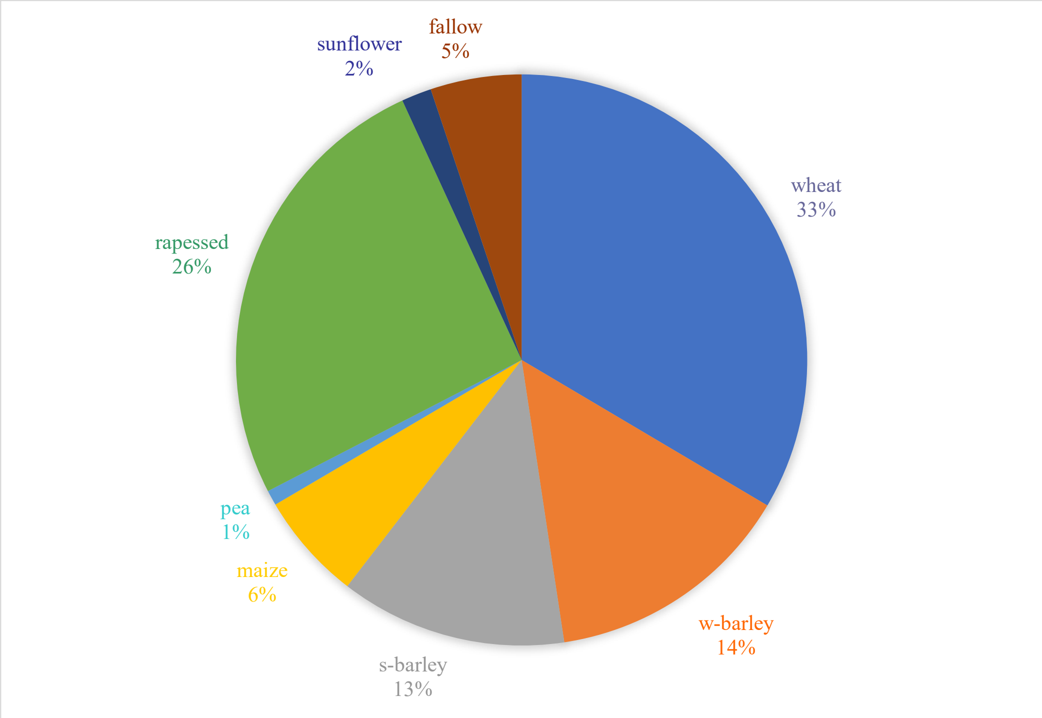
Table 1. Descriptive statistics for all variables over the period 1991-2017 (per farm and per year)

	Mean	**Min**	**Max**	**CV**
Crop product (€$_{2010}$)	164,795	15,558	972,265	63%
Protein (kg of DM)	111,633	12,747	499,870	57%
Protein price (€$_{2010}$/kg of protein)	1.5	0.9	2.9	22%
Other products (€$_{2010}$)	33,464	0	256,382	91%
Arable land (ha)	176	25	708	54%
Other surfaces (ha)	28	0	183	106%
Labor	1.7	0.2	6.4	52%
Fixed Capital (€$_{2010}$)	62,842	5,776	399,321	63%
Intermediate consumption without pesticides (€$_{2010}$)	61,209	6,610	322,920	61%
Pesticide cost (€$_{2010}$)	28,985	2,484	162,582	64%
Pesticide cost/ha (€$_{2010}$)	165	45	349	27%

On average, over the specified period, farms in our dataset yielded 111,633 kg of protein from the diverse range of crops cultivated. Wheat (33%) and rapeseed (26%) were the predominant crops, trailed by winter and spring barley at 14% and 13% respectively (Figure 1).[5] Maize and fallow land occupied nearly equal proportions (6% and 5%, respectively). Peas were the least prevalent, accounting for slightly less than 1% of the total area. For comparison, the main crops cultivated in the Meuse department included winter wheat, barley (both spring and winter varieties), and rapeseed, accounting for 82% of the total field crop land in 2021 (Mémento, 2022).

Figure 1. Shares of crops in the total crop agricultural land

[5] In our sample, wheat, barley, and rapeseed, accounted for 84% of our total crop area comparatively to 82% in the Meuse department in 2021.



ICWP averaged at 61,209 €$_{2010}$ (348 €$_{2010}$ per ha), while pesticide costs averaged 28,985 €$_{2010}$ (165 €$_{2010}$ per ha), as shown in Table 1. The main components of ICWP were fertilizers (53%), seeds (20%), fuel (15%) and other expenses (12%).

2.2 Methods

Our research aims to quantitatively assess trade-offs among three farm performance objectives using a two-stage analysis. Initially, we estimate a production frontier via a nonparametric activity model, akin to Koopmans' (1951) approach, employing data envelopment analysis (DEA) as outlined by Charnes et al. (1978). This benchmark defines optimal input-output relationships, measuring productive efficiency by the deviation from this frontier. Efficient farms show no deviation, while deviations indicate areas for potential improvement assuming similar production contexts. We evaluate each farm against objectives of maximizing profitability, protein production, and minimizing pesticide costs, analyzing gaps through indicators like revenue, protein yield, price, cost, pesticide intensity, and gross margin per hectare.

In the second step, we compare three optimal scenarios for each farm, which, devoid of technical inefficiencies, vary in technical and economic metrics. Assuming the natural goal is profitability maximization, we calculate the opportunity cost—defined as the potential margin loss per hectare—of choosing alternative goals like maximizing protein production or minimizing pesticide costs. This analysis helps define strategic pathways for Meuse farms towards either productivist or pesticide reduction strategies.

2.2.1 Modelling farming activities

We consider here a set of *N* observed farms operating under homogenous conditions (the Meuse department). They use five inputs to produce two outputs. The input vector is composed of the arable land (AL), other surfaces ((OS); i.e., pasture), labor (L), intermediate consumption (IC) and fixed capital (K). The input vector is then:

$$\mathbf{x} = (AL, OS, L, IC, K) \qquad (1),$$

At the farm level, AL is obtained by summing up the land allocated to each different crop. The land vector comprising each crop area is:

$$\boldsymbol{AL} = \left(AL_{wt}, AL_{wb}, AL_{sb}, AL_{mz}, AL_{pa}, AL_{rs}, AL_{sf}, AL_{fw}\right) \qquad (2),$$

where *wt*= wheat, *wb*= winter barley, *sb*= spring barley, *mz*= maize, *pa*=peas, *rs*= rapeseed, *sf*= sunflower and *fw*=fallow.

We denote by the subscript "*c*" any variable related to a specific crop. Thus, AL_c is a component of AL and the total land for crops is a scalar obtained as:

$$AL = \sum_{c=1}^{8} AL_c \qquad (3).$$

The intermediate consumption (IC) is obtained as the sum of two components, namely the cost for intermediate consumption without pesticides ($ICWP$) and pesticide cost (P), and for each farm, we get:

$$IC = ICWP + P \qquad (4).$$

For each of the eight possible crops cultivated by the farms, we retrieve the quantity produced (q_c) and the corresponding market price in €$_{2010}$ per kg (p_c). The revenue of each crop is given by:

$$R_c = q_c * p_c \qquad (5).$$

Consequently, total crop revenue is obtained by summing up the crop revenue for all eight crops:

$$R^1 = \sum_{c=1}^{8} R_c \qquad (6).$$

Several metrics can aggregate these different productions at the farm level.[6] One possible metric measures crop protein production, contributing to the ongoing debate advocating for the promotion of plant-based proteins in France and Europe.[7] For each crop *c*, we use the standard

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[6] The standard aggregator is the monetary unit price of each crop, as in equations (5) and (6). Alternatively, we can use the energy content for each crop. The estimations ran with energy content instead of protein production do not show any significant difference from the ones presented here.

[7] Since the 1960s, the evolution of the production systems in France and Europe have shown a considerable decline in protein production from crops. As a result, France and Europe have experienced a high level of dependence on foreign protein imported from Brazil, Argentina, and the USA (Watson et al., 2017), and the consumption of animal protein has increased at the expense of plant protein (Bues et al., 2013). Due to the adverse effects of these changes on the environment, the French government has committed to mitigate these external impacts by enhancing the local production of plant protein.

protein content of harvested biomass provided by the online encyclopedia Feedipedia,[8] an open access information system that provides information on nature, occurrence, chemical composition, nutritional value and safe use of nearly 1400 worldwide feed resources. The protein content is provided in % of dry mater. A standard rate of humidity for each crop (Std-Hmd_c) allows to convert the gross harvested quantity into dry mater. For each crop, we denote its observed yield by (Obs-YLD_c) and we calculate the dry matter yield (DM-YLD_c) as follows:

$$\text{DM-YLD}_c(\text{in kg/ha}) = \frac{\text{Obs-YLD}_c \times (100 - \text{Std-Hmd}_c)}{100} \quad (7).$$

For each crop, the dry matter yield is multiplied by the per crop protein content (Prot-cont_c), to obtain the protein yield (YLD_c):

$$\text{YLD}_c(\text{in kg/ha}) = \text{DM-YLD}_c \times \text{Prot-cont}_c \quad (8).$$

A specific crop protein production (y_c) is obtained by multiplying the protein yield by the land attributed to that crop. The total production of protein (y^1) is obtained from:

$$y^1 = \sum_{c=1}^{8} y_c \quad (9).$$

We estimate the indirect price of protein (pp) measured in $€_{2010}$ per kg of protein, by the ratio between the total crop revenue (R^1), and the total production of protein (y^1):

$$pp = \frac{R^1}{y^1} \quad (10).$$

The indirect protein price level may vary across farms due to two primary effects. Firstly, differing crop prices can result from each farm's unique bargaining power, influenced by their selling strategies and capacity to capitalize on market opportunities. Secondly, the crop mix plays a significant role, because the protein price varies strongly across crops (see Figure B in the Appendix).

Additionally, some farms in our sample may engage in supplementary activities such as cattle breeding, fruit growing, or vegetable production. These additional productions are considered in our analysis as control variables for two reasons. Firstly, we rely on accounting data where certain costs are only available at the farm level, making it impossible to allocate them between crop and livestock productions accurately. Secondly, livestock and crop production are not entirely independent at the farm level. Certain crop productions may serve as animal feed, reducing the need for external feed purchases. Moreover, animals can provide organic fertilizers to the farm, thereby reducing the costs of fertilizers. Consequently, the revenue associated with these activities, denoted as R^2, is incorporated into our analysis.

The final output vector is then:

$$\boldsymbol{y} = (y^1, R^2) \quad (11).$$

[8] https://feedipedia.org/

Assumptions regarding the production possibility set associated to the farm activity model are standard and refer to "no free lunch", boundedness, closure, free disposability, and geometrical convexity (see Banker & Maindiratta, 1986). Related to this latter assumption, we remind that it offers the benefit of being applicable to more complex production situations, thereby accommodating local non-concavity and effectively dealing with a nonconvex production possibility set. The corresponding production technology T is given by:

$$T = \{ (\mathbf{x}, \mathbf{y}) \in \mathbb{R}^{5\times2} : \mathbf{x} \text{ can produce } \mathbf{y} \} \quad (12).$$

2.2.2 Estimations strategies

Max PROF: profitability maximization scenario

Profitability, denoted π, is defined, for each farm as the ratio of crop revenue (R^1) to intermediate consumption (IC). Thus, the function to be maximized is multiplicative.

$$\pi = \frac{R^1}{\mathrm{IC}} = \frac{y^1 * \mathrm{pp}}{\mathrm{IC}} \quad (13).$$

Denote $\pi^*$the optimal level for profitability, i.e. the profitability that would be attained by a farm by adopting the same practices as their benchmark. Denote θ the gap between the observed profitability level and the optimal level, i.e. $\pi^* = \pi\theta$, with $\theta \geq 1$. Thus, an efficient farm will obtain a coefficient $\theta = 1$ whereas for an inefficient farm, $\theta > 1$. Such an inefficient farm should increase its profitability by $(\theta - 1)\%$ to reach the maximum profitability level of efficient farms, in the same production context.

The profitability extension coefficient θ can be further decomposed into a revenue change coefficient, and a cost change coefficient. Knowing that revenue itself is decomposed into protein content and protein price, we get that:

$$\pi^* = \frac{(\alpha y^1)(\beta\, pp)}{\gamma\, IC} = \frac{\alpha\beta}{\gamma}\pi \quad \text{with } \alpha, \beta, \gamma > 0 \text{ and } \frac{\alpha\beta}{\gamma} \geq 1 \quad (14)$$

where:

α = the coefficient for the protein production variation to reach the optimal level ensuring the maximum profitability achievable,

β = the coefficient for the protein price variation to reach the optimal level ensuring the maximum profitability achievable,

γ = the coefficient for intermediate consumption variation to reach the optimal level ensuring the maximum profitability achievable.

Note that in the above equation (14), the only restriction on the profitability components efficiency scores is that they are positive, and that their combination $\frac{\alpha\beta}{\gamma} \geq 1$. It follows that, to reach the maximum profitability level, a farm can appropriately adapt its protein production, protein price and intermediate consumption policies (see a more detailed explanation after the LP_MaxPROF below).

Boussemart et al. (2022) introduced a method to estimate the optimal profitability, which in our case, goes down to estimating the optimal values for θ, or in other words, the optimal values for α, β and γ. However, solving such an objective function requires solving a nonlinear program, with the risk that the resulting solutions may be only locally optimal. One solution to overcome this issue is to linearize the objective function in equation (14) by considering its logarithmic form.

$$\ln(\pi^*) = \ln(\alpha) + \ln(\beta) - \ln(\gamma) + \ln(\pi) \quad (15).$$

The objective function (equation14) is optimized under a set of constraints associated with the activity model defined in equation (12). Then, we also need to linearize the resulting constraints by considering their logarithmic forms (see LP_MaxPROF below). It's worth noting that throughout the following, the symbol "overline" will denote the natural logarithm of the variable. For instance, $\bar{z} = ln(z)$. With these notations, the (log) linear program under the variable returns to scale assumption, corresponding to the maximization of profitability for an evaluated farm a, is as follows:

$$\max_{\alpha,\beta,\gamma,\boldsymbol{\mu}} [\bar{\alpha} + \bar{\beta} - \bar{\gamma}]$$
$$\sum_n \mu_n \overline{y_n^1} \geq \bar{\alpha} + \overline{y_a^1}$$
$$\sum_n \mu_n \overline{pp_n^1} \geq \bar{\beta} + \overline{pp_a^1}$$
$$\sum_n \mu_n \overline{R_n^2} \geq \overline{R_a^2}$$
$$\sum_n \mu_n \overline{AL_n} \leq \overline{AL_a}$$
$$\sum_n \mu_n \overline{OS_n} \leq \overline{OS_a}$$
$$\sum_n \mu_n \overline{L_n} \leq \overline{L_a}$$
$$\sum_n \mu_n \overline{IC_n} \leq \bar{\gamma} + \overline{IC_a}$$
$$\sum_n \mu_n \overline{K_n} \leq \overline{K_a}$$
$$\sum_n \mu_n = 1$$
$$\mu_n \geq 0, \forall n \in N \quad \textit{(LP\_MaxPROF)}.$$

In the above program LP_MaxPROF, profitability is optimized along its three dimensions, i.e. the total protein production, the protein price, and intermediate consumption. Thus, each of the three scores obtained give the optimal increase/decrease in the variable in order to reach the highest potential profitability ratio by adapting the evaluated farm's practices to its benchmark. The exponential of $\bar{\alpha}$, ($e^{\bar{\alpha}} = \alpha$), represents the potential change in protein production to reach the highest profitability that the farm could achieve. In the same way, $e^{\bar{\beta}} = \beta$ measures the potential change in protein price and $e^{\bar{\gamma}} = \gamma$ gives the necessary change in operating cost to reach the same objective. Thus, $\frac{\alpha\beta}{\gamma} - 1$ is the highest possible increase in profitability that the farm could achieve. The farm is efficient if $\frac{\alpha\beta}{\gamma} = 1$. However, in LP_MaxPROF the values of the scores associated to each variable are not constrained meaning that several situations may occur.

- The revenue increases and the intermediate consumption decreases: $\overline{\alpha} + \overline{\beta} \geq 0, \overline{\gamma} \leq 0$.
- Both the revenue and the intermediate consumption may increase, but the increase in the revenue exceeds the increase in the intermediate consumption, $\overline{\alpha} + \overline{\beta} \geq \overline{\gamma}$, with $(\bar{\alpha} + \bar{\beta}),\ \bar{\gamma} \geq 0$
- Conversely, both the revenue and the intermediate consumption decrease, but the decrease in the intermediate consumption exceeds the decrease in the revenue. So, $\bar{\alpha} + \bar{\beta} \geq \bar{\gamma}$, with $(\bar{\alpha} + \bar{\beta}),\ \bar{\gamma} \leq 0$.

Max PROT: protein production maximization scenario

In the second scenario, the objective is to maximize protein production, to align with a general strategy designed to enhance food sovereignty and self-sufficiency, thereby reducing imports of plant-based proteins such as soybean. Similar to the previous scenario (Max PROF), we employ a DEA estimation model based on logarithmic linear combinations. However, unlike in the previous scenario, the price of protein is not considered as a constraint in this scenario. This omission allows to determine the protein price associated with the optimal protein production for the evaluated farm a.[9] The resulting price may be higher, lower, or equal to the observed price.

In the following, denote δ the efficiency score measuring the gap between the evaluated farm's protein production and its maximum protein production achievable by adopting the benchmark practices. We obtain the following model:

[9] This calculation is done by retrieving the protein prices of the farms composing the benchmark of the evaluated farm a.

$$
\begin{aligned}
&\max_{\delta,\boldsymbol{\mu}} \bar{\delta} \\
&\sum_{n=1}^{N} \mu_n \overline{y_n^1} \geq \bar{\delta} + \overline{y_a^1} \\
&\sum_{n=1}^{N} \mu_n \overline{R_n^2} \geq \overline{R_a^2} \\
&\sum_{n=1}^{N} \mu_n \overline{AL_n} \leq \overline{AL_a} \\
&\sum_{n=1}^{N} \mu_n \overline{OS_n} \leq \overline{OS_a} \\
&\sum_{n=1}^{N} \mu_n \overline{L_n} \leq \overline{L_a} \\
&\sum_{n=1}^{N} \mu_n \overline{IC_n} \leq \overline{IC_a} \\
&\sum_{n=1}^{N} \mu_n \overline{K_n} \leq \overline{K_a} \\
&\sum_{n=1}^{N} \mu_n = 1 \\
&\mu_n \geq 0, \forall n \in N
\end{aligned}
\qquad (LP\_MaxPROT).
$$

In this model $\bar{\delta}$ $s$tands for the optimal increase in the protein production. For an efficient farm, LP_MaxPROT will result in $\bar{\delta} = 0 \Leftrightarrow \delta = 1$ whereas for an inefficient farm $\bar{\delta} > 0 \Leftrightarrow \delta > 1$.

Notice that yields resulting from this scenario will always be higher than the observed ones, since the resulting arable land variable cannot be higher than the observed one.

Min PEST: pesticide cost minimization scenario

In the third scenario, the objective is to minimize pesticide costs, considered as a proxy of pesticide use reduction. Previous research (Butault et al., 2011) has identified a positive correlation between pesticide use, measured by the Treatment Frequency Index (TFI), and pesticide costs, especially in arable field crops. In this scenario, intermediate consumption is decomposed into two components (equation 4): intermediate consumption without pesticides (ICWP) and pesticide costs (P). Additionally, in this scenario, we focus on reducing pesticide intensity (PHa), defined as the ratio of pesticide cost to total arable land. Therefore, we impose an equality constraint on the variable representing arable land.

Moreover, literature on pesticide use at the farm level suggests that a decrease in pesticide intensity may lead to substitution or complementarity effects regarding the use of other inputs, such as land surfaces allocated to other activities, labor, equipment, and other intermediate consumption without pesticides (Boussemart et al., 2016). To account for these potential substitution and/or complementarity effects, we omit the associated constraints in LP_MinPEST. Consequently, we can determine whether the "optimal" levels of input use are higher (indicating substitution effects), lower (indicating complementarity effects), or equal to the observed levels. The corresponding logarithmic linearization of this model is as follows:

$$\min_{\sigma,\boldsymbol{\mu}} \overline{\sigma}$$
$$\sum_{n=1}^{N} \mu_n \overline{R_n^1} \geq \overline{R_a^1}$$
$$\sum_{n=1}^{N} \mu_n \overline{R_n^2} \geq \overline{R_a^2}$$
$$\sum_{n=1}^{N} \mu_n \overline{AL_n} = \overline{AL1_a} \qquad (LP\_MinPEST).$$
$$\sum_{n=1}^{N} \mu_n \overline{P_n} \leq \overline{\sigma} + \overline{P_a}$$
$$\sum_{n=1}^{N} \mu_n = 1$$
$$\mu_n \geq 0, \forall n \in N$$

In LP_MinPEST, $\overline{\sigma}$ gives the optimal decrease in the pesticides cost. For an efficient farm, we have $\overline{\sigma} = 0 \Leftrightarrow \sigma = 1$, and for an inefficient one: $\overline{\sigma} < 0 \Leftrightarrow 0 < \sigma < 1$.

2.2.3 Various performance indicators and opportunity cost analysis

Our two stages analysis first assesses performance gaps between actual farm situations and benchmarks across three objectives, using metrics like revenue, protein yield, and gross margin per hectare. In the second stage, we compare three optimal scenarios—free of technical inefficiency—on these metrics. Assuming profitability as the primary goal, we calculate the opportunity costs of choosing alternatives, such as maximizing protein production or minimizing pesticide costs, against this goal.

Revenue performance indicators

In LP_MaxPROF, where the objective is profitability maximization, revenue is a component of the objective function. The optimal solution of this program gives the highest possible ratio of revenue to cost. Additionally, both protein production and protein price[10] are treated as variables to optimize and are thus linked to specific efficiency scores.

In LP_MaxPROT, the focus is on maximizing protein production for each farm, without direct consideration of protein prices. Revenue in this scenario is calculated by multiplying the optimal protein production by the price associated with the farms comprising the benchmark.

[10] As mentioned before, protein prices can vary from one farm to another due either to a specific sales strategy or to a distinct crop mix.

In LP_MinPEST, the objective is to minimize pesticide costs. Here, revenue is regarded as a constraint and its components are not directly maximized. Protein production and prices are determined in this program based on their respective levels associated with the farms comprising the benchmark.

Crop diversification indicator

All three scenarios aim to eliminate technical farm inefficiencies through various methods, such as Integrated Pest Management techniques—selecting resistant cultivars, companion planting, and using biocontrol (Barzman et al., 2015). However, crop diversification also enhances farm profitability and ecosystem services like soil and water quality (Beillouin et al., 2020; Nilsson et al., 2022; Tamburini et al., 2020).

Crop diversification can be seen as the distribution of different crop areas in the total arable land. Total arable land has been treated differently in the three scenarios. In the first two scenarios, the total land surface can be adjusted downward or kept constant to improve efficiency. In the pesticide scenario, arable land is kept constant to ensure that the model implicitly reduces pesticide intensity. Crop diversification in agricultural space is assessed using the Herfindahl-Hirschmann Index (HHI), a widely used measure of market concentration and competition. Denoting $s_c = \frac{AL_c}{AL}$, the share of crop *c* in the total arable land, we compute $HHI = \sum_{c=1}^{8} s_c^2$. The more diversified the crop mix, the closer the HHI is to 0. Conversely, a farm with only one crop type will observe an HHI=1.

Cost performance indicators

Costs are disaggregated into two components: intermediate consumption without pesticides (ICWP) costs and pesticide costs (P). In LP_MaxPROF, costs are one of the components of the objective function (at the denominator in the arithmetic specification). The benchmark characterization enables the derivation of the ICWP and P of the "optimal" intermediate consumption (IC). Indeed, substitution effects between these two components are possible and of interest to study. For instance, reducing pesticide use might prompt farmers to increase mechanical weeding, leading to higher energy consumption, or alternatively to decrease fertilizers (that tend to favor diseases and weeds), leading to lower fertilizer costs.

In LP_MaxPROT, intermediate consumption (IC) serves as a constraint. The resulting cost components are obtained from the reference farms forming the benchmark. Here, too, substitution effects between the two components of IC are conceivable.

Finally in LP_MinPEST, ICWP is not a constraint, and its performance level is determined from the farms comprising the benchmark. It's worth noting that in this scenario too, there may be substitution or complementarity effects between ICWP and P.

Profitability and gross margin per ha performance indicators

The profitability ratio indicates the farm's relative capability to convert one euro of intermediate consumption into crop related revenue. This analysis extends to the gross margin per ha, defined as the difference between revenue and intermediate consumption expressed with regard to the arable land.

In LP_MaxPROF, we establish the optimal level of profitability, from which we derive associated revenue and cost levels to subsequently calculate the optimal gross margin per ha. Previously, we outlined methods for determining revenue and cost performances in LP_MaxPROT and LP_MinPEST. These variables enable us to infer the profitability ratio and associated gross margin for these two scenarios.

Opportunity cost analysis

The three scenarios studied so far all represent efficient production situations on the production frontier. As it can be expected, each of these scenarios represents an improvement in profitability and gross margin per ha compared to the observed situation. However, reaching a specific scenario will entail different types of adjustments in terms of crop choices, crop valorization and cost management. It is reasonable to believe that, if farmers are committed to reduce inefficiencies, they would probably do so in the direction of reaching the maximum profitability. Consequently, to align farming practices with alternative scenarios, farmers might experience a reduction in gross margin per ha. The difference between the gross margin attainable in any of the alternative scenarios and the gross margin achievable in the Max PROF scenario delineates the opportunity cost associated with the alternative scenario. This opportunity cost can then be explored into its two components, namely revenue and cost.

Furthermore, in the case of the Max PROT scenario, we quantify the relative impact of a 1% increase in protein yield on the percentage change in gross margin per ha. By denoting the gross margin per ha as MRGN and protein yield as YLD, and utilizing the scenario employed for computing the respective variable as a subscript, this measure is obtained as follows:

$$\epsilon_{MRGN/YLD} = \frac{\frac{MRGN_{MaxPROT}}{MRGN_{MaxPROF}} - 1}{\frac{YLD_{MaxPROT}}{YLD_{MaxPROF}} - 1} \quad (16).$$

Another indicator of interest is the % change of pesticide cost per ha (PHa) due to a 1% increase in the protein yield between the two scenarios considered, as in the equation (17) below.

$$\epsilon_{Pest/YLD} = \frac{\frac{PHa_{MaxPROT}}{PHa_{MaxPROF}} - 1}{\frac{YLD_{MaxPROT}}{YLD_{MaxPROF}} - 1} \quad (17).$$

In the case of the pesticide minimization scenario, we can estimate the relative impact of 1% decrease in the pesticide cost per ha on the percentage change in the gross margin per ha by:

$$\epsilon_{MRGN/Pest} = \frac{\frac{MRGN_{MinPEST}}{MRGN_{MaxPROF}} - 1}{\frac{PHa_{MinPEST}}{PHa_{MaxPROF}} - 1} \quad (18).$$

In this case too, we can compute the % change in the protein yield due to a 1% decrease in the pesticide cost per ha as follows:

$$\epsilon_{YLD/Pest} = \frac{\frac{YLD_{MinPEST}}{YLD_{MaxPROF}} - 1}{\frac{PHa_{MinPEST}}{PHa_{MaxPROF}} - 1} \quad (19).$$

In the following, we explore a method to ensure that farmers maintain the same level of gross margin per ha under a pesticide reduction policy as they would by prioritizing profitability maximization. Essentially, we are looking for a strategy that incentivizes farmers to shift away from their usual goal of maximizing profitability and instead adopt measures to reduce pesticide use. The proposed mechanism involves increasing protein prices for concerned farmers, allowing them to compensate for their potential loss in revenue. By adopting a label that effectively communicates a farmer's commitment to best practices in pesticide reduction, these farmers could potentially negotiate higher prices to cover their opportunity costs. For a given level of achievable intermediate costs per ha in the pesticide minimization scenario ($ICHa_{MinPest}$), we calculate the average revenue per ha, R*, assuming it compensates for the gross margin reduction in a scenario where pesticide use is minimized.

$$\begin{aligned} &MRGN_{MaxPROF} = MRGN_{MinPEST} \iff \\ &MRGN_{MaxPROF} = R^* - ICHa_{MinPEST} \iff \\ &R^* = MRGN_{MaxPROF} + ICHa_{MinPEST} \end{aligned} \quad (20).$$

Then, for a given yield obtained in this scenario, we deduce the associated protein price denoted pp^* by:

$$pp^* = \frac{R^*}{YLD_{MinPEST}} \quad (21).$$

Thanks to the above pesticide-reduction compensating price, we compute its % change when, departing from a profitability maximization scenario, the pesticide cost per ha decrease by 1% as:

$$\epsilon_{pp^*/Pest} = \frac{\frac{pp^*}{pp_{MaxPROF}} - 1}{\frac{PHa_{MinPEST}}{PHa_{MaxPROF}} - 1} \quad (22).$$

3. Results and discussion

3.1 Performance analysis in the three scenarios with regards to the observed situation

3.1.1. Revenue performance

The first two scenarios, focused on profitability maximization (Max PROF) and protein production maximization (Max PROT), provide an increase in the protein yield by 5% and 10%, respectively (Figure 2). This increase goes hand in hand with a 4% improvement in protein prices in the scenario Max PROF while the protein price remains unchanged in scenario Max PROT, suggesting that protein yields and prices do not appear to be correlated in this context. Only the scenario focused on minimizing pesticide use (Min PEST) results in a slight decrease in the protein yield (-2%). Nevertheless, this protein is better valued on the market, with a price increase of +5%. Therefore, in this scenario, the protein yield is negatively correlated with the protein price, most likely due to a shift in the crop mix in favor of higher valued products, such as maize and sunflower (see Figure 4.d for the optimal crop mix in this scenario as well as the Figure B in the Appendix for the per crop protein prices).

The combined effect of protein yield and price leads to a positive impact on farmers' crop revenue in all three scenarios. Even in Scenario Min PEST, where associated protein yields decrease, the potential for revenue increase remains positive, at 3%.

Crop yield increases for each crop in both the Max PROF and Max PROT scenarios (Figure 3). However, the reduction in pesticide intensity in the Min PEST scenario leads to lower crop yield improvements than in the previous two scenarios. Moreover, for some crops such as wheat, winter barley, and rapeseed, potential yields even slightly decrease. This decrease in crop yield could be partly related to incomplete control of weeds, diseases or pathogens, but also to technical options of farmers wishing to decrease the reliance on pesticide (e.g., choice of cultivars based on resistance to diseases rather than on yielding potential, delay in cereal sowing to escape weeds and diseases associated to moderate fertilization, see for example Lechenet et al., 2016).

Figure 2. Variation in protein yield and price and its impact on farms' revenue per ha in each scenario compared to the observed situation

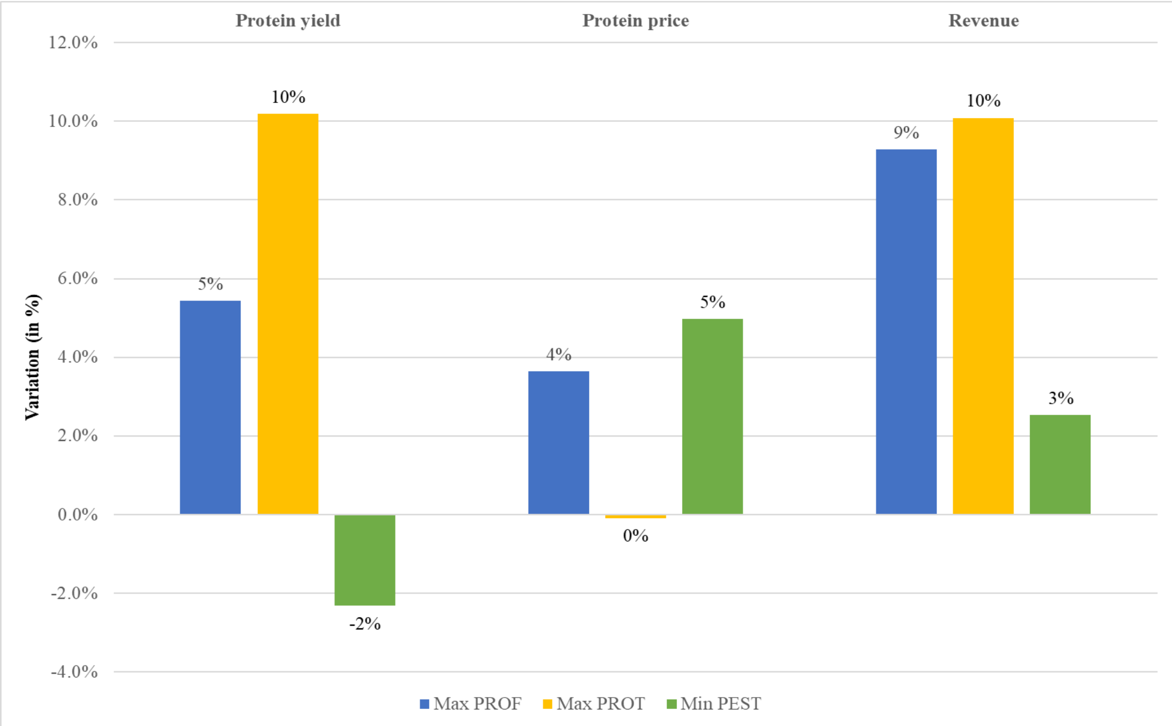


Figure 3. Variation in yields per crop, for the entire sample and the entire period 1991-2017, in each scenario, compared to the observed situation

3.1.2. Variation in crop areas and crop diversification index

The optimal total crop area decreases by -16 % in the Max PROF scenario, compared to the observed level, indicating that smaller-sized farms yield higher profitability per ha than larger ones (Table 2). Conversely, in the Max PROT scenario, the optimal total crop area remains almost unchanged, with a marginal difference of -1% from the observed level. Lastly, in the pesticide cost minimization scenario, our objective is to reduce pesticide intensity rather than alter total crop area. Therefore, we maintain the total crop area unchanged, focusing instead on decreasing pesticide use per ha.

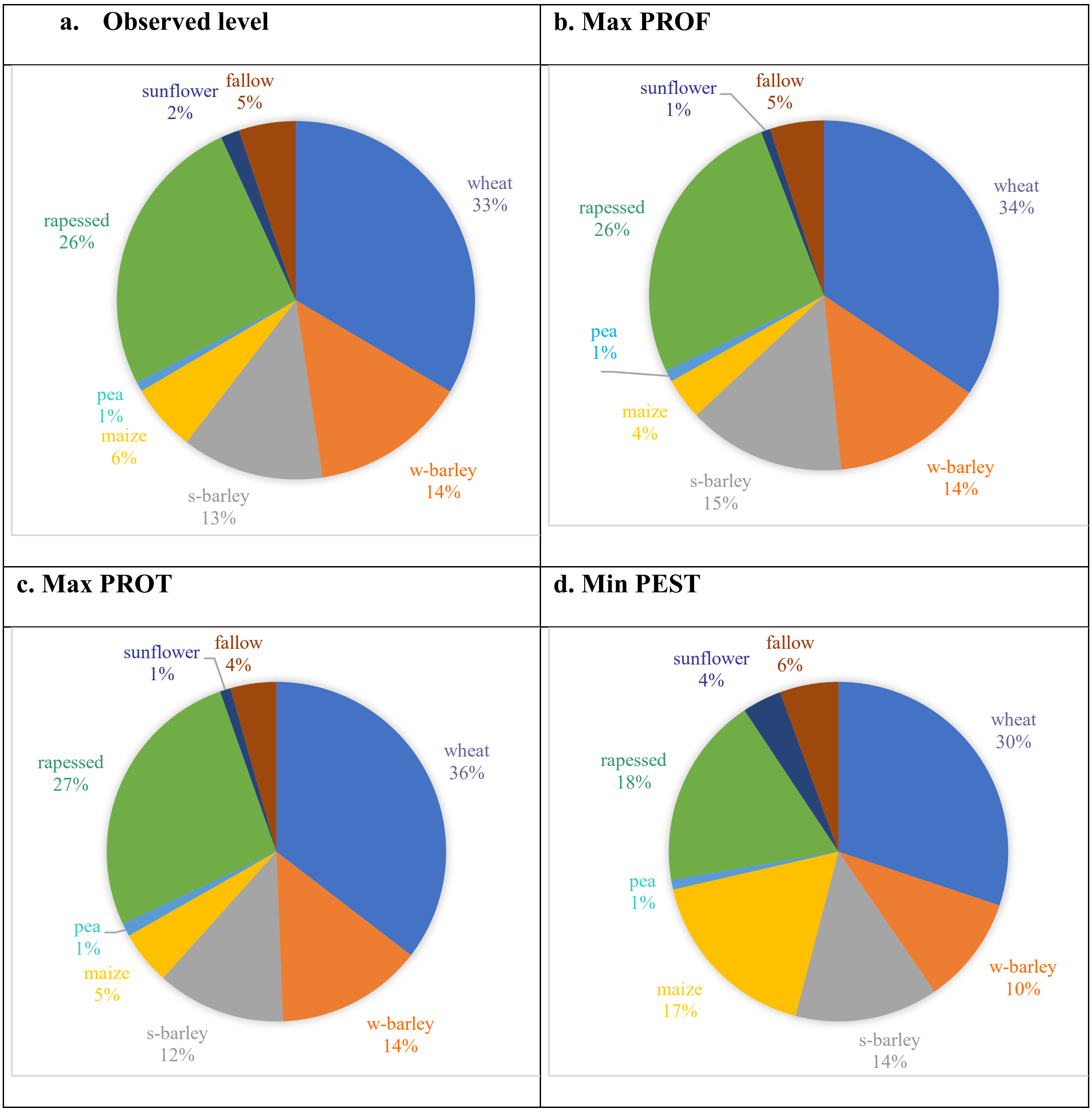
Table 2. Impact of each scenario on the evolution of the whole sample total crop area and the average per farm for the entire period (in ha)

Situation	Global (ha)[1]	Average per farm (ha)	Variation with regard to the observed in %
Observed	509,887	176	/
Max PROF	426,707	147	-16%
Max PROT	504,466	174	-1%
Min PEST	509,887	176	0%

(1): the surfaces are computed as the cumulated total arable land surface for the entire period analyzed.

Scenarios Max PROF and Max PROT do not have a substantial impact on the distribution of area per crop (Figure 4). This suggests that the specialization in some crops such as wheat and rapeseed can be an effective way to maximize profitability or protein production according to our sample of farms, when pesticide reduction is not a concern. It is surprising that the objective of maximizing the production of plant proteins does not lead to an increase in the share of protein-rich legume crops. This result might be related to the farm sample in the Meuse district, that includes very few legume crops, hence leaving little opportunity to have legume crops in benchmark farms, even in this scenario Max PROT. In the third scenario, the minimization of pesticide cost leads to a slight decrease in wheat (from 33% to 30%), winter barley (from 14% to 10%), and rapeseed (from 26% to 18%). In contrast, the shares of maize, sunflower and spring barley increase. In a study on pesticide use in France, Guinet et al. (2023) showed that rapeseed, winter wheat and winter barley required higher pesticide inputs compared to sunflower, maize and spring barley. Adjusting the share of crops in favor of those crops requiring less pesticides contributes to minimize pesticides in the third scenario.

Figure 4. Evolution of crop distribution



Related to these results, it is interesting to study the HHI index for crop diversification in each scenario. In Table 3 we notice that the HHI remains stable in the Max PROF and Max PROT scenarios compared to the observed situation. This prompts the idea that higher yields obtained for these scenarios are not associated with crop diversification (Figure 4 above). Instead, they can be associated to a better technical efficiency (e.g., improved nitrogen use efficiency due to better synchronization between crop nitrogen requirements and fertilizer nitrogen inputs). However, in the Min Pest scenario, the HHI is lower compared to the observed situation due to crop rotation diversification (see Figure 4 above).

Table 3. HHI index for crop diversification at the global scale over the period 1991-2017

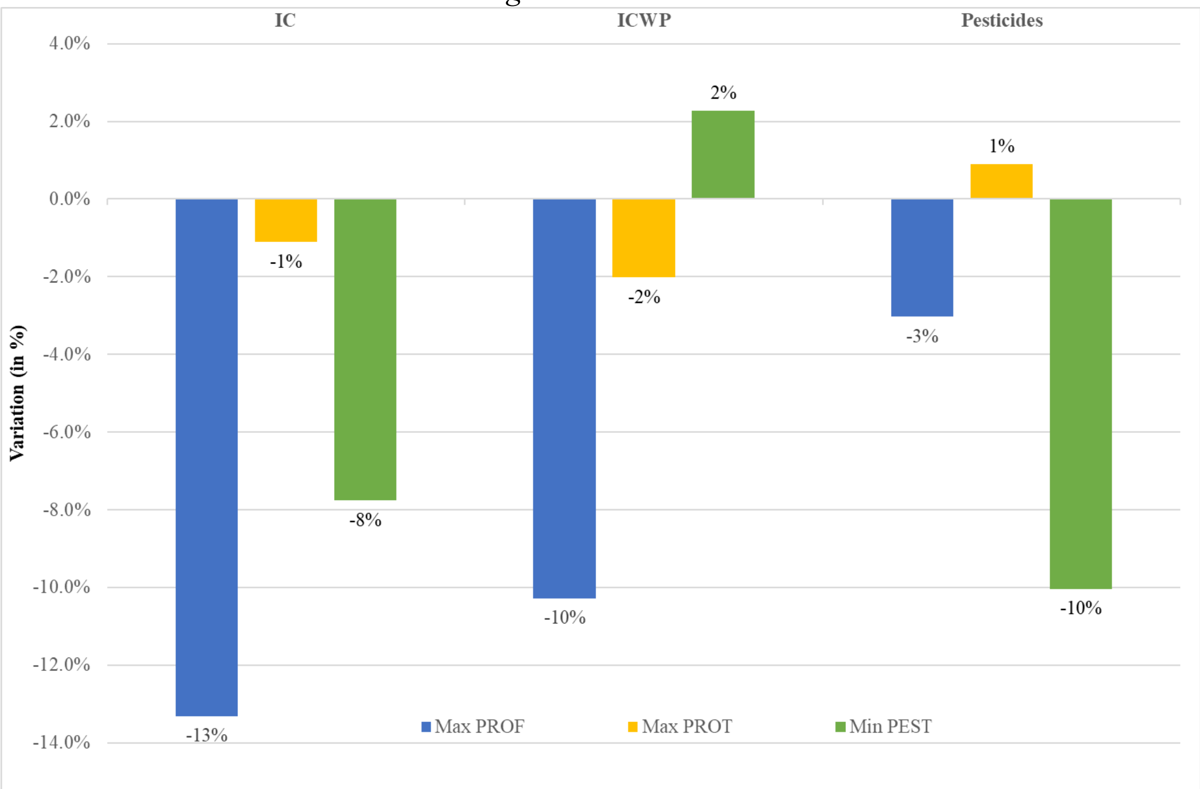
Observed situation	Max PROF	Max PROT	Min PEST
0.222	**0.232**	**0.236**	**0.188**

3.1.2. Cost performance

Projecting farms onto the benchmark enables a decrease in total intermediate consumption of 13 % in the Max PROF scenario and 8 % in the Min PEST scenario (Figure 5). Conversely, there is no notable decrease in intermediate consumption in the Max PROT scenario (-1%).

In Figure 5, the percentage changes in each component are obtained as variations with regards to the intermediate consumption (IC). The ICWP component decreases by -10% for the Max PROF scenario and -2% for the Max PROT scenario. However, in the Min PEST scenario, the associated ICWP increases above their observed level by 2%. This indicates a substitution effect in this scenario between the decrease in pesticide use and the increase in other intermediate consumption. In the Min PEST scenario, as expected, the decrease in the pesticide cost with regards to the intermediate consumption is the most notable one, -10% whereas in the Max PROF scenario, this reduction is only -3%. However, the objective of maximizing protein production appears to be incompatible with reducing pesticide intensity, as we observe a slight increase in pesticide costs in the total intermediate consumption of +1%.

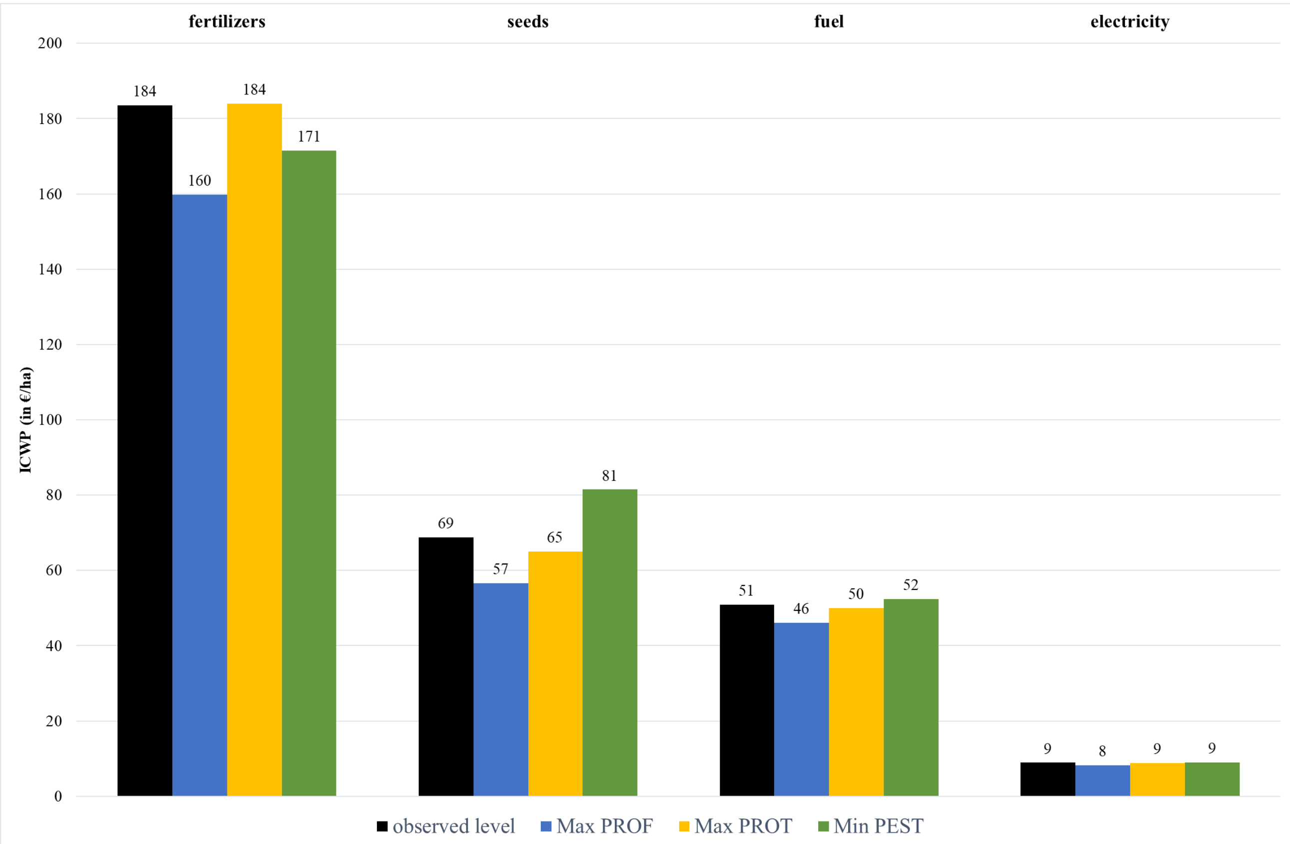
Figure 5. Potential variation of intermediate consumptions per ha and its components, ICWP and pesticide cost (in % of the observed total intermediate consumption level) for each scenario with regards to the observed situation



Compared to the observed pesticide intensity, the Min PEST scenario decreases pesticide intensity by -31%, the Max PROF scenario decreases it by -9% , while this indicator increases in the Max PROT scenario by 3%.

Furthermore, we explored the evolution of the various components of ICWP related to crop activity (Figure 6). All costs decrease in the Max PROF scenario. In the Max PROT scenario, expenses generally remain constant, except for seed costs, which marginally decrease. In the Min PEST scenario, the reduction in pesticide use is combined with a decrease in fertilizer costs, while seed costs increase. There is no remarkable impact on fuel while electricity cost increased slightly in this scenario. Improved cost efficiency in each scenario can be achieved through a variety of strategies. For instance, in the Max PROF scenario, where crop distribution remains largely unchanged (Figure 4), fertilizer use efficiency may has been improved thanks to timely spreading, fractioned fertilization and the use of decision-support tools. In contrast, the Min PEST scenario demonstrates how crop rotation diversification could lead to reduced fertilization. Figure 4 indicates for this scenario an increase in crops that require less nitrogen, such as sunflower and fallow, as opposed to more demanding crops like rapeseed or winter cereals. Additionally, in the Min PEST scenario, the presence of more spring and summer crops (spring barley, maize, sunflower) may account for higher seed costs, as illustrated in Figure 6. This increase could be due to the introduction of cover crops between two cash crops.

Figure 6. Main components of ICWP in €$_{2010}$/ha

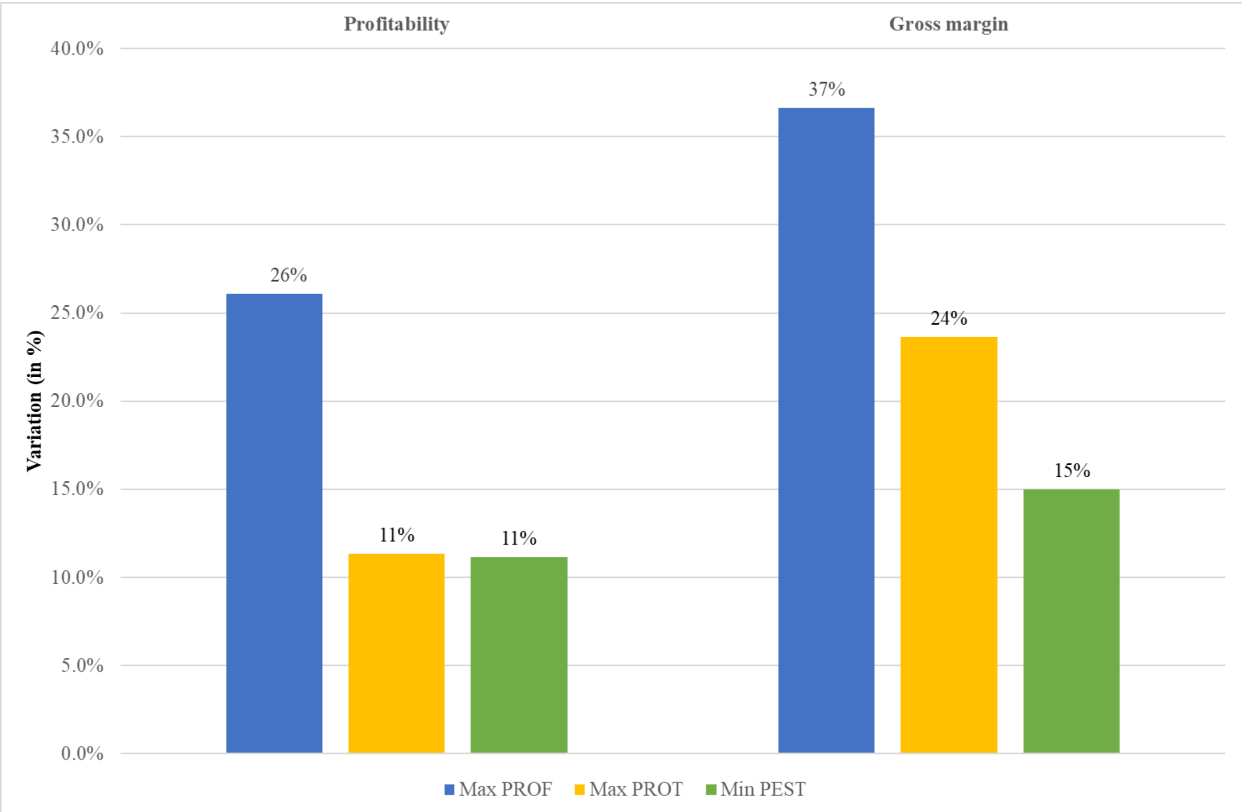


Considering that the estimations aimed at achieving minimum pesticide use (LP_MinPEST) did not directly account for the other resources required for crop production (such as other surfaces, labor, and equipment), it is intriguing to identify the levels that would be attained if all farms had reached their benchmarks. From this perspective, the farms would not need to alter their other activities, as the area used for other activities (OS) remains consistent with the observed area for the entire sample and throughout the entire period (+0.1%). Aligning with minimal pesticide use does not imply a change in capital depreciation cost either (-0.3%). However, we do observe a substitution effect regarding the total labor used at the farm level, which would need to increase by 12% to minimize pesticide use. Potentially, efficient practices compatible with the Min PEST scenario require in general a higher quantity of labor dedicated to implementing alternative practices for managing pests, for example, mechanical weeding. These practices also involve a higher fuel consumption, which is slightly observed in Figure 7.

3.1.3. Profitability and gross margin performances

Unsurprisingly, compared to the observed situation, the highest profitability ratio increase is obtained in the Max PROF scenario, with +26%, against +11% in both Max PROT and Min PEST scenarios (Figure 7). In the scenario minimizing pesticide, despite the decrease in protein yields described above, profitability is increased thanks to an increase in the protein price and a simultaneous decrease in intermediate consumption (cf. Figures 2 and 5, respectively). All three scenarios lead to a positive impact on the gross margin.

Figure 7. Profitability ratio and gross margin (per ha) evolutions compared to the observed levels, in the three scenarios.



3.2. Opportunity cost analysis and the tradeoffs between the three scenarios

This section analyses the tradeoffs between the profitability maximization scenario, considered as the baseline, and either the protein maximization scenario or the pesticide minimization scenario. We assume that farmers' primary rationale is to increase profitability through an optimal allocation of resources. Given this assumption, the alternative scenarios may incur potential financial losses compared to the baseline, representing opportunity costs for the farmer.[11]

The baseline scenario, focused on profitability maximization, outperforms the alternative two scenarios in gross margin achievement, aligning with expectations (Figure 8). However, a detailed breakdown of this gross margin into revenue and costs unveils a more nuanced picture. Specifically, the profitability scenario attains the lowest intermediate consumption excluding pesticides at 295 $€_{2010}$/ha. In contrast, the pesticide minimization scenario achieves the expected outcome of the lowest pesticide cost at 113$€_{2010}$/ha. Notably, the highest revenue per ha is recorded in the protein maximization scenario, amounting to 1032 $€_{2010}$/ha.

Shifting on the production frontier from the target of maximizing profitability to the target of maximizing protein production would result in farmers earning an additional 8 $€_{2010}$/ha in revenue (1032$€_{2010}$ versus 1024$€_{2010}$, i.e., +0.7%, see Figure 8). This slight revenue increase is attributed to a positive quantity effect, with a roughly 4.5% increase in protein yield (30 kg/ha), offset by a 3.6% reduction in the market value of protein. However, this scenario also leads to increased intermediate consumption of 64 $€_{2010}$/ha, broken down into an additional 43 $€_{2010}$/ha for ICWP and a 21$€_{2010}$/ha increase in pesticide costs (Figure 9). Consequently, the net effect on gross margin per ha is a reduction of 55$€_{2010}$/ha. In relative terms, by applying equation (16), a 1% increase in protein yields due to the adoption of the Max PROT scenario over the Max PROF scenario would result in a 2.12% decrease in gross margin. This result suggests that promoting productivity-driven strategies does not always result in improved financial outcomes for farmers. Additionally, the elasticity of yield to pesticide cost per ha, as detailed in equation (17), is 3.01. This implies that a 1% increase in protein yields, from adopting the Max PROT scenario over the Max PROF scenario, leads to a 3.01% increase in pesticide intensity. The relatively high elasticity values for both gross margin and pesticide use to protein yield variation highlight the suboptimal economic and environmental sustainability of the Max PROT strategy.

Nevertheless, these results should be interpreted with caution. Indeed, the adaptation of agricultural strategies to enhance plant protein production are highly depending on the data available with current practices in the Meuse department where there are almost no legume crops. Consequently, the scenario evaluated here relies mainly on an intensification of inputs to maximize crop yields with rather low protein content. Another approach could be to increase the share of protein-rich legume crops, that do not need nitrogen fertilization. Such a scenario

[11] Nevertheless, it is worth reminding that the preceding sub-section has shown that the three benchmarks all lead to an improvement in the revenue and cost indicators compared to the observed situation (with one very minor exception, regarding pesticide cost in the protein maximization scenario which observed an increase of 5$€_{2010}$ per ha).

would probably produce very different results regarding intermediate consumption, that could decrease instead of increase as it is the case in the Max PROT scenario based on current practices in the Meuse department.

Giving up the target of maximizing profitability to set the target of minimizing pesticide inputs would correspond to a potential opportunity cost of 63 $€_{2010}$/ha (Figure 8). This 6.2% decrease in potential revenue is primarily attributed to a significant drop in protein yield by 7.4%, offset by a slight positive price effect of about 1.3% (Figure 9). In this scenario, the ICWP would increase by 65 $€_{2010}$/ha, while pesticide expenses would diminish by 36 $€_{2010}$/ha, resulting in an overall operational cost increase of 29 $€_{2010}$/ha. These combined factors would result in a net decline in potential gross margin per ha of 92 $€_{2010}$/ha (Figure 8), highlighting the potential economic implications of prioritizing pesticide cost reduction over profitability. In relative terms, a 1% decrease in pesticide cost due to the shift from the Max PROF scenario towards the Min PEST one, would result in a potential reduction of 0.66% in the gross margin (equation 18), and a 0.31% decrease in the protein yields (i.e. -2 kg of protein /ha, equation 19). The low elasticity values for both margin loss and protein yields to pesticide reductions suggest that pursuing policies for pesticide reduction could be economically viable and address protein sovereignty concerns.

Figure 8. Potential progression in gross margin and its components in each scenario

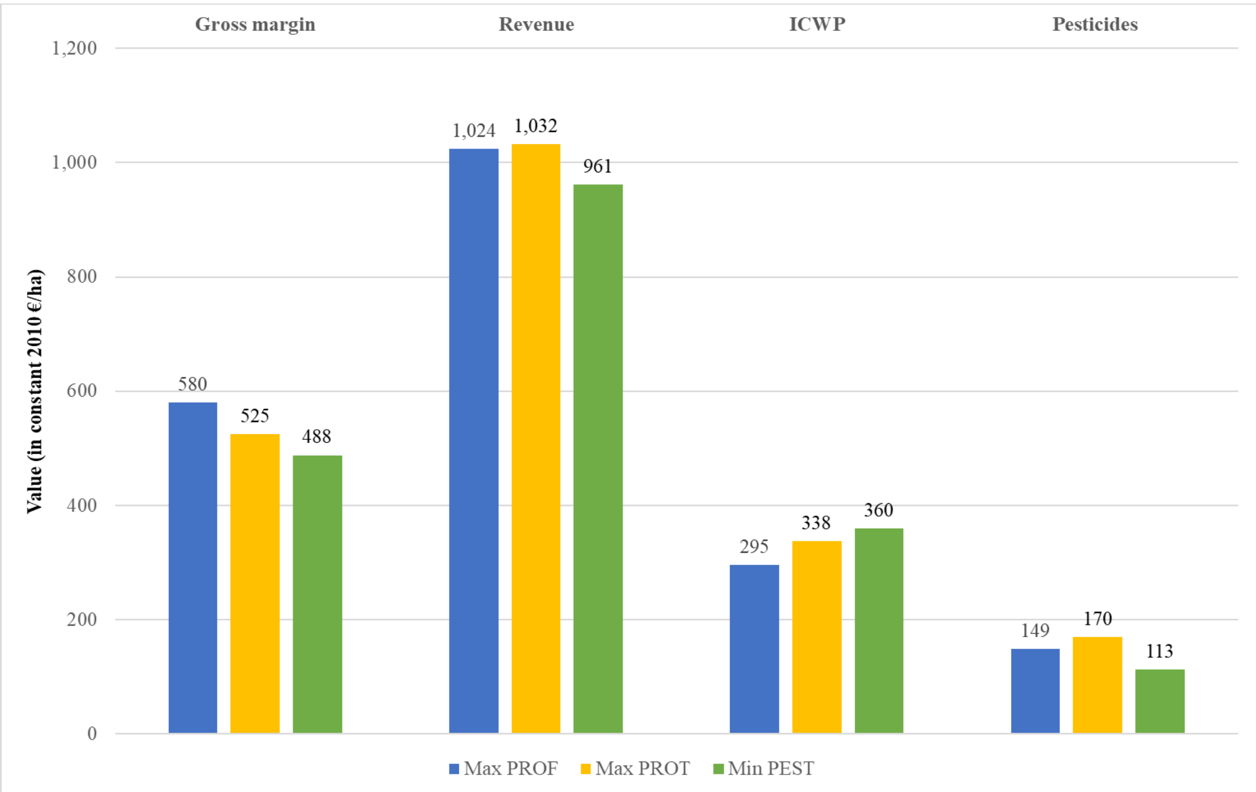
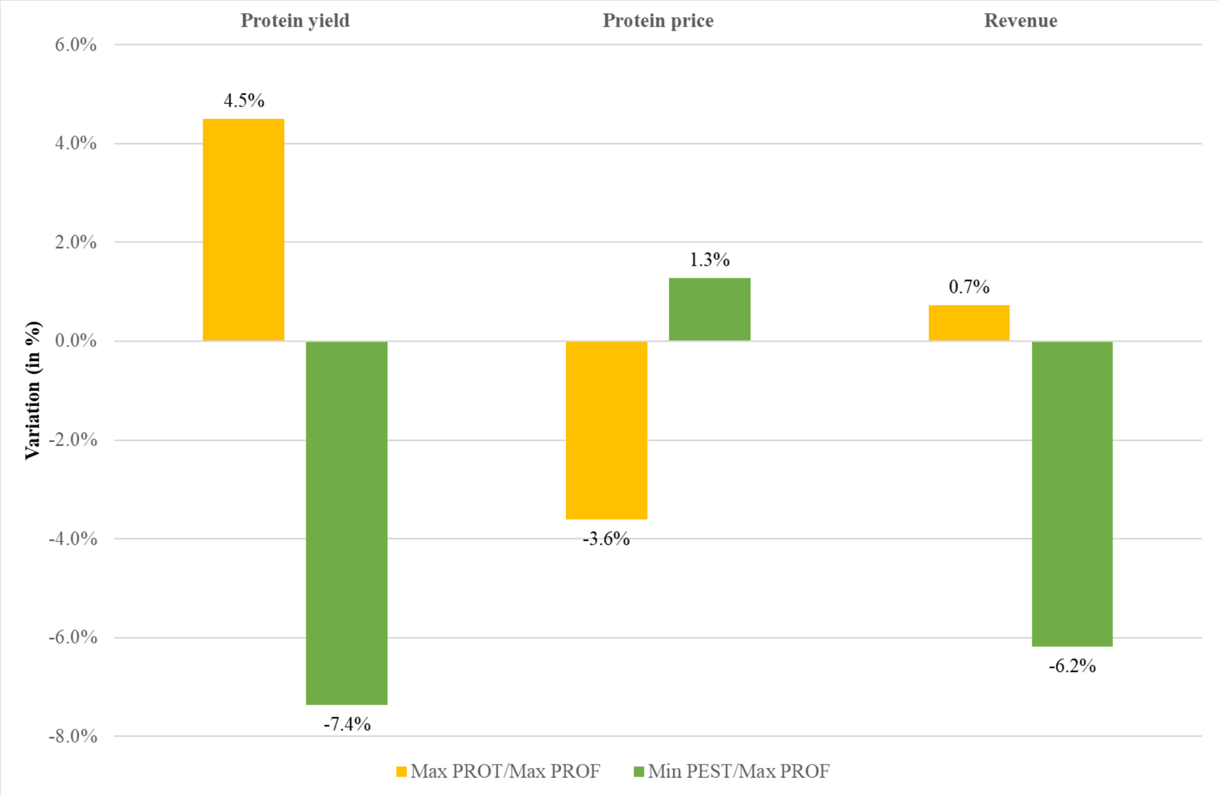


Figure 9. Variation in the revenue components between the different scenarios (in %)



The preceding analysis carries significant implications for agricultural policy, particularly concerning potential price compensations to farmers for their potential opportunity losses. The protein price resulting from the Min PEST scenario is 1.55€$_{2010}$. However, the price that would allow to offset the potential gross margin per ha loss relative to the profitability maximization scenario is 1.70€$_{2010}$ as computed in equation (21). In relative terms, decreasing pesticide intensity by 1% would result in a 0.45% increase in the plant protein price (equation 22), indicating a relatively low opportunity costs for downstream clients.

One possible approach for promoting farming practices to reduce pesticide use involves holding downstream partners (such as supermarkets, agri-food industries, and consumers) accountable by proposing a price increase. This increase would be enabled by full disclosure regarding pesticide use and information provided to consumers, for instance, through a label. Such an adjustment would support farmers engaged in pesticide-reduction practices to reach the potential maximum margins corresponding to the profitability scenario. Variations in the final price paid by consumers could occur based on price negotiation agreements in the agro-industrial sector and could be lower than the necessary 11% increase of prices paid to farmers that would make the target of minimizing pesticide input as profitable as the target of maximizing the profitability (and on average more profitable than the current observed systems, which is an important incentive for change).

4. Conclusion

In our study, we examined the interactions among profitability, protein supply, and pesticide use on arable farms in France's Meuse department. We considered three scenarios—maximizing profitability, enhancing protein production, and reducing pesticide use—to assess the impact of adapting farming practices. Our findings suggest that from a profitability standpoint, farmers would benefit in any scenario. However, aligning all department farms to the most profitable or protein-enhancing practices would involve improving crop and farm management without diversifying crops. The highest protein yields are achieved with intensive input use, particularly pesticides. Conversely, reducing pesticide use would necessitate increased crop diversification. A strategy combining reduced pesticide use with boosted plant protein production would likely involve a shift towards more legume crops, reducing nitrogen fertilization needs. Currently, this legume-based strategy remains unexplored in the studied region.

Comparing the profitability maximization scenario with alternatives of protein maximization and pesticide minimization revealed potential trade-offs. On one hand, the suppression of all inefficiencies within a strategy of protein maximizing by intensifying inputs would result in opportunity costs of 55 €$_{2010}$/ha compared to the suppression of inefficiencies within a strategy of profitability maximization. Moreover, on the frontier of efficient systems, a 1% increase in protein production leads to a decrease of the gross margin per ha by 2.1% and requires a 3% increase in pesticide inputs. On the other hand, the suppression of inefficiencies within a strategy of pesticide minimization compared to a suppression of inefficiencies through a profitability maximization objective would result in opportunity costs of 92 €$_{2010}$/ha. Thus, on the frontier of efficient systems, a 1% decrease in pesticide inputs leads to a decrease in the gross margin per ha by 0.66%, and a decrease in protein production by 0.31%.

This study first suggests that the opportunity costs of minimizing pesticides could be offset by higher market prices, supported by the inelasticity of plant protein prices and consumer willingness to pay more for perceived quality. Additionally, constructive intra-industry negotiations could lead to better pricing for farmers adopting these practices, aligning economic incentives with environmental sustainability. Secondly, maximizing yields, often seen as beneficial, actually leads to significant margin losses compared to focusing on profitability. Thirdly, in the Meuse department, compensating for the costs of maximizing protein through market prices is challenging due to consumer reluctance, especially when higher yields involve more pesticides.

However, this study focuses on farms with limited diversity in management strategies, particularly in legume production. Introducing legumes could drastically alter farm performance, enhancing protein self-sufficiency and food sovereignty. As sustainable agriculture requires significant operational redesign, extending this analysis to more innovative farms could validate our findings across diverse agricultural models.

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Appendix

Table A. Number of farms observed per year in this study

Year	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**
Obs.	92	132	115	124	155	165	167	160	144	118	118	114	106	30
Year	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**Total**
Obs.	64	71	107	117	99	133	118	101	88	80	71	59	52	**2900**

Figure B. Distribution of crop protein prices expressed in constant €$_{2010}$/Kg over the period 1991-2017