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RESEARCH ARTICLE

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The impact of alternative feeding strategies on total factor productivity growth of pig farming: Empirical evidence from EU countries

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Abstract

Aim of study: To investigate the impact of adopting new feeding precision technology on pig production.

Area of study: Four EU countries (Germany, France, Poland and Spain) during the period 2010–2015.

Material and methods: The Färe-Primont index was used to estimate total factor productivity change and its components, technological change and efficiency change.

Main results: German, French and Spanish farms experienced total factor productivity (TFP) progress, while Polish farms did not for both feeding strategies. Our empirical findings suggest a high impact on the productivity of ad libitum feeding technique compared to the restricted one for all countries.

Research highlights: Precision feeding strategies provide another avenue to more sustainable livestock production and further evidence that implementing individual ad libitum feeding systems for pigs could enhance farm's productivity

Additional key words: data envelopment analysis; productivity; färe-primont index; feeding technologies; pig farms.

Abbreviations used: CAP (Common Agricultural Policy); EU (European Union); FADN (Farm Accountancy Data Network); TFP (Total Factor Productivity); TFPE (Total Factor Productivity Efficiency)

Authors' contributions: Conceived and designed the research; wrote the paper: AAS, BG, JHCM and JMG. Analyzed and interpreted the data: AAS and BG. All authors read and approved the final manuscript.

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Introduction

Given the expectation that the world population would reach 9.7 billion by 2050, food demand will grow equally leading to overutilization of natural resources. Indeed, agricultural practices, especially those used in modern intensive agricultural systems, are increasingly being recognized by their negative environmental impacts. It is expected that a significant proportion of the projected increase in global food demand will come from livestock production (Thornton, 2010). In this context, the importance of productivity growth in the agricultural sector relies on ensuring a sufficient rapid growth of output to satisfy the increasing demands for agro-food products by the society.

Feeding costs represent the largest proportion of the total production costs in pig farming (Woyengo *et al.*, 2014). The feeding strategy adopted by farmers has important implications for economic performance, technological innovation and the overall input use in the pig production (Gaines *et al.*, 2012). Nowadays, modern feeding techniques are defined at group level and the nutrient requirements linked to growth stage is managed using feeding curves that adjust the food ration during either biphase or multiphase feeding strategies (Niemi *et al.*, 2010). However, the pig's ability to convert nutrients into body tissues can vary among individual pigs depending on environmental and genetic influences (Pomar *et al.*, 2003). Considering that traditional feeding strategies do not allow for differences in nutritional requirements between individual animals, these strategies cannot optimize the efficiency of individual animals and hence the efficient use of feed on the farm (Andretta *et al.*, 2014).

Improving livestock production sustainability can be achieved by increasing the overall feed efficiency through optimizing feed management practices. The concept of precision farming mainly relies on the existence of variability in animal performance (Wathes *et al.*, 2008). It is well recognized that real-time monitoring of animals' growth is a necessary part of efficient production strategies (Nasirahmadi *et al.*, 2017). Precision feeding involves the use of feeding techniques that allow delivering the right dietary amount of feed with the right quality to be given to each animal in the herd at the right time (Pomar *et al.*, 2009). Improving feed efficiency through optimized feeding strategies is key to boost productivity growth and limit livestock production's environmental footprint. Improvement in agricultural productivity is prerequisite for economic development since it allows allocating resources such as labor and capital to expand other economic sectors (O'Donnell, 2010). Total factor productivity (TFP) indices measure the effect of improvements in technology obtained from research and development as well as investments in infrastructure such as irrigation, roads and electricity (Mukherjee & Kuroda, 2003). High TFP level leads not only to reach higher output from adopting technology and efficient utilization of resources but also contributes to enhance socio economic development and the sustainability of ecosystems (De Miguel *et al.*, 2015). It is thus relevant to investigate the impact of different feeding precision strategies through estimating TFP change, using farm-level data during the period 2010–2015 for pig production systems.

Improving farms' productivity through the adoption of new technologies would help farmers reduce production costs and ensure the economic viability and sustainability of their holdings (Finger *et al.*, 2019). Several studies proposed alternative theoretical models of technology adoption to assess the impact of adopting new technology on productivity of firms. After adopting new equipment, productivity growth could slow down at the beginning and then later rise depending on the period of technology learning (Klenow, 1998). Greenwood *et al.* (1997) suggested that investments in new equipment could be considered as a quantitatively important source of technology adoption. Moreover, the literature on adjustment costs and on firm-level investment reveals that accounting profit increases more strongly to past investments than to more recent investment (Pakes & Griliches, 1984).

Previous research studies explored the productivity growth of pig farms in European countries. For the period 1980-1996, Gardebroek & Lansink (2003) reported that specialized pig breeding farms with high productivity growth have more buildings and machinery than farms with low TFP. In another study, Kleinhanss (2013) indicated a deterioration of TFP of German farms specialized in piglet production, while no TFP change for pig fattening farms has been observed for the 2000-2010 period. In contrast, Piot-Lepetit & Moing (2007) found a productivity increase in the French pig sector during 1996–2001, which was boosted by increased efficiency, before being driven by technological progress. Čechura *et al.* (2014) showed an increasing trend in TFP for pig farms among most European Union (EU) member states, with technological change being the main contributor to productivity growth.

Most studies that focused on the assessment of agricultural productivity growth have often used the Malmquist index. However, the latter does not satisfy the transitivity[1] property and can only be used to make reliable binary comparisons (*i.e.*, comparisons involving only two time periods). The Malmquist index has been criticized for not being multiplicatively accurate and, consequently, the ratio between an aggregate output index and an aggregate input index cannot be defined (O'Donnell, 2012, 2014). In addition to the above-mentioned shortcomings, another limitation of the Malmquist index is that it does not account for changes in the input/output mix (O'donnell, 2011). Taking into account the aforementioned limitations of the Malmquist index, our empirical study builds on the Färe-Primont index, which has its theoretical foundations in Färe & Primont (1995) and it satisfies the multiplicatively completeness property and the transitivity property (O'Donnell, 2011). In spite of the interesting features of this method, its use has been limited to a few empirical studies in the agricultural sector (Rahman & Salim, 2013; Baráth & Fertő, 2017; Dakpo *et al.*, 2019).

The objective of this article is to examine the impact of adopting feeding precision technology on pig production systems. Two alternative feeding techniques namely, the *ad libitum* and the restricted feeding strategies, are used for this purpose. Both strategies have been applied to the fattening cycle, the individual daily adjustment of the nutritional characteristics enabled optimization of the feed

[1] The transitivity property means that the overall impacts over time can be evaluated using sub-period results, for instance, The the productivity growth between t_1 and t_3 can be assessed through t_2. In other words, the transitivity property can be described by: $(t_1, t_3) = I(t_1, t_2) \times I(t_2, t_3)$, where $I(\cdot)$ is an index number. See Fried *et al.* (2008) for further details.

efficiency of pigs. The *ad libitum* strategy allows pigs to express their potential and permits collecting data concerning their behavior, while the restricted feeding strategy represents the classic condition of pig production during the fattening period in Europe.

Material and methods

The European pig sector

The EU is the world's second largest pork producer behind China with around 150 million pigs in 2018. Although the number of EU pig farms has diminished during the last decade, pig meat production has continued to grow, allowing the EU to reach self-sufficiency and to become the main exporter of pork products in the world. In 2018, The EU pig meat sector represents 8.5% of the overall EU-27 agricultural production, which is the largest share compared to other types of meat production (bovine, sheep and goats and poultry). During the same year, about 23.8 million tonnes of pig meat were produced, which represents 35% of the total EU meat output.

When we look at the situation within countries, the highest production of pig meat was observed in Germany (5.2 million tonnes), Spain (4.6 million tonnes), France (2.2 million tonnes) and Poland (1.9 million tonnes); these four countries combined represent more than 60% of the overall pig production of the EU (Eurostat, 2020).

If we analyze the structure of the pig meat sector, there are important differences across member states. While some countries (*e.g.* Romania) are characterized by small and diversified pig farming with one or two animals, there are countries (*e.g.* Germany and Spain) and regions with intensive production and high herd densities. It is true that the degree of vertical integration observed in the poultry industry is not seen in the EU pig sector, where up to three productive phases can be pointed out (breeding, transition and fattening). In Spain, the pig production sector is controlled by vertically integrated firms which supply inputs to farmers who are contracted to breed and fatten the pigs. There is also a high degree of integration of the slaughtering process. The EU pig sector is becoming more and more spatially concentrated. In France, this trend was driven by producer groups, marketing and technical cooperatives. Following the creation of these producer groups, small farms are disappearing gradually while pig farms of more than 100 animals have continued to grow (Larue and Latruffe, 2009). A distribution of total pig farms across countries is presented in Table 1. The table shows that the total number of farms is decreasing. This is compatible with the argument that small pig farms are disappearing and the productivity growth is supported by farms with large herd size. It is worth mentioning that more than half of the EU pig farms are located in Romania. Among the four countries considered in this study, the number of pigs per farm varies from 40.6 in Poland to 727.2 in France, while German and Spanish farms have an average stocking density of 584 and 466.8 pigs per farm, respectively (Eurostat, 2020).

In 1992, with the implementation of direct payments per hectare of specific crops and per head of specific livestock, the MacSharry Common Agricultural Policy (CAP) reform began a transition from commodity (price) support to producer (income) support. Although, the EU pig meat sector did not benefit much from the CAP subsidies (Willems *et al.*, 2016), some specific schemes have been used in few situations to support pig prices during crisis periods. For instance, in 2017, the European Commission has decided to allow CAP funds to be used to support Polish pig farmers who have been forced to abandon their activities due to African swine fever.

Methods

In being a useful tool to diagnose a firm's performance, assessment of productivity growth has drawn broad research interest. It is also important for policymakers who are interested in enhancing firms' competitiveness and promoting sustainable practices. Assessing the performance of pig producers at the country level can be carried out using a wide range of performance indicators. The Malmquist Index is one of the most commonly used approaches to measure TFP change over time. However, this method has been criticized for being not complete and

Table 1. A distribution of total number of farms across selected countries (by numbers and percentages to the EU)

	Germany		Spain		France		Poland	
	Farms	**%**	**Farms**	**%**	**Farms**	**%**	**Farms**	**%**
2005	88,680	2.31%	115,760	3.02%	41,890	1.09%	701,660	18.28%
2007	79,420	2.19%	108,160	2.98%	35,290	0.97%	664,020	18.31%
2010	60,100	2.07%	69,770	2.40%	24,450	0.84%	388,460	13.36%
2013	49,140	2.24%	51,770	2.36%	18,520	0.84%	278,400	12.69%

lead to biased estimates of efficiency change and technological change (O'Donnell, 2008, 2010). To overcome this shortcoming, O'Donnell (2014) proposed the Färe–Primont productivity index. Although this TFP index requires specific assumptions about the production technology (*e.g.*, return to scale, free disposability), it encompasses several advantages including multiplicative completeness and transitivity. The Färe-Primont index can thus be used for multi-temporal and multilateral comparisons (O'Donnell, 2012). Our methodological framework is built upon this recent innovative index to measure the productivity growth of pig producers for selected EU countries. In the following lines, we describe the assumptions that underline the production technology and the methods used to compute the total factor productivity change and its components.

The production technology can be specified as follows:

$$\Psi_t = \{(y^t, x^t): x^t \text{ can produce } y^t\}, \tag{1}$$

where a vector of input quantities $x \in \mathbb{R}_+^N$ is used to produce a vector of outputs quantities $y \in \mathbb{R}_+^M$. Following Färe & Primont (1995), we assume that Ψ_t verifies the usual axioms of the production theory including strong disposability of inputs and outputs, non-emptiness and no free lunch for $x \in \mathbb{R}_+^N$.

The corresponding output distance function of Ψ_t can be defined as:

$$D^O(x,y) = \inf_{\theta} \{ \theta > 0: (x,\frac{y}{\theta}) \in \Psi_t \tag{2.1}$$

Similarly, an input-oriented version of the distance function is defined as:

$$D^I(x,y) = \sup_{\lambda} \{ \lambda > 0: (\frac{x}{\lambda}, y) \in \Psi_t \tag{2.2}$$

These distance functions constitute the building blocks to construct our measure of TFP growth. The productivity growth is measured as the ratio of an output quantity index to an input quantity index (O'Donnell, 2010):

$$TFP_t = \frac{Y_t}{X_t} \tag{3}$$

where $Y_t = Y(y_t)$ is the aggregate level of outputs and $X_t = X(x_{nt})$ are the aggregated inputs. The aggregator functions $Y(.)$ and $X(.)$ that are based on the distance functions in (2.1) and (2.2) are non-negative, non-decreasing, linearly homogeneous and scalar-valued functions. The associated TFP that measures productivity change from t to t+1 is:

$$TFP_{t,t+1} = \frac{TFP_{t+1}}{TFP_t} = \frac{Y_{t+1}/X_{t+1}}{Y_t/X_t} \tag{4}$$

The TFP index in Eq. (4) can be further decomposed into several measures, technical change and efficiency change (O'Donnell, 2008). Specifically, the efficiency change (TFPE) captures the difference between an observed level of productivity and the maximal level of possible productivity. Thus, the efficiency component of TFP corresponds to:

$$TFPE_t = \frac{TFP_t}{TFP_t^*} \tag{5}$$

where $TFP_t^* = Y_t^*/X_t^*$ is the maximum possible TFP under the technology observed at a certain time period t. From Eq. (3), the TFP change between two periods of time t and t+1 is:

$$TFP_{t,t+1} = \frac{TFP_{t+1}}{TFP_t} = \frac{TFP_{t+1}^*}{TFP_t^*} \times \frac{TFPE_{t+1}}{TFPE_t} \tag{6}$$

where the term TFP_{t+1}^*/TFP_t^* measures the technical change, while the second one $TFPE_{t+1}/TFPE_t$ indicates the overall efficiency change component of productivity change. The TFPE can be further decomposed into three components: output-oriented technical efficiency change (OTE), output-oriented scale efficiency change (OSE) and residual mix efficiency change (RME).

$$TFPE_t = OTE_t \times OSE_t \times RME_t \tag{7}$$

Based on the above TFPE specifications, the TFPE change between t and t+1 can be expressed as follows:

$$TFPE_{t,t+1} = \frac{OTE_{t+1}}{OTE_t} \times \frac{OSE_{t+1}}{OSE_t} \times \frac{RME_{t+1}}{RME_t} \tag{8}$$

Using Eqs. (8) and (6), the Färe-Primont index of productivity change between period t and period t+1 can be decomposed as follows:

$$TFP_{t,t+1} = \frac{TFP_{t+1}^*}{TFP_t^*} \times \frac{OTE_{t+1}}{OTE_t} \times \frac{OSE_{t+1}}{OSE_t} \times \frac{RME_{t+1}}{RME_t} \tag{9}$$

Färe-Primont index requires the estimation of the underlying production frontiers, which can be derived by first solving the following linear programs:

$$D^O(x_0, y_0, t_0)^{-1} = \max_{\theta,\gamma}\{\theta: \theta y_0 \leq Y'\gamma; \quad X'\gamma \leq x_0; \gamma' = 1; \gamma \geq 0\} \tag{10}$$

$$D^I(x_0, y_0, t_0)^{-1} = \min_{\lambda,\gamma}\{\lambda: Y'\gamma \geq y_0; \quad \lambda x_0 \geq X'\gamma; \gamma' = 1; \gamma \geq 0\} \tag{11}$$

where X is a $J \times N$ matrix of observed inputs, Y is the $J \times K$ matrix of outputs, γ is the $J \times 1$ vector of intensity variable and the constraint γ'=1 assumes a variable return to scale (VRS) technology. The dual formulations of $D^O(x_0, y_0, t_0)^{-1}$ and $D^I(x_0, y_0, t_0)^{-1}$ can be presented as follows:

$$D^O(x_0, y_0, t_0)^{-1} = \min_{\omega,\rho,\varsigma}\{ x_0'\omega + \varsigma : X\omega - Y\rho + \varsigma \geq 0; \quad y_0'\rho = 1; \omega \geq 0; \rho \geq 0 \tag{12}$$

$$D^I(x_0, y_0, t_0)^{-1} = \max_{\mu,\nu,\xi}\{y_0'\mu + \xi : Y\mu - X\nu + \xi \leq 0; \\ x_0'\nu = 1; \mu \geq 0; \nu \geq 0\} \tag{13}$$

where ω, ρ and ς denote the shadow values associated with inputs, outputs and convexity constraint, respectively, in the output distance function. Similarly, μ, ν and ξ represent the same shadow values when computing the input distance function.

The first-order partial derivatives of the output and input distance can be viewed as revenue- and cost-deflated output and input shadow prices (Färe and Grosskopf, 1990) as:

$$p_0^* = \frac{\partial D^O(x_0, \tilde{y}_0, t_0)}{\partial \tilde{y}_0} = \frac{\tilde{y}_0'\rho}{x_0'\omega + \varsigma} \tag{14}$$

$$w_0^* = \frac{\partial D^I(x_0, \tilde{y}_0, t_0)}{\partial x_0'} = \frac{x_0'\nu}{\tilde{y}_0'\mu + \xi} \tag{15}$$

Using these shadow prices, the aggregated outputs and inputs can be computed as:

$$\tilde{Y}(\tilde{y}) = \tilde{y}'p_0^* \tag{16}$$

$$X(x) = x'w_0^* \tag{17}$$

Note that this estimation procedure relies on a balanced panel data. It is true that productivity growth can be calculated using an unbalanced panel, however, the index will be undefined for missing observations (Färe *et al.*, 1994). Furthermore, the use of unbalanced panel data is recommended when data availability is poor (Jin *et al.*, 2010), which is not our case. Moreover, some of the popular software options to compute these productivity indices cannot handle unbalanced panels. For instance, the popular DEAP software of (Coelli, 1996) explicitly requires a balanced panel. The same is required when computing productivity indices using the "productivity" package in R.

Data description

This study was limited to leading producers of pig meat in the European Union (*i.e.*, France, Germany, Poland, and Spain) representing almost 70% of the total production, respectively. Farm-level data were obtained from the Farm Accountancy Data Network (FADN) database and covered the period 2010-2015. Data are gathered by surveying a rotating sample of farms where farms do not stay in the sample for the whole period. FADN data include structural and accountancy data for farms and is often used to monitor the income and business activities of agricultural holdings in EU member states and allow evaluating the impact of the CAP. Data available include farm outputs, input use, and the financial and structural characteristics. Farms are selected based on revenues obtained from pig production. To ensure that pig production is the main farm output, farms whose pig output represents at least 70% of total farm income were selected[2]. This criterion allows obtaining a relatively homogeneous sample of farms.

The dataset is a balanced[3] panel that contains a total of 3402 observations. The choice of our variables is based on economic theory, our own experiences and is conforms to standard practice in the literature (especially Lansink & Reinhard, 2004; Latruffe *et al.*, 2013) . Output value includes deflated revenues from the production of piglets, fattening pigs and pork. Four input variables are considered in our analysis, namely capital, labour, feed and other inputs. Capital represents fixed inputs such as machinery, agricultural land and farm buildings expressed in constant prices. Paid and unpaid labour is expressed in hours. Feed consists of purchased feed, measured in terms of deflated values. Other inputs include other specific costs (*e.g.*, piglets and veterinary costs) and operating non-specific costs (*e.g.*, upkeep of machinery and buildings, energy costs, contract work, taxes and other dues, and other direct costs. Summary statistics of output and input variables are reported in Table 2.

Improving livestock production sustainability by increasing feed efficiency and by reducing the environmental impact of livestock farms requires building new management systems for precision farming. Therefore new precision feeding systems were developed within the feed-a-gene project. Precision feeding is implemented to: (1) measure and determine the requirements of each animal or group in real time; (2) provide to each animal or group a quantity of feed adjusted to their requirements. The developed precision feeding systems have been used for two feeding strategies (*ad libitum* and restricted feeding). In *ad libitum* feeding, the feed is available at all times, while in restricted feeding, refers to restricting the amount of feed while still ensuring nutritional requirements. Both feeding strategies are well-known (for individual or on a group basis); however, the present study deals with feeding techniques that combine new precision

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[2] A farm is considered specialized if more than 70% of overall farm revenues were obtained from pig production. Farms with a revenue from the pig production of less than 70% of the total income were excluded from the sample, this suggest that most mixed crop-livestock farms were not incorporated. In a setting where productivity growth and technical change is measured using a data envelopment analysis, the distinction between different farm types is important. A prerequisite for the use of DEA is that farms share the same technology.

[3] FADN database contains yearly data for a sample of EU farms that are representative of the EU farm population in term of regions, production specializations and economic size. However, while balancing our sample and concentrating on specialized pig farms and excluding less specialized farms, some observations very often are lost, thus limiting the extent to which the results can be generalised to the full farm population level.

Table 2. Descriptive statistics for the variables used in the analysis

	Ad libitum strategy				Restricted strategy			
	Mean	**St. Dev.**	**Min.**	**Max.**	**Mean**	**St. Dev.**	**Min.**	**Max.**
France 2010-2015 (498 observations)								
Output (€)	491,180.45	380,084.24	2,226.55	2,348,621.00	485,360.01	375,681.03	2,226.55	2,348,621.00
Feed (€)	298,897.49	218,651.31	23,973.36	1,509,500.40	309,766.09	225,761.07	25,799.01	1,509,500.40
Capital (€)	462,539.18	357,860.21	8,011.65	2,779,582.98	462,539.18	357,860.21	8,011.65	2,779,582.98
Labor (hours)	4,363.71	2,902.93	1,600.00	18,914.00	4,363.71	2,902.93	1,600.00	18,914.00
Other inputs (€)	28,686.65	18,382.29	3,356.65	137,282.18	28,686.65	18,382.29	3,356.65	137,282.18
Germany 2010-2015 (798 observations)								
Output (€)	292,842.59	204,019.72	29,209.07	1,837,165.00	289,464.05	202,091.19	29,209.07	1,837,165.00
Feed (€)	134,719.92	100,201.13	6,188.71	1,450,842.00	139,153.77	101,480.07	6,660.00	1,450,842.00
Capital (€)	821,670.55	627,167.14	14,575.06	5,727,478.09	821,670.55	627,167.14	14,575.06	5,727,478.09
Labor (hours)	4,298.60	3,187.00	906.00	46,299.00	4,298.60	3,187.00	906.00	46,299.00
Other inputs (€)	15,295.13	19,984.73	1,063.96	327,623.65	15,295.13	19,984.73	1,063.96	327,623.65
Poland 2010-2015 (1626 observations)								
Output (€)	121,102.49	197,314.15	1,273.23	2,049,288.35	119,684.42	195,064.21	1,254.71	2,049,288.35
Feed (€)	69,603.52	108,831.30	2,406.73	1,627,702.10	72,249.25	113,828.68	2,590.01	1,751,657.09
Capital (€)	370,708.26	358,794.48	39,903.02	3,140,039.52	370,708.26	358,794.48	39,903.02	3,140,039.52
Labor (hours)	5,049.04	3,689.35	1,143.20	35,000.00	5,049.04	3,689.35	1,143.20	35,000.00
Other inputs (€)	1,642.48	3,846.23	20.60	76,711.14	1,642.48	3,846.23	20.60	76,711.14
Spain 2010-2015 (480 observations)								
Output (€)	454,870.45	462,651.90	1,079.69	3,595,573.62	449,142.85	454,973.59	1,079.69	3,510,616.41
Feed (€)	300,084.08	314,280.65	1,049.42	2,350,220.04	311,625.92	330,030.11	1,129.33	2,529,197.20
Capital (€)	422,478.12	539,536.46	11,594.26	4,705,814.45	422,478.12	539,536.46	11,594.26	4,705,814.45
Labor (hours)	5,114.82	4,381.70	913.00	44,253.00	5,114.82	4,381.70	913.00	44,253.00
Other inputs (€)	6,471.59	7,828.78	191.78	83,548.36	6,471.59	7,828.78	191.78	83,548.36

feeding systems with feeding strategies (*ad libitum* and restricted).

Information on the technical impact of, and costs attributed to, feeding innovations obtained from experimental samples developed within feed-a-gene project[4]. Information obtained included the main outcome of the innovation and its corresponding costs, expected change in feed costs, feed intake and feed conversion indicators, mortality rates, lean meat content and expected change in the output prices. The change in both technical and economic performance is expressed as a percentage compared to the control group. The empirical analysis has been extrapolated to the micro-economic dataset obtained from FADN to estimate the economic impact of these technologies. The costs of each alternative technique varied according to the feeding technologies. The precision feeding technique can operate for ten years. The additional investment costs borne by farmers to adopt the necessary equipment ranges from € 1300 to 2000 to feed on average 20-25 pigs. Two different precision feeding strategies were evaluated (*ad libitum* feeding strategy and restricted feeding strategy). Each precision feeding technique was contrasted with a biphase feeding strategy applied to a group of pigs. The experiments[5] resulting from the use of the former feeding system would reduce feed intake by 5.06% and slightly increases body weight gain by 1.15%. In contrast, the restricted feeding strategy results in increasing the daily feed intake by 2.17% and reducing body weight gain by 1.24%.

In order to extrapolate the experimental results across countries, some input and output variables have been re-

[4] The Feed-a-Gene project aims to better adapt different components of monogastric livestock production systems (*i.e.*, pigs, poultry and rabbits) to improve the overall efficiency and to reduce the environmental impact. https://www.feed-a-gene.eu/

[5] Two types of experiment were conducted in Feed-a-Gene concerning precision feeding for fattening pigs: (i) INRA tested *ad libitum* precision feeding in the experimental facilities in Saint-Gilles (France). (ii) IFIP tested restricted precision feeding at the experimental facilities in Romillé (France). For each experiment, pigs were fed individually. Each precision feeding strategy was compared to a biphase feeding strategy applied to a group of pigs. Further information and technical details can be found in the deliverables available in the project web site as well as in other referenced publications (https://www.feed-a-gene.eu/).

calculated. More specifically, and based on the feed intake results for both strategies, a new variable that represents feed has been calculated for each one of the feeding strategies. Similarly, for each of the feeding strategies, a new variable that reflects output was computed based on the body weight gain results. Since the additional investment costs of the feeding devices are the same whether the pigs have an *ad libitum* or restricted feeding, both feeding systems share the same capital variable, and the same other inputs variable.

During 2010-2015 French farms were, on average, the largest farms in terms of total output produced with € 491,000 under the *ad libitum* feeding, compared to slightly over € 454,000 for Spanish pig farms, while Polish farms had the lowest output with an average of no more than € 122,000. In terms of feed use, French and Spanish farms had the highest feed consumption on average.

Results and discussion

TFP results for the four countries over the period 2010-2015 are presented in Table 3. The Färe-Primont indexes were computed using the productivity package in R developed by Dakpo *et al.* (2017). Regarding the *ad libitum* feeding strategy, TFP increases during the period of analysis for Germany, France and Spain recording an average value greater than one, while results show a TFP decrease of 16.7% for the Polish farms. The productivity growth slowdown experienced by Polish farms can be mainly attributed to a reduction in the rate of technological change. This confirms the existing technological gap between Polish agriculture and more modern European agriculture in terms of modern infrastructure (Szeląg-Sikora *et al.*, 2015). In contrast, the German pig farms showed the highest average TFP change of +21.3%. These results are consistent with previous studies that showed that German agriculture is among the most productive in Europe (Rizov *et al.*, 2013). The relevant improvement in TFP for German pig producers could be largely explained by the high rate of change in efficiency score (20.9%), in particular, obtained from scale efficiency (12.1%) and residual mix efficiency (16.6%). These results indicate that despite their technological stagnation, German farms are nevertheless able to significantly improve scale and scope economies.

Over the same period and using the *ad libitum* feeding technique, the Spanish farms experienced an annual growth in TFP of about 12%. As opposed to German farms, the productivity growth in Spain is mainly caused by the relatively high rate of technical change of about 11.5%. This significant frontier shift could be explained by the recent restructuring of the Spanish swine sector that ensures a strong integration with high-dimensioned structures and high investment and technical expertise (Valverde, 2015). The results also indicate that French pig farms have experienced relatively stable TFP during the analyzed period with an average increase of 4.4%. Furthermore, French farms present no efficiency change (dEC of 0.984 on average) and an increase in technological change of 6.3%. Consistent with Brümmer *et al.*'s (2002) results, this technological decline can be seen as an opportunity for farmers to get closer to the best practice frontier.

The Färe-Primont results obtained for the restricted feeding strategy follow the same trend as the *ad libitum* strategy, but at slightly lower levels. Cai *et al.* (2008) and Boddicker *et al.* (2011a) reported a reduced feed intake under *ad libitum* feeding strategy, while under restricted feeding system no significant difference in feed consumption has been found (Boddicker *et al.*, 2011b). These findings are in line with our results, as our feed cost estimates are based on reduced feed intake of 5.1% under *ad libitum* feeding, while feed intake has increased by 2.2% for restricted feeding. This difference in results for feed intake may be explanatory of TFP differences between *ad libitum* and restricted feeding.

For comparison purposes, descriptive figures for the evolution of TFP changes over the study period for both

Table 3. Average change in TFP and its components for the whole period and for each country

	Germany		France		Poland		Spain	
	Ad libitum	**R**	***Ad libitum***	**R**	***Ad libitum***	**R**	***Ad libitum***	**R**
TFP	1.213	1.174	1.044	1.009	0.833	0.824	1.120	1.067
dTC	1.014	0.998	1.063	1.036	0.724	0.716	1.115	1.040
dEC	1.209	1.189	0.984	0.975	1.170	1.170	1.010	1.033
dITE	0.988	0.988	1.015	1.015	1.073	1.073	1.053	1.053
dISE	1.121	1.121	1.008	1.008	1.491	1.491	1.043	1.043
dRME	1.166	1.145	0.973	0.964	0.847	0.847	0.964	0.986

TFP: Total factor productivity change, dTC: Technological change, dEC: Efficiency change, dITE: Input technical efficiency change, dISE: Input scale efficiency change, dRME: Residual mix efficiency change, R: restricted. An index value >1, <1, =1, indicates an improvement, a decrease and no change in performance compared to the base year (2010), respectively.

feeding systems are presented. Our research results suggest that TFP changes were either high or on an increasing pattern for all the four countries under investigation. Furthermore, Fig. 1 shows two patterns: one pattern for *ad libitum* feeding, where France, Germany and Spain with common minimum TFP peaks in 2012 (before introducing the new precision feeding system); and one pattern for restricted feeding with common minimum TFP peaks (for France, Poland and Spain) that coincide with the introduction of the precision system in 2013. The average annual growth rates of TFP reveal that, for *ad libitum* feeding technology, Germany has the highest potential to increase TFP for the years 2010–2011 (20.7%) while the highest decline is observed for Poland for the same period (18.7%). The adoption of new precision feeding equipment allows Polish farms to achieve the highest increase with regard to *ad libitum* feeding system between 2014 and 2015 (12.3%).

In order to compare results obtained from *ad libitum* and restricted feeding strategies, differences in TFP change between the two feeding types are plotted in Fig. 2 and a t-test is conducted to investigate whether there is

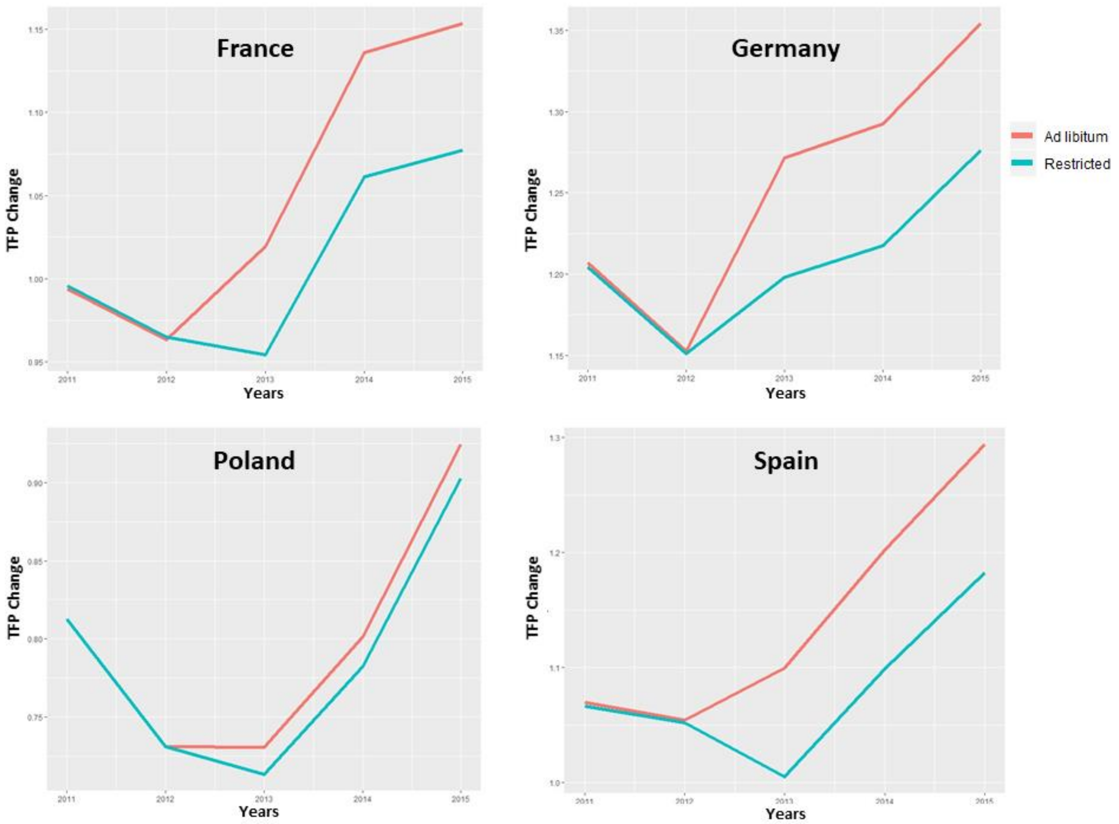

Figure 1. TFP change evolution over the period 2010-2015 for each feeding technique and for each country

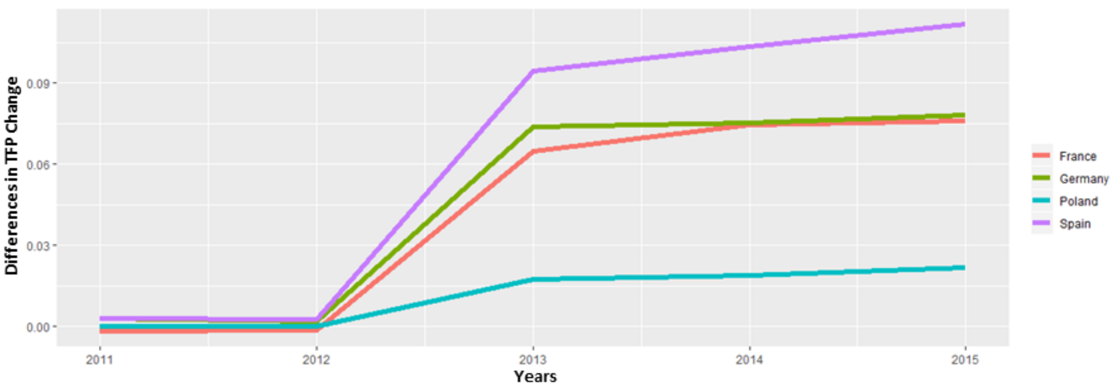

Figure 2. Evolution of differences in TFP change between the *ad libitum* feeding and restricted feeding strategy for each country

a significant difference in total factor productivity changes between farms implementing *ad libitum* or restricted feeding strategy. The t-test is used to account for differences between both systems for the period 2013-2015 (Table 4). Results show that the magnitudes of differences in TFP changes differ across countries. Investments in the *ad libitum* feeding precision technologies allow Spanish farms to reach the highest differences in TFP change with an average of 10.32%, followed by Germany (7.57%) and France (7.17%). These results are statistically significant for both Spain and France while for German pig farms, the difference between the two systems does not seem to be sufficient evidence to support *ad libitum* feeding over the restricted system.

Polish farms have experienced on average a significant difference in TFP between *ad libitum* and restricted feeding of around 2%. This finding is consistent with the fact that Polish farms are typically small-sized holdings (Latruffe *et al.*, 2004), and implementing precision feeding system should not be the priority of polish livestock farming. Rather Poland's agricultural authorities should improve farmers' access to inputs by improving access to credit, having the right machinery and help farmers to increase their cash flow to purchase high quality inputs and invest in modern infrastructure.

Table 4. Average differences in TFP change (standard deviation in parenthesis) between the ad libitum and restricted feeding strategy for each country from 2013–2015.

Country	*ad libitum*	Restricted	t-value	Pr(T>t)
France	1.103 (0.182)	1.031 (0.173)	2.603	0.010
Germany	1.306 (0.586)	1.230 (0.554)	1.083	0.280
Poland	0.819 (0.126)	0.799 (0.123)	1.814	0.070
Spain	1.199 (0.338)	1.095 (0.306)	2.026	0.044

Figures 3 and 4 show the cumulative evolutions of the TFP components (technological change, efficiency change) over the period studied. First, both feeding strategies follow the same pattern during the period 2010-2015 in terms of technological change and efficiency change. For instance, for France, technological change was the major source of TFP change, while, with respect to efficiency change evolution, French farms are less likely to have a clear increasing or decreasing pattern over time. In contrast, German farms exhibit a deterioration in technological change indicating an average increase of 14.63% at the beginning to a negative average technological change in 2015 (-10.97%). Moreover, summarizing these two components shows an opposite trend[6] between technological change and efficiency change (*e.g.* for Germany, Spain and Poland). This technological regress for German farms is not expected but might reflect the fact that many of the net investments were directed towards the expansion of operations and not necessarily towards developing production processes. One might speculate that technological regress could lead to increased risk exposure which results in higher profit variability which in turn leads

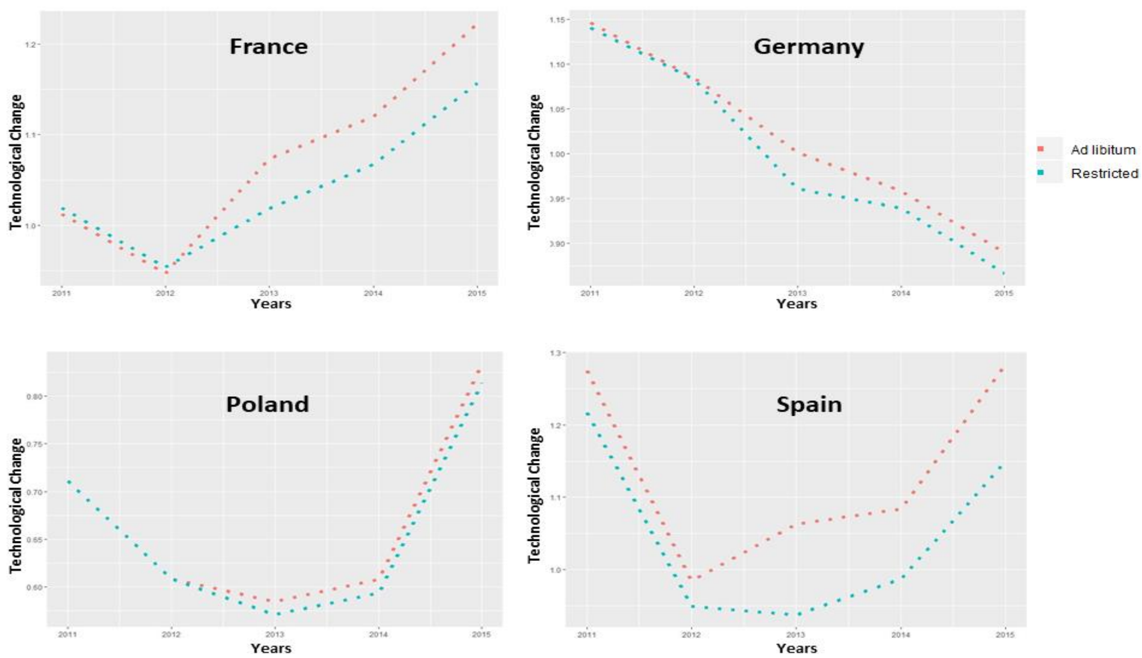

Figure 3. Technological change evolution over the period 2010-2015 for each feeding technique and for each country

[6] This finding is common in the literature and indicates that farmers are not able to adjust instantaneously to the new production process (Latruffe *et al.*, 2012).

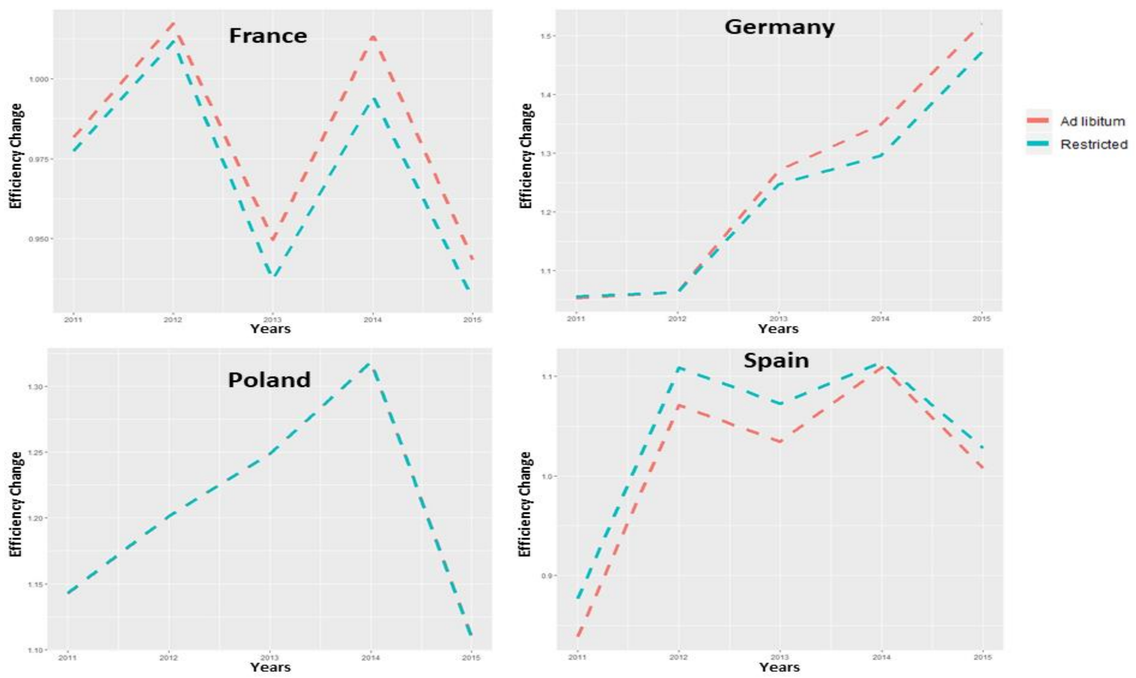

Figure 4. Efficiency change evolution over the period 2010-2015 for each feeding technique and for each country

to negative effects on the probability of adopting new technology.

It should, however, be borne in mind that only a few studies have addressed TFP change in pig production systems in EU countries, making it difficult a full comparison of our results with the literature. The results remain discordant, for instance, Balcombe *et al.* (2008) found that Polish farms were characterized more by stagnation in productivity than by a regression. Lansink & Reinhard (2004) reported that new technologies such as multi-phase feeding and pigs with high genetic capacity increase Dutch pig farms ' productivity by 4% under variable returns to scale. Not focusing on TFP per se but using a nonparametric data envelopment analysis to estimate technical efficiency of a sample of extensive Spanish livestock farms, Gaspar *et al.* (2009) indicated that farms with a livestock mix including pig were the most efficient. One of the explanations in the existing literature for these conflicting results may be the use of different statistical methods for TFP assessment.

Technological progress is a necessary component for the growth of agricultural productivity, and consequently, the economic prosperity of countries. The new global agriculture is productive than ever before, primarily because of labor-saving technological change (Edan *et al.*, 2009). A decrease in farm productivity as a result of technology adoption would constitute such an undesirable effect. While this adverse effect has to be avoided, it is preferable from an environmental protection perspective to account for climate change challenges and societal concerns. Against this background, it is crucial to develop technologies that support sustainable productivity growth. Since farmers' willingness to adopt innovative farming practices is suggested to be driven by profit-maximisation (Willock *et al.*, 1999), farmers are unlikely to adopt new technologies unless there is a positive economic outcome. In this context, Chavas (2018) note that farmers fear not only loss in the expected returns, but also the variability in returns. Our analysis empirically investigates the productivity effects of adopting new feeding precision technology. Overall, the average productivity growth estimates we obtained for each member state confirm relevant earlier studies on the computation of total factor productivity in agriculture. Rizov *et al.* (2013) reported an average TFP growth of German poultry and pig meat farms for the period 1990–2008 of around 20%. For the same period, this value was found to be +11% for French farms. Balcombe *et al.* (2008) found an average annual TFP decline of 2% for Polish farms between 1996 and 2000. Whereas, Acosta & De los Santos-Montero (2019) reported an average yearly TFP increase of 2.9% for monogastric farms the period 1992–2014.

Although some studies have compared restricted *vs ad libitum* feeding strategy in terms of their effect on pig performance indicators (such as feed efficiency and body weight gain; Schneider *et al.*, 2011; Newman *et al.*, 2014), however, the productivity effect of restricted and *ad libitum* feeding has not been investigated so far. In general, it seems that pigs restrictively fed ate less and grew slower than pigs fed free access (*ad libitum*) (Colpoys *et al.*, 2016). Our TFP change results across countries underpin the findings detected for feed efficiency and changes in body weight gain. This is consistent with notion that *ad* *libitum* access to feed can lead to productivity improvement (Zwicker *et al.*, 2013).

However, there are reasons for caution in drawing such conclusions that arise both from the database and from our empirical model. First, uncertainty and risk are key factors of innovations especially in the agricultural sector where both the social (*e.g.* farmer) and environmental (agronomic and ecological conditions) dimensions play a crucial role on the suitability and relevance of an innovation to the farm (Huffman, 2020). In the majority of cases, the farmer does not know in advance whether or not the adopted innovation will be suitable given the specific conditions in which farming activities take place. Further uncertainty is expected on how effectively to use the new technology, especially when it is used in combination with other productive inputs (*e.g.* feed). Farmers' skills and managerial ability in farming also matter in such a situation. The above-mentioned factors could create uncertainty and affect farms' performance. Second, It should be mentioned that while the inputs and/or outputs are associated with inefficiency, ignoring the random aspect of the data generation process does not exclude the existence of endogeneity problems in the measurement of productivity in DEA frameworks. Endogeneity could then lead to modelling biases and erroneous inferences (Orea and Zofio, 2019), this is why the results have to be evaluated with some caution.

Productivity assessment of precision feeding can shed light on the sustainability performance of agricultural systems and help policymakers in the design and implementation of new policy measures to promote sustainability. In this context, the objective of this paper is to assess productivity growth between two feeding precision technologies in pig production systems. To this aim, we use FADN data to evaluate TFP change, technological change and efficiency change, for the four EU countries (Germany, Spain, France and Poland) during the period 2010–2015. This allows us to account for heterogeneous farming systems across countries in terms of agricultural characteristics and specific livestock production systems. Precision feeding approaches provide another avenue to more sustainable livestock production. Our study provides supporting evidence that implementing individual *ad libitum* feeding systems for pigs improves productivity growth compared to a traditional biphase feeding option. On the other hand, a precision feeding system based on a restricted feeding strategy leads to lower productivity growth.

Specifically, for both the *ad libitum* and restricted strategies, our empirical findings indicated that German, Spanish and French farms exhibit TFP progress, while the opposite was found for the Polish farms. This suggests that there is substantial scope for productivity improvement of Polish livestock production. For *ad libitum* (restricted) strategy, the smallest average increase was experienced by the French farms which is 4.4% (0.9%) and the largest by the German farms which was 21.3% (17.4%). German farms achieve the highest efficiency change for *ad libitum* (20.9%) and restricted strategy (18.9%) but suffered stagnation in terms of technical change, while Spanish farms support the opposite. Such variation between countries in terms of productivity growth can guide policy-makers in designing and selecting programmes to improve farms' performance.

In terms of differences between *ad libitum* feeding and for restricted feeding. The adoption of technological feeding innovation would allow Spanish pig industry to reach the largest differences in TFP change with an average of 10.32%, followed by Germany (7.57%) and France (7.17%), while Polish farms have experienced lower difference in TFP between the two feeding types of around 1.93%. Thus, our research results support the *ad libitum* strategy which is more profitable in terms of productivity growth compared to the restricted feeding strategy. We conclude that the effectiveness of any of these precision strategies could potentially reduce input use and thus improve farmers' attitudes towards the management of resources.

In terms of policy recommendations, our findings advise for country-specific measures that for generic measures. For example, one of the official priorities of the CAP is to support farmers and improve agricultural productivity. To achieve this goal, the results for Poland suggest measures which facilitate improving technological change. According to Brümmer *et al.* (2002) a stable and reliable institutional environment tends to be a prerequisite for economic prosperity. Moreover, our results imply that policymakers wishing to reduce input use should encourage pig producers to become more involved with precision farming, with a special focus on the *ad libitum* precision feeding strategy. However, an important point worth emphasizing is the high costs associated with the implementation of precision feeding systems which may prohibit their general use, meaning that farmers would require a considerable financial and human assistance or collaborative efforts to exchange knowledge and experience. Otherwise, inequalities in efficiency and productivity performance may increase and enlarge the gap between efficient and inefficient farms. this gap could be partly closed through implementing appropriate training programs helping farmers to develop new skills.

It should be made clear that the evidence presented in this paper concerns only the productivity effect of precision farming, and does not account for other aspects of the precision feeding (such as environmental and sustainability issues), In particular, precision feeding under the restricted strategy is not expected to improve the overall feed performance, but can boost the nitrogen efficiency. Hence, the incorporation of environmental indicators and the use of productivity indices that allow environmental externalities to depend on productive inputs such as the ones proposed by Yang & Pollitt (2012) would be a promising area for future work. Another caveat of this analysis might stem from the labor variable used, comparing TFP growth between the *ad libitum* and restricted feeding strategy while accounting for labor gaps, would require the ability to measure the labor input under the different feeding strategies. Under the assumption that precision farming is a labor-saving technology, we expect TFP growth to be higher, as farmers may adopt such technology to maximize individual animal performance and thus minimize the use of labor. Identifying how different levels of labor affect under different precision feeding systems productivity growth would be another interesting area for future research.

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