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Full length article

The role of rational decisions in technical inefficiency analysis of Spanish pig farms: The influence of water use management

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ABSTRACT

There has been limited research on the degree to which rational inefficiency arises when environmental factors are considered. Thus, our goal is to contribute to the literature by applying the concept of rational inefficiency to pig farming and investigating the relationship between water use and farm technical efficiency levels. This research aims to provide a better understanding of the complex interactions between pig farming production, the natural environment, and economic performance. The stochastic frontier analysis is applied to a cross-section dataset of 523 Catalan farms specialized in pig production in 2018. The main findings of this study are as follows: First, Catalan pig farming exhibits high levels of technical efficiency with an average score of 0.94, which is consistent with the high intensity and concentration of Spanish pork production. Second, there is no compelling evidence to support the rational inefficiency hypothesis, particularly when comparing the rational efficient and multi-efficient groups.

1. Introduction

During the last decade, the European pig sector has seen an increase in the herd size, a decrease in the total number of farms, an increase in the average farm size and higher levels of productivity (Cabas Monje et al., 2023). With about 150 million pigs in 2018, the European Union (EU) has surpassed China as the world's biggest pork producer (Eurostat, 2020). Due to an ongoing reform process that began in the 1960s, Spanish pig farming primarily relies on an intensive and highly concentrated production system (Augère-Granier, 2020). Despite the fact that the number of pig farms has declined by more than two-thirds (128,000 holdings have gone out of business) in the last decade, the average farm size has increased fourfold. Pig farms with more than 100 pigs have rapidly increased, resulting in a highly dynamic productive sector (Larue and Latruffe, 2009). This pattern may be attributed to the high degree of vertical integration along the supply chain where corporations provide farmers with necessary inputs (feedstuff, piglets and other pig production needs) to farmers to rear and fatten pigs (Ait-Sidhoum et al., 2021). The spatial distribution of pig production in Spain is mainly concentrated in three autonomous communities namely, Catalonia (26 %), Aragon (26 %) and Castilla-León (14 %) accounting together for 65 % of the national production (MAPA, 2019). Further, Catalonia leads the pig industry, accounting for 41 % of total national meat pork output.

The protection of water resources is widely acknowledged as one of humanity's most critical issues (Connor, 2016) and a serious threat to the status of EU waters as envisaged in the European Water Framework Directive (Berbel and Expósito, 2018) and the Sustainable Development Goals (SDGs) of the United Nation (Vörösmarty et al., 2018). Low water security has a detrimental impact on SDGs relating to food security, water scarcity, climate change, biodiversity loss, health risks and water quality (Gain et al., 2016; Hanjra and Qureshi, 2010; Rabalais et al., 2009). For instance, the total annual drought losses (1981–2010) in the European Union and the United Kingdom are estimated at €9 billion (Naumann et al., 2021). Given these circumstances, it is clear that water security has become a difficult issue, particularly in Mediterranean regions and, in particular, in Spain, as a result of recurring episodes of water stress (Rodríguez-Villanueva and Sauri, 2021). Slurry management is another critical aspect of livestock farms and has received significant attention. As is well known, manure can be used to meet crops' nutritional needs while reducing the use of chemical fertilisers. Slurry waste management that is efficient would help to reduce several negative externalities on humans and the environment. Furthermore, the concentration of intensive farming systems in small areas increases

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Table 1
Summary of selected literature on the relationship between agri-environmental measures and economic performance.

Reference	Economic indicator	Agri-environmental practices	Main conclusion
Arata & Sckokai (2016)	Farm output and farm income	An aggregated measure of agri-environmental subsidies across five E.U. member states (United Kingdom, Spain, Italy, France, and Germany)	Despite their environmental constraints, agri-environmental practices do not seem to impact farm income
Dakpo et al. (2021)	Technical efficiency	Agri-environmental schemes (e.g. low use of nitrogen fertilizers; no-tillage and no pesticides on permanent grassland, etc.) in French livestock farming	Implementing environmentally-friendly practices does not seem to have an effect on technical efficiency
Sauer et al. (2012)	Technical and allocative efficiency	Agri-environmental practices covered by Environmental Stewardship and Nitrate Vulnerable Zones Schemes for UK cereal farms	While schemes show only minor effects on farm efficiency, results show that farmers were able to adjust their farming strategies to the schemes' conditions
Mennig & Sauer (2020)	Productivity growth	Agri-environmental measures (e.g. restrict the use of mineral fertilisers and pesticides and limit livestock density) for permanent grassland in Bavaria	Results show the Agri-environmental measures designed for dairy farms have no effect on farm productivity.

pollution risk, particularly in vulnerable zones in Catalonia, which limits slurry waste and nutrient application, which may end up in the water stream, causing other environmental damages. Using sustainable and efficient livestock practices for both water use and slurry waste could help overcome these problems.

Agriculture, which contributes significantly to humanity's water footprint, particularly through intensive livestock systems, is increasingly associated with negative environmental impacts such as groundwater pollution and greenhouse gas emissions (Bernabucci, 2019; Kim et al., 2021; Torres-Martínez et al., 2021). Agricultural scientists have suggested that the increase in food demand should be met by environmentally sustainable practices (Garnett and Godfray, 2012). This calls for not only increased production to meet food demand but also the implementation of practices to reduce environmental impacts. Therefore, farm economic performance must consider both environmental and societal factors. Concurrently, considerable research effort has been devoted over the previous few decades to the measurement of technical efficiency as a measure of farms' economic performance (Chen et al., 2009; Latruffe et al., 2004; Shen and Lin, 2017). Technical efficiency evaluates how efficiently farms utilize inputs like labor, capital, and land to maximize outputs. This research is crucial for two primary reasons: first, from a societal perspective, it helps identify inefficient producers, leading to the development of monitoring tools to enhance farmers' livelihoods and the sector's competitiveness; second, efficiency estimates hold importance for policy purposes, aligning with the goals of the Common Agricultural Policy (CAP).

The conventional view of technical inefficiency is that it results from the decision-maker's lack of knowledge or experience. However, Stigler (1976) argued that fluctuations in efficiency could be caused by unobserved factors influencing production decisions, such as entrepreneurial capacity. Building on this concept, Bogetoft & Hougaard (2003) proposed the concept of rational inefficiency, which suggests that inefficiency levels can be caused by deliberate production decisions. For example, a company may decide to pay higher wages than necessary in order to improve its reputation and retain employees, thereby avoiding unexpected costs associated with high employee turnover (Bogetoft and Hougaard, 2003, pp. 244). Similarly, a farmer may choose to use less water than necessary in order to conserve the resource and reduce its environmental impact, thereby reducing unexpected costs associated with water scarcity or regulation (World Bank, 2021). These examples could illustrate that inefficiency[1] is not always a sign of poor management or lack of knowledge, but rather a strategic choice that reflects the trade-offs and constraints faced by the decision-makers.

This study investigates rational inefficiency in pig farming performance, focusing specifically on water use and slurry management decisions. Pig farming has a significant environmental impact, making it critical to investigate the relationship between water management and farm economics. Due to data availability, environmental concerns, and recent pig production growth affecting water quality in Catalonia, the Catalan pig farming sector was chosen as a case study. Despite existing research on agricultural efficiency and environmental issues, the relationship between livestock production efficiency and water concerns has received little attention. This paper pioneers this exploration among Catalan pig producers, with implications for sustainable water management in the context of climate change and potential applications of circular economy principles in agriculture.

To date, the rational inefficiency hypothesis proposed by Bogetoft and Hougaard (2003) has not been tested in an integrated context of both productive efficiency and environmentally friendly decision-making. While there have been two empirical studies on the rational inefficiency hypothesis in the agricultural sector (Adamie and Hansson, 2021; Hansson et al., 2018), they have only focused on animal welfare and do not consider issues of environmental sustainability. Ideas related to farms' inefficiency and environmentally rational decisions can be found in the literature evaluating the impact of agri-environmental programs on-farm economic performance (Arata and Sckokai, 2016; Dakpo et al., 2021; Mennig and Sauer, 2020; Sauer et al., 2012). Despite the fact that this literature does not specifically address the rational inefficiency notion, the absence of a significant effect (as shown in Table 1) and the voluntary aspect of agri-environmental schemes suggests that environmentally friendly practices might have been implemented even without payment. In this context, several studies have shown that non-economic aspects are important motivational factors influencing farmers' participation in agri-environmental schemes (Lastra-Bravo et al., 2015; Morris, 2004) with the level of payment being a key determinant of the adoption (Hasler et al., 2019). Nevertheless, the assessment of farmers' rationale behind their farming activities usually depends on the specific context under analysis[2].

2. Study area: Catalonia

Our study aims to investigate the concept of "rational inefficiency" within the context of pig farming. Specifically, we are interested in

[1] In agricultural production, inefficiency is usually interpreted as bad management of the farmers, which could be a sign that he/she fails to find the optimal composition of the inputs required to generate the maximum attainable output quantity.

[2] This means that different factors, such as environmental, economic, social and cultural aspects, may influence the decisions and practices of farmers in different regions and situations. For example, some farmers may adopt organic farming methods to improve their soil health, reduce their input costs, and access niche markets. Other farmers may choose conventional farming methods to increase their yields, meet the demand of large-scale buyers, and cope with pests and diseases. Some farmers may also combine elements of both organic and conventional farming to achieve a balance between productivity, profitability and sustainability. Therefore, it is important to understand the context-specific motivations and constraints of farmers when assessing their farming activities.

understanding how farmers' decisions about water usage and managing slurry (a mixture of animal waste and water) relate to the overall performance of their farms. Pig farming has some significant environmental consequences, such as resource depletion, groundwater pollution, and contributions to greenhouse gas emissions. These environmental issues have become especially prominent in Catalonia, an autonomous community in northeastern Spain. Because of its heavy reliance on pig production as a cornerstone of its livestock system, this region is facing significant challenges. As documented by Kamilaris et al. (2018), this dependence has played a critical role in intensifying environmental challenges throughout the past few decades.

We chose to focus on the Catalan pig farming sector for a few key reasons. First, we had access to comprehensive data and vital indicators related to water usage and slurry management in this region. Second, compared to other food production sectors, the environmental impact of water use in pig farming is quite substantial. Additionally, we have witnessed a notable surge in pig production in Catalonia in recent years. According to data from the Catalan Department of Climate Action (2023), the number of pigs has shown a significant increase, surging from 5 million to 8 million pigs between 1997 and 2021. As a result of this increase in the size of pig herds, the annual production of slurries has increased by approximately 15 million tonnes per year (Bonmatí et al., 2015). This significant increase in slurry production has had far-reaching consequences for the region, most notably groundwater contamination caused by elevated nitrate levels. According to the Catalan Water Agency (CWA), the presence of excessive nitrates in the region's groundwater has resulted in a deterioration of groundwater quality, affecting approximately 41 % of Catalonia's groundwater reserves in 2016. Furthermore, Catalonia has one of the highest pig densities in Europe, with a pig density of 242.27/km^2 (Kamilaris et al., 2020; Peñuelas et al., 2021). The concentration of intensive farming systems in small increases the risk of pollution, especially in vulnerable zones, heightening the need to manage slurry waste and nutrient application effectively to prevent potential contamination of water sources and other environmental damage.

Water security is a growing concern in Mediterranean regions, including Catalonia. Solutions like the CWA's recent 40 % reduction in agricultural water use and proposals covering water collection, purification, and opportunity costs are available. However, implementing new water tariffs in livestock production, particularly within Catalan pig farms, could increase costs and impact viability. Despite the pig sector's significance, little is known about its water usage and management, emphasizing the need to explore water's role in pig production for effective resource management policies, particularly in demand conservation.

In addition, livestock manure management is subject to specific legislation. For instance, the nitrates directive 91/676/EEC (EC, 1991) imposes limits on manure application in order to prevent nitrate infiltration into groundwater and protect water quality. Furthermore, in response to Royal Decree 306/2020 (RD, 2020), new regulations are being developed to reduce greenhouse gas and ammonia emissions during slurry storage. Livestock farmers face increasing regulatory pressure to adopt sustainable and efficient practices for water use and slurry waste, which may have implications for their economic performance and competitiveness.

3. Theoretical model and hypotheses

We use a production function approach where a pig producer i produces output Y with a vector of inputs X_n, conditional on (technical) efficiency E:

$$Y_i = f(X_{in})\ g(E)_i) \tag{1}$$

E_i accounts for farm performance differences that aren't due to input use or a common technological level. Further, while the literature indicates that farmers' production decisions are suggested to be driven by profit-maximization, other studies support the hypothesis that farmers' production decisions can not only depend on profitability and productivity indicators, but also on non-economic criteria such as ethics, social and environmental values (Stern et al., 1999). We, therefore, assume that a pig producer's efficiency can be expressed as:

$$E_i = g(water\ use_i, slurryrelease_i) + v_i + \ u_i \tag{2}$$

Eq. (2) shows that pig farms' efficiency is a function of the water use and slurry release, a firm-specific stochastic noise term, v_i and the firm-specific technical inefficiency term, u_i. Pig farms are considered to perform at a specific inefficiency score, u_i, that could be affected by factors that are under the control of the farmer (contextual factors or the type of business strategy used in pig farming). For example, temperature, ventilation, lighting, water, and waste management are all physical environment-related factors. Others, like herd structure, biosecurity, and animal welfare, are social in nature. The stochastic noise component v_i might be influenced by unobserved factors or factors that cannot be controlled by the farmers (such as input and output prices, weather conditions and agricultural regulations).

In this study, we specifically explore the relationship between farmers' technical efficiency and water use and slurry release. Farmers' awareness of environmental conditions in terms of understanding the risks of climate change is expected to explain their attitude towards water conservation and environmental protection (Rezaei et al., 2017). Therefore, we are interested in finding support for the following relationship between water and slurry management and farm technical efficiency:

H1: Farmers' commitments in terms of water management have a negative effect on farm efficiency.

This first hypothesis is related to the idea of rational inefficiency. On one hand, the adoption of voluntary water conservation measures may reflect farmers' flexibility and ability to implement practices for improving sustainable production (Reimer et al., 2012; Yazdanpanah et al., 2014). Implementing these measures may necessitate additional resources, such as time and funds, as well as diverting attention and resources away from other aspects of the farm, such as productivity. Therefore, we could expect that decisions related to water conservation can negatively affect the efficiency of the farm. On the other hand, we expect that farmers' awareness of environmental problems related to slurry removal will lead to managerial transformations that may require changes in farm infrastructure or management practices, potentially impacting overall efficiency (da Rosa Couto et al., 2015). Both aspects would negatively affect the overall productivity of the pig farm and, thus, our technical efficiency indicator.

From a classic economic perspective, a rational farmer will choose to implement environmentally friendly practices, if and only if, the associated economic benefits outweigh the cost of implementation (De Graaff et al., 2008; Maybery et al., 2005). This is consistent with the argument found in several studies analyzing agri-environment schemes that the level of remuneration is a key determinant of adoption (Cullen et al., 2021; Siebert et al., 2006). Thus, in the absence of real exogenous factors that can serve as incentives for the provision of environmental benefits, such as policy interventions, the following hypothesis is proposed:

***H2**: There is no dependence* between *farmers' commitments in terms of water and slurry management and having low efficiency scores.*

The willingness of implementing conservation and environmental management practices is asssumed to be typically related to a profit maximization condition. This is especially true in one of the most competitive and profitable farming industries, such as the Spanish pig sector (Augère-Granier, 2020). These practices could include actions such as reducing water use, improving slurry treatment, or adopting more sustainable feed sources, which can have positive impacts on the environment and animal welfare. However, farmers may only implement these measures if they perceive adequate incentives, such as subsidies, payments for environmental services, or market premiums. Alternatively, some farmers may choose to implement some of the practices that require minimal changes in their farming activities and have minor impacts on their economic performance (Kleijn et al., 2011), mainly for reputational and market reasons.

4. Methodology

The first step of our empirical analysis aims at assessing technical efficiency for a sample of pig farms in Catalonia, Spain. SFA (Stochastic Frontier Analysis) and DEA (Data Envelopment Analysis) are two popular methods for measuring the technical efficiency of production units. DEA is a non-parametric method that does not assume any functional form for the production function, but uses linear programming to construct an empirical frontier based on the best-practice observations in the data. DEA can handle multiple inputs and outputs, and can incorporate different types of returns to scale. DEA does not require any distributional assumptions, but it assumes that all deviations from the frontier are due to inefficiency, and may be influenced by extreme values and sample size. In this paper, we employ SFA which is a parametric method that assumes a specific functional form for the production function and uses statistical techniques to estimate the parameters and the inefficiency term. SFA[3] can account for random noise and measurement error in the data, as well as contextual factors that affect efficiency.

Production function is the "*quantitative or mathematical description of the various technical production possibilities faced by a firm. The production function relates the maximum output(s) in physical terms to alternative levels of the inputs in physical terms*" (Beattie et al., 2009, p. 3) and it can be described as:

$$y_i = f(x_i;\beta) + \varepsilon_i \tag{3}$$

where y_i indicates the maximum quantity of the output (y) that farm i can obtain with a vector of given input quantities, x_i, and β is a vector of technology parameters to be estimated. When the production function is estimated, the regression represents more a "best-fit" and "average" than the maximum attainable output. Hence, the notion of the frontier is introduced, where the production frontier is an extension of the production function incorporating the theoretical constraint of all observations lying underneath the theoretical extreme of the maximum obtainable output (Greene, 2008). This gap between the estimation of the average production function and the theoretical foundation as a maximum achievable output function has been identified and discussed by Farrell (1957) as technical efficiency.

Including technical efficiency in the production function, we derive a production frontier generally described by:

$$y_i = f(x_i;\beta) + v_i - u_i \tag{4}$$

where v_i is a two-sided, symmetric and normally distributed error term with $E(v_i) = 0$ and $Var(v_i) = \sigma_v^2$ representing those factors that cannot be controlled by the farmers (such as weather conditions, conflicts in labor market, etc.) or omitted explanatory variables. $u_i$is a one-sided, non-negative error term with $E(u_i) = \mu_i$ and $Var(u_i) = \sigma_{u_i}^2$ associated with the short fall of the produced output from the production frontier, due to technical inefficiency, and can be explained by a set of managerial variables Z_{mi}. The one-sided disturbance reflects the fact that each farm's production should lie on or below the production frontier and represents factors under the farmer's control. Finally, it is assumed that v_i and u_i are independently distributed of each other and of the variables specifying the production frontier. In this study, we consider a translog specification of the stochastic production frontier with one output, 4 inputs, and 2 contextual variables. More specifically, the translog production function is as follows:

$$\begin{aligned}
&\ln Sales_i = \beta_0 + \beta_1 \ln Feed_i + \beta_2 \ln VetCost_i + \beta_3 \ln HousManag_i + \beta_4 \ln Piglets_i + \frac{1}{2}\beta_{11} \ln Feed_i^2 + \\
&\beta_{12} \ln Feed_i \ln VetCost_i + \beta_{13} \ln Feed_i \ln HousManag_i + \beta_{14} \ln Feed_i \ln Piglets_i + \frac{1}{2}\beta_{22} \ln VetCost_i^2 + \\
&\beta_{23} \ln VetCost_i \ln HousManag_i + \beta_{24} \ln VetCost_i \ln Piglets_i + \frac{1}{2}\beta_{33} \ln HousManag_i^2 + \\
&\beta_{34} \ln HousManag_i \ln Piglets_i + \frac{1}{2}\beta_{44} \ln Piglets_i^2 + a_1 Phase1_i + a_2 Phase2_i + v_i - u_i
\end{aligned} \tag{5}$$

Eq. (5) was estimated by maximum likelihood using R. The variance parameters that derived from the maximum likelihood estimation verify the two following equations $\sigma^2 = \sigma_v^2 + \sigma_u^2$ and $\gamma = \sigma_u^2/\sigma^2$, where $0 \le \gamma \le 1$. The parameter γ presents the percentage of the deviations from the average production function that is due to the technical inefficiency, while the term $(1-\gamma)$ is attributed to factors that cannot be controlled by the farms. P_i are phase dummies (three phases: piglets production, transition, and fattening)

5. Data

Our research focuses on pig producers operating in the Spanish region of Catalonia. By focusing on this sector, a relatively homogenous sample of pig farms can be created. Although each pig farmers' production line and business strategy may differ, the productive system can be considered relatively uniform in terms of required inputs and possible outputs. Given that the pig farming sector is one of the main sectors of the European Union's food industry, we can assume that our findings are representative on a broader scope and generalizable to other agricultural sectors with similar features. Furthermore, there are at least two reasons why focusing on the pig farming sector may be of interest in the analysis of technical efficiency. First, from a managerial perspective, it is important to analyze the performance of this sector given the significant structural changes that have occurred to it over the past decades. Second, intensive pig production is associated with environmental issues concerning mainly water pollution resulting from wastewater. Thus, pig farmers face the challenge of successfully reducing the negative environmental impacts while maintaining the profitability of the sector.

[3] SFA also requires strong assumptions about the distribution of inefficiency and noise, and may be sensitive to outliers and misspecification

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

	Mean	Std. Dev.	Min	Max
Inputs				
Feed (euros)	784,480.43	2490,290.20	11,368.12	44,148,110.89
Veterinary costs (euros)	57,079.84	88,215.82	343.63	1546,499.98
Housing and Management (euros)	303,556.02	613,589.35	6146.45	10,270,954.25
Piglets (euros)	777,212.10	1962,795.37	15,387.07	36,289,384.02
Outputs				
Sales (euros)	1909,898.24	5345,050.08	73,488.00	95,947,953.92
Others				
Water (M^3)	17,707.87	60,688.65	136.53	1097,478.29
Slurry (M^3)	12,282.69	40,823.99	87.27	728,720.11

Source: own elaboration based on SIP database.

Table 3
Maximum likelihood estimation of the translog specification.

	Estimate	Std. Error	*z* value
(Intercept)	0.168	0.478	0.35
Ln Feed	0.289*	0.160	1.8
Ln Veterinary costs	−0.275***	0.096	−2.87
Ln HousManag	0.389**	0.188	2.07
Ln Piglets	0.670***	0.113	5.92
(Ln Feed)^2	0.425***	0.058	7.36
(Ln Veterinary costs)^2	0.017	0.011	1.49
(Ln HousManag)^2	0.165***	0.047	3.55
(Ln Piglets)^2	0.214***	0.019	11.17
Ln Feed * Ln Veterinary costs	0.005	0.017	0.33
Ln Feed * Ln HousManag	−0.147***	0.043	−3.44
Ln Feed * Ln Piglets	−0.272***	0.031	−8.72
Ln Veterinary costs * Ln HousManag	−0.042**	0.021	−2.02
Ln Veterinary costs * Ln Piglets	0.040***	0.011	3.71
Ln HousManag * Ln Piglets	0.004	0.020	0.19
Phase 1	−0.191***	0.024	−8.01
Phase 2	0.269***	0.031	8.77
SigmaSq	0.014***	0.002	5.78
Gamma	0.420**	0.181	2.32
log likelihood	459		
Observations	523		
Mean technical efficiency	0.942		

In our empirical analysis, we rely on cross-sectional farm-level production data for a set of 523 specialist Catalan pig farms in 2018 obtained from the Production Information Systems (SIP) agency[45], which specializes in the financial management of livestock companies. The dataset includes detailed technical and economic information for each farm. On average, our sample farms fatten approximately 32,000 pigs per year that are slaughtered at 110 kg live weight. The vast majority of farmers (90 %) reared pigs in an integrated management system. Furthermore, in Spain, this production system is dominated by vertically integrated firms that supply farmers with feed, pigs, and production standards for breeding and fattening the animals (Augère-Granier, 2020). This business model would enable the pig industry to meet tight product specifications while satisfying the society's demand to reduce the environmental impact of livestock production (Schofield et al., 2002). In our estimation approach, total farm sales represent the output variable. Farm inputs include the cost of piglets, purchased feed, housing and management, and veterinary costs. Housing and management includes the costs of personnel, energy, maintenance, amortization, financial costs, and other general expenses. The costs of piglets and feed are the most important inputs in pig farming in terms of their contribution to the production process. Table 2 presents summary statistics of the variables used in the study.

On average, our sample farms use more than 17,700 M^3 of water and generate around 12,280 M^3 of slurry. These two variables are the main variables of interest in the 2nd-stage analysis, allowing for the rational inefficiency hypothesis to be tested. These two potential determinants of farmers' efficiency have been selected based on the challenges associated with pig farming[6].

6. Results

6.1. Stochastic production frontier estimates

Table 3 presents the results for the estimated Translog[7] function for the pig production in Spain. A positive (negative) coefficient indicates that an increase in the input is associated with an increase (decrease) in farm output. The estimated coefficients of the input variables of the production frontier model are all positive except the coefficient of the veterinary costs, which has a negative sign. This negative sign may indicate that farmers with low veterinary costs save money not only in terms of direct production cost, but also indirectly through a healthier and more productive herd (Sanders et al., 2012). Regarding the three phases of pig production, the results of Table 2 reveal that there is a negative percentage change in sales associated with being in the transition phase of pig production (compared to phase of piglet production) while all other input variables held fixed. On the other hand, sales are 27 % higher in the phase of fattening compared to the phase of piglet production with ceteris paribus.

The parameter γ presents the percentage of deviations from the average production function that is due to technical inefficiency, while the term (1-γ) is attributed to factors that cannot be controlled by the farmers. If γ is zero then there is no inefficiency in the model and the results from the SFA should be equal to OLS results. In contrast, if γ is one, the noise term v is not significant and all deviations from the production frontier are explained by technical inefficiency. In this study, γ is equal to 0.42 indicating that both noise and inefficiency are important components in explaining the distance from the production frontier with most of this deviation being attributed to noise. More specifically, 58 % of the distance of a farm from the production frontier

[4] SIP is a consultant's agency specialized in the financial management of livestock farms in Catalonia, Spain, Italy and Portugal. It helps farmers to monitor their income and business activities and to improve their efficiency performance and competiveness levels.

[5] https://www.sipconsultors.com/en/pigs/empresa

[6] In this study, we use water intensity as an indicator of water use performance. Water productivity is defined as the economic output generated per volume of water applied or consumed by the crop. This indicator has been criticized by some authors for leading to biased results since the significant growth in economic output may mask the actual water consumption or environmental impacts (Ozcelik et al., 2021; Rodriguez et al., 2020; Berbel et al., 2018; Scheierling et al., 2016). However, we argue that water intensity is a suitable indicator for our purpose, which is to compare the relative performance of water use among farms in the same year and region

[7] Translog functional form has been selected over the Cobb–Douglas specification for the production, as the Likelihood Ratio (LR) test clearly rejected the Cobb Douglas functional form.

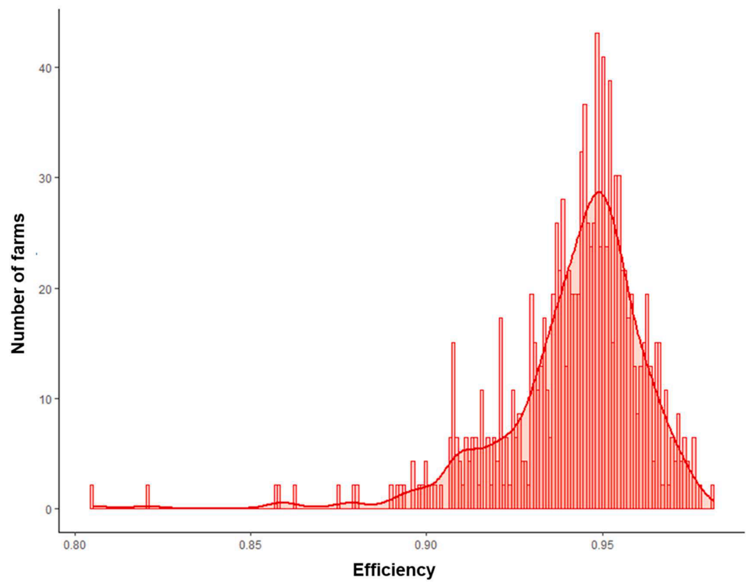

Fig. 1. Distribution of technical efficiency scores with kernel density function.

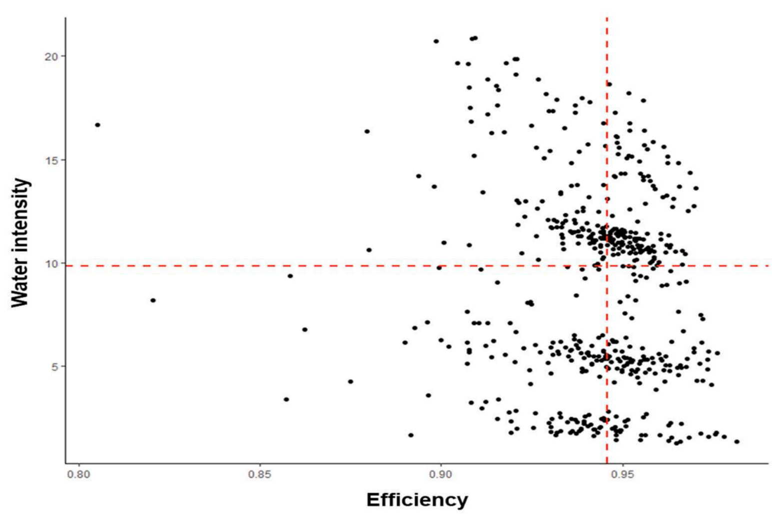

Fig. 2. Scatter plot matrix describing the relationship between water use and efficiency scores. (The red dashed lines indicate the median of both indicators).

is explained by random noise, while the rest of it is attributed to inefficiency.

6.2. Technical efficiency estimates

Fig. 1 presents the histogram of the technical efficiency distribution with a fitted nonparametric kernel density function. The left-skewed distribution of the efficiency scores indicates that many farms are located very close to the efficient frontier. More specifically, the average technical efficiency score is 0.942 with more than a third of the farms having an efficiency score greater than 0.950. These scores indicate that Catalan pig farms are performing well in terms of delivering the maximum feasible output from a given set of inputs, while there is limited scope for efficiency improvement in the region. Since an output-oriented functional form was estimated, on average, the inefficient farms could enhance their output by no more than 5 % without increasing their input use levels.

6.3. Examining the hypothesis of rational inefficiency

6.3.1. Classification of farms based on water, slurry, and efficiency metrics

The dispersion graphs that show the relationship between water and slurry to output ratios and efficiency ratings are plotted in Figs. 2 and 3, respectively. Based on the median value of the water used per output produced (water/output) and slurry released per output produced (slurry/output), and the efficiency scores, the farms are classified into four groups. Farms that exceeded the median for both water intensity and slurry ratio and scored below the median for efficiency scores were categorized as the “inefficient” group (G1). Those with water intensity, slurry ratio, and efficiency ratings above the median were classified as "technically efficient" (G2). The “rational inefficient” group (G3) includes farms with water intensity and slurry ratio values below the median, while their efficiency levels are below the median. Finally, farms with water intensity and slurry ratio levels below the median and efficiency scores above the median are classified as "multi-efficient" (G4). We present the descriptive statistics of each group in Appendix Tables A1 and A2.

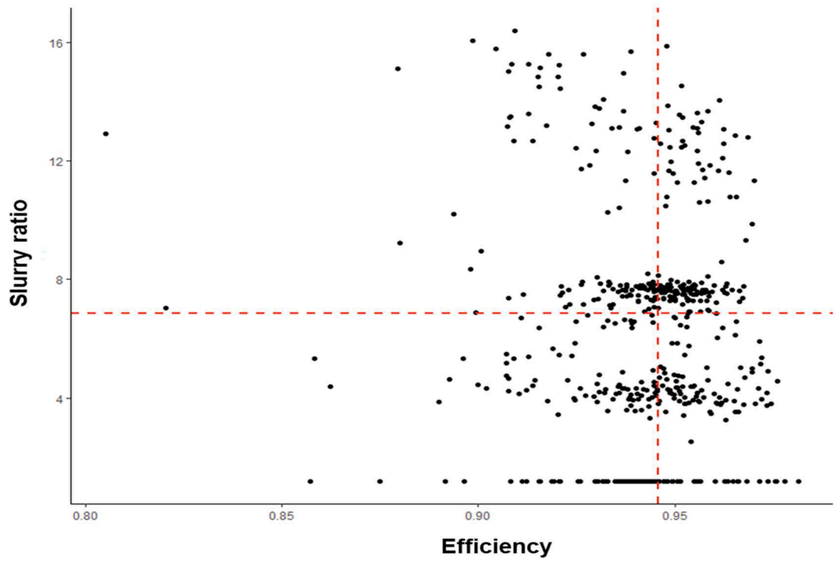

Fig. 3. Scatter plot matrix describing the relationship between slurry management and efficiency scores. (The red dashed lines indicate the median of both indicators).

Table 4
Comparison of water intensity between the rational inefficiency (RI) group and the other groups.

Water intensity	G3: Rational	G1: Inefficient	G2:TE	G4: Multi-efficient
	4.723	13.419	12.243	4.929
T-test		−25.551	−28.425	−0.737
p-value		0.000	0.000	0.462
N	131	131	133	128
Support for RI hypothesis		Yes	Yes	No

Table 5
Comparison of the slurry ratio between the rational inefficiency group and the other groups.

Slurry ratio	G3: Rational	G1: Inefficient	G2:TE	G4: Multi-efficient
	3.387	9.841	9.075	3.660
T-test		−20.233	−22.351	−1.235
p-value		0.000	0.000	0.218
N	138	124	137	124
Support for RI hypothesis	Yes	Yes	Yes	No

Table 6
Number of farms across the four groups and the results of Chi-square test.

		Technical efficiency				Technical efficiency	
		below	above			below	above
Water ratio	above	128	133	**Slurry ratio**	above	124	124
	below	131	133		below	138	137
Pearson Chi-square		0.017		Pearson Chi-square		1.195	
p-value		0.895		*p*-value		0.274	

6.3.2. Assessing differences in water and slurry ratios between rational inefficiency group and other farm groups

6.3.2.1. Water intensity. In the following analysis, it is determined whether there is a significant difference in the average level of water or slurry ratios between farms belonging to the rational inefficiency group and farms in other groups. The comparison is carried out by means of a two-sample *t*-test. Our results are shown in Tables 4 and 5. Overall, the farms belonging to the rational inefficiency group had significantly lower values of water intensity compared with the other groups. These lower levels of water use in the rational inefficiency group indicate that these farms would potentially choose to use less water, thereby reducing their technical efficiency scores. This can be interpreted as empirical evidence for the hypothesis of the existence of rational inefficiency among pig farms.

More specifically, the results in Table 4 suggest that farms belonging to the rational inefficiency group with relatively low levels of efficiency use significantly less water than the inefficient (G1) and the technically efficient (G2) groups. This is because a decrease in water use should eventually lead to lower output, thus lower levels of efficiency. This further supports the idea that the rational inefficient farms' position is due to rational production decisions, as their inefficiency is offset by lower amounts of water. On the other hand, our results reveal no significant differences between the rational inefficient farms and the group of multi-efficient farms (G4) that show at the same time high levels of technical efficiency and a reduced amount of water use.

6.3.2.2. Slurry ratio. Turning now to the results of the relationship between technical efficiency and the amount of slurry released per output produced (Table 5), results indicate that rational inefficient farms perform better than those belonging to the inefficient and technically efficient groups, owing to a minimum slurry ratio. Since we assume rational production behavior, it is likely that rational inefficient farmers would prefer to release less slurry per output and thus reduce environmental pollution rather than maximizing their technical efficiency. Consistently with our previous findings, we found no significant differences between the rational inefficient farms and the group of multi-efficient farms in terms of their released slurry (Table 5). This implies that while the rational inefficient farms are doing a good job in terms of their slurry management compared with other groups, they could improve their technical efficiency through even better decision making. Moreover, although the amounts of released slurry by the multi-efficient farms and the rational inefficient farms is relatively similar, our results suggest significant differences between the two groups in terms of technical efficiency, one group (G4) performing very well, while the rational inefficient group exhibits inefficiency that could be attributed to a sustainable slurry management strategy in pig production. It is likely that these distinct levels of technical efficiency involve the use of different production practices.

6.3.3. Examining synergies and trade-offs

We have also explored the distribution of the farms across different groups. Testing whether the four groups are equally balanced or not, is one way to understand whether there would be synergies or trade-offs between farm technical efficiency and water use or slurry release. For that purpose, similarly to what has been done in this study, we have divided the sample into four groups according to the median value of their efficiency scores and water or slurry to output ratios. In order to test whether there is independence between the different sub-samples, we rely on the Chi-square test statistic. This test compares multiple groups to investigate whether there is a statistical relationship between two categorical variables. The number of farms across the four groups and test statistics are shown in Table 6. Results indicate that neither the technical efficiency scores nor the water or slurry to output ratios are determinant factors that affect the independence between the groups. This provides empirical evidence of a lack of trade-off possibilities between the amounts of water use or slurry released and farm technical efficiency. Therefore, there is no statistical evidence to support that the farms belonging to the rational inefficient prioritize sustainable water management practices over efficiency improving techniques.

7. Discussion

7.1. Technical efficiency

Agricultural technical inefficiency is frequently viewed as a waste of natural resources since it entails using an excessive amount of inputs to produce too little output. The frequent droughts hitting the Mediterranean region, and the growing demand for large amount of water in pig farming is challenging the sustainability of livestock farming systems. Relying on the rational inefficiency concept introduced by Bogetoft and Hougaard (2003), this paper aims to investigate whether water use may explain some of the observed technical inefficiency in Catalan pig farming.

Our findings show that technical efficiency is high in Catalan pig farms. This is consistent with the fact that pig production in Catalonia has experienced rapid growth and structural transformation in recent decades, resulting in more intensive and efficient production practices (Ramsey et al., 2013). This is compatible with Lence (2005) vision that such high performance could be attributed to the adoption of technological innovations, integrated contractual arrangements, changes in environmental regulations and consumption habits. Additionally, Latruffe et al. (2004) have shown that the degree of integration with downstream markets is an important factor affecting farms' technical efficiency. Upstream and downstream integration can lead to efficiency improvement because of input sharing and demand matching (Duranton and Puga, 2004). Further, our results are in line with various related research papers, examples of such studies include Lansink and Reinhard (2004), who reported technical efficiency levels of 0.90 for Dutch pig farms. Similar values have been reported for Swedish pig production systems by Labajova et al. (2016) and Manevska-Tasevska et al. (2017). Galanopoulos et al. (2006) estimated the efficiency of a sample of commercial pig farming in Greece, and found efficiency ratings on the order of 0.83.

7.2. Hypothesis of rational inefficiency

Our results provide nuanced support for the hypothesis of rational inefficiency. We found that this theory holds when comparing the farms located in the rational inefficient group (G3) to the technically efficient group (G2). Following this hypothesis, one could explain that the observed inefficiency levels for these farms are, in fact, the result of low levels of water use. Assuming that both group farmers (G3 and G2) are driven by profit-maximizing objectives (which can be achieved through higher efficiency and savings effects), the low performance of the rational inefficient farms in comparison to the technically efficient farms may thus not be attributed to poor production decisions, but rather, to the farmer's awareness on pollution and environmental issues related to water resources. These findings provide empirical support for the idea that failing to account for producer motivation and awareness may lead to the conflation of poor production outcomes resulting from rational decisions with inefficiency (Pérez Urdiales et al., 2016). Third, we found that comparing the rational efficient group to the multi-efficient group provides less clear evidence of rational inefficiency. Specifically, our results show that the farms belonging to the rational inefficiency group obtain relatively similar values in terms of water use and slurry management to those of the multi-efficiency farms. These low efficiency scores of the rational inefficient farms compared with the multi-efficient group could be interpreted as a result of farmers' rational decisions, which most likely place a greater weight on water scarcity and environmental pollution than on higher economic performance. However, assuming a profit-maximizing behavior for all farmers, it is unlikely that rational inefficient farmers would implement sustainable water management practices making them worse off. Further, this finding is consistent with the result of the Chi-square independence test, which indicates no association between the groups and farms are equally distributed between the rational inefficient and the multi-efficient group.

7.3. Policy implication and proposals for further research

The paper's intended audience includes practitioners, policymakers, and researchers interested in determining whether some of the observed inefficiency on farms is the result of farmers‘ rational behavior. While this work is necessarily limited by data availability, it serves as a call to action for future research in this area. Decision-makers would benefit greatly from alternative analyses based on farm-level data from other regions or countries.

To summarize, our findings provide inconclusive support for the hypothesis of rational inefficiency among Catalan pig farms. Future research on the relationship between efficiency and water scarcity and farmers' environmental attitudes among pig producers or farmers engaged in other types of productive activities, as well as from different regions or countries would allow to test the consistency of our findings. Although the European pig sector did not receive sufficient support from

EU policy-makers (Willems et al., 2016), our study has important policy implications by presenting evidence of the lack of trade-off between water management and farm efficiency. Because these farmers are not paying for their water use, the implementation of a water use fee would encourage farmers to use water more efficiently and thus reduce environmental pollution resulting from pig wastewater. However, according to Unió de Pagesos (the largest farmer association in Catalonia), the pig sector would reject such a proposal with the argument that their farms are supplied from private sources and their resources. Further, the sector has engaged in significant investment efforts to improve water use efficiency (Valiño et al., 2019). Since some farmers are driven by rational considerations, policies such the water fee would be perceived as counterproductive by the farmers belonging the rational inefficient group. Instead, policies should support these farmers to catch up with the multi-efficient group.

Further extensions of this work would be to investigate the relative contribution of water use to productive efficiency among the four groups. It would also be interesting to compare our results with those derived from a non-parametric model. Additional research would be to investigate the determinants of technical efficiency, which would allow assessing whether the effect of relevant contextual variables on technical efficiency is different across different groups. Finally, we would like to acknowledge the main limitation of this study from our perspective. The most significant challenge we faced was the scarcity of data. In particular, we had insufficient information about water use breakdown. Consequently, future research investigating the impact of recycled or reclaimed water on technical efficiency and overall farm productivity could help develop more sustainable and economically viable pig farming practices.

8. Concluding remarks

This article studies the influence of water use and slurry management on pig farmers' technical efficiency. More precisely, we are interested in exploring whether farmers' technical inefficiency could be the consequence of rational production decisions. This is relevant given the high rates and the environmental impacts of agricultural water use in Europe. Our model is illustrated using a set of specialist Catalan pig farms for the year 2018. Our main results are the following: First, the average level of technical efficiency in Catalan pig farming is found to be around 0.94, which is in line with the fact that Spanish pork production is highly intensive and heavily concentrated. Second, a potential situation of rational inefficiency among pig farms is suggested between the rational inefficient group and the technically efficient group. Third, there is less convincing evidence of the rational inefficiency hypothesis between the rational efficient group and the multi-efficient group. These findings stress the importance of implementing policies that incentivize farmers to use water more efficiently rather than policies that restrict the development of the sector.

Data availability

Data and material will be made available on reasonable request to the authors.

Ethical approval

Not applicable.

Consent to participate

Not applicable.

Consent to publish

All authors approved the submission and consented to publication.

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Amer Ait Sidhoum: Conceptualization, Data curation, Methodology, Writing – original draft, Writing – review & editing. **Maria Vrachioli:** Conceptualization, Methodology, Writing – review & editing. **Bouali Guesmi:** Data curation, Writing – review & editing. **J. Maria Gil:** Data curation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

Tables A1,A2

Table A1
Descriptive statistics of the four groups (Water use comparison).

	G1		G2		G3		G4	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Feed (euros)	1270,563.90	4007,943.72	1164,679.86	2791,276.13	354,387.98	305,932.14	332,126.16	246,653.52
Veterinary cost (euros)	64,251.39	140,827.59	45,971.71	60,598.91	56,368.65	58,778.50	62,010.12	64,222.06
Housing and Management (euros)	392,491.17	928,583.28	384,325.81	728,291.43	226,858.99	223,422.92	207,106.23	178,923.29
Piglets (euros)	968,741.89	3289,724.32	812,097.25	2019,239.93	705,062.76	495,926.24	618,785.81	444,564.36
Sales (euros)	2568,760.86	8666,091.00	2443,900.76	5988,363.47	1282,403.41	957,905.93	1322,933.26	917,106.34

Table A2
Descriptive statistics of the four groups (Slurry management comparison).

	G1 Mean	Std. Dev.	G2 Mean	Std. Dev.	G3 Mean	Std. Dev.	G4 Mean	Std. Dev.
Feed (euros)	1298,005.68	4117,538.63	1136,748.39	2754,713.19	376,202.84	326,015.05	336,129.36	249,056.22
Veterinary cost (euros)	64,608.91	143,983.18	45,018.28	59,979.99	56,447.25	59,014.94	63,580.88	64,620.18
Housing and Management (euros)	405,956.07	952,419.21	373,924.47	719,814.85	223,161.71	219,903.72	212,881.28	179,746.21
Piglets (euros)	991,747.02	3379,966.01	798,318.99	1991,924.60	697,766.52	487,853.78	627,772.71	443,892.17
Sales (euros)	2624,023.83	8904,626.34	2391,440.73	5908,226.08	1297,996.84	947,577.08	1344,732.90	918,125.83

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