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Farm efficiency related to animal welfare performance and management of sheep farms in marginal areas of Central Italy: a two-stage DEA model

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ABSTRACT

The development of specific actions to increase animal health and welfare is indicated as a strategy to improve the efficiency and sustainability of many livestock systems, including sheep farming. In this paper, efficiency measures are provided to confirm the hypothesis that farms that are higher-performing in terms of animal welfare and management are also more technically efficient. A two-stage Data Envelopment Analysis (DEA) approach was adopted with the following twofold objectives: 1) to evaluate the efficiency and super-efficiency of 76 meat-producing sheep farms situated in marginal lands in central Italy, through DEA and Super-DEA (S-DEA) models; and 2) to assess the influence of animal welfare and management indicators on technical efficiency values through the application of a Tobit regression model. An overall efficiency performance varying within a range of 0.44–1 was estimated, with an average value of 0.80, implying a potential increase of 20% in terms of output production from both management and scale improvements. The 'pure' technical inefficiency was found to contribute three times more than scale inefficiency in determining the overall technical inefficiency. Adopting a more extensive farming system and increasing replacement rate were found to affect negatively the efficiency scores. On the other hand, having less than 5% of animals with body condition score beyond acceptable limits, presence of access control structures, well managed lambing pens, and dedicated feed stocking areas resulted in a positive influence on efficiency. Improvements in animal welfare aspects did not appear to be farm-scale-dependent.

HIGHLIGHTS

- DEA and Super-DEA models were applied to assess sheep farm technical efficiency in Central Italy.
- An overall potential 20% increase in output production was estimated.
- Animal welfare factors were found to significantly affect efficiency performance.

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Introduction

The sheep sector in Italy in 2018 is represented by 7,179,150 head, and the population has remained almost unchanged over the past 5 years (Eurostat 2018). Of the number of animals raised, 93.5% are concentrated in central and southern Italy. The specialised sheep and goat farms cover almost 12% of Italian agricultural area (Eurostat 2018) and are often located in disadvantaged areas subject to abandonment, thus making them particularly important in terms of environmental protection. Small ruminant production relies on a grass-based feeding system in areas with poor agronomic potential and high environmental value. Hay supplementation is very common, especially when pasture is scarce, while the use of concentrate feeds is mainly reserved for dairy breeds such as Sarda or Comisana. Conversely, management systems for meat-type or dual purpose breeds are less intensive and mostly based on forages.

According to EFSA (2014), most sheep farming systems in central Italy can be defined either as 'semi-intensive' ('management systems where animals are kept intensively during night and some part of the day and are moved to fenced or unfenced owned or rented

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pastures during some period of the day') or 'semi-extensive' ('management systems where the stockperson (and dogs if used) is not continuously with the sheep'), all of them being generally coupled with low energy and fertiliser consumption (Budimir et al. 2016).

Sheep farmers' income is consistently among the lowest of all other agricultural sectors, with inadequate farm-gate prices of primary products and poor monetisation of its by-products. Production costs have risen significantly in recent years, whereas income has remained stagnant, thus reducing the overall profitability. Moreover, sheep farmers in Italy are an ageing population and the sector is also being hampered by a lack of technical services and training, resulting in very varied levels of productivity (Rossi 2017).

Since productivity and farm profitability are both dealing with farm efficiency, a brief distinction between the two concepts has to be made. Productivity is directly related to technical efficiency, which occurs when it is not possible to increase the output without increasing the inputs (decrease the input without reducing the output). Therefore, while technical efficiency aims to minimise inputs (maximise outputs), the economic efficiency goal is the costs minimisation (revenues maximisation), which might or might not imply a lower input use (higher output production) (Russell 1985).

Economic efficiency mainly depends on the prices related to the factors of production and to the resulting outputs. In this sense, technical efficiency represents a pre-requisite for economic efficiency, which remains the main farm goal. In this perspective, every improving strategy aimed at achieving economic efficiency should, at first, pursue technical efficiency, which is a necessary condition to get better economic performances.

Improvement of health and welfare of sheep flocks is a key objective for future progress in terms of productivity and competitiveness. Herd programmes developed in bovine dairy farms from the 1960s have been only partially extended to sheep farms (Spedding et al. 2007). This is probably due to the lack of economic resources, since sheep farming is generally characterised by low incomes, and to the episodic pattern of production typical of sheep flocks (Spedding et al. 2007). Therefore, tools for systematic collection and health and production data analysis widely used on cattle farms have been only marginally introduced into sheep farms. Analysing farm efficiency in relation to animal welfare performance should, in the near future, represent a primary objective in the field of sheep farming management.

In this perspective, the development of tailored actions to improve the health and welfare of sheep flocks has been indicated as a strategy to improve the productivity (technical efficiency) and economic sustainability of sheep farming (Ferroni et al. 2020; Santeramo et al. 2020). In this contest, animal welfare is analysed in a fully integrated approach, considering not only behavioural and animal-based measures, but all the management practices able to influence health status and productivity (de Vries et al. 2013). In an extensive setting characterised by a high level of behavioural freedom, sheep welfare can be greatly improved through correct sanitary and nutritional management (Dwyer 2009). Enhancing animal health status can increase biological efficiency in terms of quantity and quality of production, as well as reducing veterinary costs, thus improving overall farm productivity (Caroprese et al. 2016). A growing demand for animal-welfare-friendly products has been recorded from the consumers, increasing their market value. (European Commission 2009, Bozzo et al. 2019). In such a context, the implementation of an integrated efficiency and econometric analysis of the sheep livestock sector assumes an increasingly strategic importance in driving the decisions of all the stakeholders involved in the management of animal welfare (farmers, public decision makers and category associations).

In the agricultural sector, an increasing number of studies have applied a two-stage DEA (Data Envelopment Analysis) methodological framework with the following two main purposes: 1) to determine the efficiency level and the potential output increase (input reduction) of inefficient Decision-Making Units (DMUs), under the hypothesis of different returns to scale; 2) to analyse the effects on efficiency scores of structural and environmental factors characterising farm management (Liu et al. 2013). DEA, alone or combined in a second-stage framework, has been used by authors dealing with the technical efficiency in both extensive and intensive production systems (Gaspar et al. 2009).

Accordingly, in this study, a DEA framework for the estimation of the farm efficiency frontier was combined with regression analysis in order to better investigate the role of animal welfare management and production practices as efficiency determinants. To the best of our knowledge, this represents the first study in which a two-stage DEA model has been adopted to evaluate the efficiency and super-efficiency of meat-producing sheep farms situated in marginal lands, and to estimate the influence of animal welfare indicators on technical efficiency values. By assuming technical efficiency as a proxy for economic profitability (Allendorf and Wettemann 2015), this study would contribute to the growing literature concerning animal welfare economics by focussing on the relationship between animal well-being and economic performances, which is still recognised as an under-investigated topic needing additional in-depth economic research (Lusk and Norwood 2011; Allendorf and Wettemann 2015).

Methodology

Data collection

The study population consisted of 76 selected sheep farms that took part in the 'Woolfair Project', which addressed the improvement in resilience, animal welfare and competitiveness of sheep farming in marginal lands in four regions of central Italy (Abruzzo, Lazio, Marche and Umbria). Due to the recruitment criteria, the sample cannot be considered as representative of the national sheep farming sector, although it is reasonably indicative of the reality of meat-producing sheep farming in marginal areas of central Italy. Most farms sampled can be classified either as 'semi-intensive' or 'semi-extensive' systems (EFSA 2014) and include a large number of genotypes (mostly crossbred between meat-type and Merino breeds).

Data were collected between 2018 and 2019 through direct surveys of farm owners, carried out by a single veterinarian who was properly trained for this task. The inquiry comprised of two different set of questions: the '*Woolfair*' and the '*SanBenBioFarm*' questionnaires. The first was specially designed for the project and consisted of 33 questions relating to general farm management with a focus on nutritional, wool management and economic aspects. The second questionnaire was developed by the Istituto Zooprofilattico Sperimentale dell'Umbria e delle Marche 'Togo Rosati' as part of a general farm monitoring system and focussed on four sectors of farm management: health, welfare, biosecurity and drug use. Both questionnaires were designed through a consensus of expert opinion, which is regarded as a valid approach to these of studies (Phythian et al. 2011). The survey method implied that some answers necessarily represented a subjective description of the farmers' perception of reality. Nevertheless, many items, such as cleanliness of premises and animals, presence of infirmary and feed stocking areas, and evaluation of animal-based measures such as body condition score (BCS), represented objective observations carried out by the veterinarian in charge. In particular, BCS was evaluated using a 5-point scale, using a quarter-unit precision according to Munoz et al. (2019).

Other items were defined according to Bertocchi et al. (2018) and the Classyfarm® checklists (available at http://www.classyfarm.it/check-list/). The veterinarian responsible for data recording was trained in expressing objective and measurable values regarding cleanliness of premises and of animals, space adequacy and lambing management, among others presented in Table 1.

Table 1. Variables entered in the Tobit regression models.

Area	Variable	Definition and measurement	Farms classified as '0'	Farms classified as '1'	Mean	Standard deviation
Farming system	FARMSYS	1 = semi-intensive/semi-extensive farming system; 0 = confined farming system	17	59	0.776	0.419
Animal housing and structural aspects	INFIRMARY	1 = presence of infirmary area; 0 = otherwise	46	30	0.395	0.492
	PRECACCESS	1 = presence access control structures, yet procedures for vehicles and visitors are incomplete and unsystematic; 0 = otherwise	38	38	0.500	0.503
	SPACEADEQUACY1	1 = just sufficient housing space in the resting areas and/or feeding space just sufficient for the number of housed animals; 0 = otherwise	48	28	0.368	0.486
	SPACEADEQUACY2	1 = more than adequate housing space in the resting areas and/or feeding space in excess of the required; 0 = otherwise	58	18	0.395	0.492
	BIRTHMANAG	1 = presence of birthing pens, correct use of birthing pens and sufficient bedding hygiene; 0 = absence of birthing pens or incorrect use	24	52	0.684	0.468

(*continued*)

Table 1. Continued.

Area	Variable	Definition and measurement	Farms classified as '0'	Farms classified as '1'	Mean	Standard deviation
		of birthing pens and inadequate hygiene of bedding				
	STOCKINGAREAS	1 = presence of dedicated feed stocking areas; 0 = otherwise	38	38	0.500	0.503
Cleaning practices	CLEANHOUSE1	1 = fairly clean premises for almost all breeding groups; 0 = otherwise	36	40	0.526	0.503
	CLEANHOUSE2	1 = correctly managed, clean and dry premises for all breading groups; 0 = otherwise	56	20	0.263	0.443
	CLEANLIVESTOCK	1 = less than 20% of dirty livestock; 0 = more than 20% of dirty livestock	13	63	0.829	0.379
Technical assistance and training	VETASSIST	1 = presence of veterinary technical assistance; 0 = otherwise	14	62	0.816	0.390
	WORKTRAIN1	1 = workers have at least 7 years of working experience with no training course or less than 7 years of working experience with attendance of at least one training course on farming; 0 = otherwise	33	43	0.566	0.499
	WORKTRAIN2	1 = workers have at least 7 years of working experience and a training course on farming; 0 = otherwise	50	26	0.342	0.478
Health and veterinary aspects	BCS1	1 = between 5% and 10% of animals with BCS beyond acceptable limits; 0 = otherwise	63	13	0.171	0.379
	BCS2	1 = less than 5% of animals have BCS beyond acceptable limits; 0 = otherwise	29	47	0.618	0.489
	VACCINSMANAG1	1= presence of an empirical vaccination program; 0 = otherwise	65	11	0.145	0.354
	VACCINSMANAG2	1 = presence of a vaccination program defined by the veterinarian; 0 = otherwise	67	9	0.118	0.325
Watering and feeding practices	WATERAV1	1 = presence of fully working water troughs for all groups; 0 = otherwise	30	46	0.605	0.478
	WATERAV2	1 = *Ad libitum* access to water for all groups is available; 0 = otherwise	56	20	0.263	0.492
	RATIONMANAG	1 = specific ration for each breeding group (ewe-lambs, dry-off period, lactation) is adopted; 0 = empirical ration and no evaluation of nutritional requirements	50	26	0.342	0.443
	FEEDMANAG	1 = grazing and in-stable supplement of hay and grains and other unprocessed feeds is provided; 0 = grazing and in-stable supplement of hay and processed commercial feeds (pellet, etc.)	7	69	0.908	0.291
	FEEDSELFSUFF	1 = feed is totally self-supplied; 0 = otherwise	60	16	0.211	0.291
Grazing practices	GRAZING	1 = animals graze all year long; 0 = otherwise	39	37	0.487	0.503
	ROTGRAZING	1 = rotational grazing is adopted; 0 = otherwise	39	37	0.487	0.503
			Min	Max	Mean	Standard deviation
Replacement rate	REPLRATE	%	0.000	49.000	22.019	11.403

Two-stage DEA approach

This study aimed to evaluate the technical efficiency of a sample of meat-producing sheep farms through DEA and Super-Data Envelopment Analysis (S-DEA; Charnes et al. 1997). Considering a time horizon of one year, a number of parameters were included in this analysis as inputs of the productive process: i) labour employment (work hours), ii) feed supply (total quantity of fodder and concentrate purchased), iii) surface area destined for productions reused in zootechnical activities, and iv) Livestock Units (LSU). Annual meat and wool production, which represent the main items contributing to the saleable gross output of the sheep farms taken into consideration, were considered as outputs.

According to the methodological framework discussed in the introduction, the present study adopted a two-stage DEA approach. Significant qualitative and quantitative welfare parameters and indicators associated with the different dimensions of animal welfare were then included in the model as covariates to evaluate their influence on technical efficiency.

First stage: DEA models

In general, DEA is a method that uses linear programming techniques to determine the relative efficiency of DMUs (Decision Making Units) (Charnes et al. 1997). The method was developed in 1978 (Charnes et al. 1978), and its core formulation is based on the assumption of a monotonic relationship of linear proportionality between input and output, which results in an efficiency value between 0 and 1 (Charnes et al. 1997). The closer the value is to 1, the more efficient is the DMU; accordingly, the closer it is to 0, the more inefficient it is.

Over the years, a number of DEA models have been proposed, characterised by different structures and functional form assumptions, as well as by distinct restrictions and natures of considered inputs and outputs. However, the most used traditional DEA models can be traced back to two main categories: 1) the CCR (Charnes, Cooper and Rhodes) model, which provides an evaluation of total efficiency by assuming constant returns to scale (CRS); 2) the BCC (Banker, Charnes and Cooper) model, which considers variable returns to scale (VRS) and estimates the 'pure' technical efficiency by excluding the effect of the scale efficiency factor. Since most inputs are fixed in the short period, and the majority of the farms adopt either a semi-extensive or a semi-intensive rearing system, the output-oriented version of CCR and BCC DEA models were implemented.

Assuming that the DMU set is $k = \{1,2,\dots,K\}$, where each DMU has a set of inputs $i = \{1,2,\dots,I\}$ and two j outputs, the k-th DMU produces y_{jk} units of output by using x_{ik} units of i-th inputs, and letting λ_k be an intensity variable that measures the extent to which an activity is used in the production process, the CCR output-oriented model (Charnes et al. 1978) for the DMUo under evaluation (where $o = \{1,\dots,K\}$), could be formalised as follows:

$$
\begin{aligned}
&Max_{\theta_o,\lambda_k}\theta_o \\
&\text{s.t.} \\
&\sum_{k=1}^{K}\lambda_k x_{ik} \le x_{io}, \forall i = 1,2,\dots,I; \\
&\sum_{k=1}^{K}\lambda_k y_{jk} - \theta_o y_o \ge 0, \forall j = 1,2; \\
&\lambda_k \ge 0, k = 1,2,\dots,K;
\end{aligned}
\tag{1}
$$

where θ_o^* is the optimal value, representing the ratio between the output achievable by DMU$_o$, by keeping constant the level of inputs and the actual output level; λ_k is an intensity variable, measuring the extent to which an activity is used in the production process.

By adding the following convexity constraint to Model 1, it is possible to obtain the VRS BCC output-oriented model (Banker et al. 1984):

$$\sum_{k=1}^{K}\lambda_k = 1; \tag{2}$$

DMU$_o$ is defined as efficient and operating on the frontier when $\theta_o^* = 1, \lambda_o^* = 0$, and $\lambda_k^* = 0 \forall k \ne o$, with $*$ indicating the optimal value of each variable obtained from the two models.

As in our case, many studies have implemented both CCR and BCC models in order to split the overall technical efficiency into 'pure' technical efficiency and scale efficiency. Moreover, no strong evidence about the assumptions of scale economics have been found in the literature concerning sheep dairy farming (Fraser and Cordina 1999; Kovács and Emvalomatis 2011).

The overall output-oriented technical efficiency (OTE$_o$) of DMU$_o$ can be expressed as:

$$\text{OTE}_o = \frac{1}{\theta_o^{CCR*}} \tag{3}$$

where OTE$_o$ varies in the range [0,1] and 1 represent full overall technical efficiency. The 'pure' output-oriented technical efficiency (TE$_o$) of the DMU$_o$ can be expressed as:

$$\text{TE}_o = \frac{1}{\theta_o^{BCC*}} \tag{4}$$

where TE$_o$ varies in the range [0,1] and 1 represent full technical efficiency. By taking the ratio of OTE$_o$ and TE$_o$, it is possible to derive the scale efficiency as follows:

$$\text{SE}_o = \frac{OTE_o}{TE_o} \tag{5}$$

when $SE_o = 1$, DMU$_o$ operates at an optimal size because OTE_o and TE_o are coincident; if $SE_o < 1$ DMU_o operates at increasing returns to scale (IRS) and could therefore improve its efficiency by increasing the production size; if $SE_o > 1$ the DMU is operating at decreasing returns to scale (DRS) and by reducing the production scale the DMU could improve its efficiency.

Super-efficiency DEA model

As pointed out by many authors, DEA model results, being relative measures, are strictly affected by the characteristics of the considered sample and, in particular, by the presence of possible outliers.

In addition, when a large number of DMUs are considered, it has been noticed that such models tend to overestimate the number of efficient units, especially in situations of multi-inputs and multi-outputs.

To overcome such limitations, and to discriminate better among DEA-efficient DMUs, the S-DEA model has been implemented. Its formulation is similar to the standard DEA model, with the difference that the DMU_o under evaluation is excluded from the reference set:

$$\begin{aligned} & Max_{\theta_o,\lambda_k}\theta_o^S \\ & \text{s.t.} \\ & \sum_{k=1,k\neq o}^{K} \lambda_k x_{ik} \leq x_{io}, \forall i = 1,2,\ldots,I; \\ & \sum_{k=1,k\neq o}^{K} \lambda_k y_{jk} - \theta_o y_o \geq 0, \forall j = 1,2; \\ & \lambda_k \geq 0; k = 1,2,\ldots,K, k \neq o \end{aligned} \tag{6}$$

The output-oriented CRS super-efficiency ($S\text{-}EFF_o$) of DMU_o can be expressed as:

$$S\_EFF_o = \frac{1}{\theta_o^S} \tag{7}$$

The value of $S\text{-}EFF_o$ of an overall technically efficient farm could be greater than 1, while inefficient farms have the same scores obtained from the CCR model, assuming CRS.

Since it has been widely demonstrated that super-efficiency models under the assumption of VRS suffer from infeasibility problems (Banker et al. 1984; Seiford and Zhu 1999; Lee and Zhu 2012), only the super-efficiency model based upon CRS conditions was implemented in this paper. All the above-mentioned models were solved in the General Algebraic Modelling System (GAMS) environment.

Second stage: censored regression analysis

To analyse the effect of animal welfare factors on the efficiency of the sheep farms involved, a regression model was estimated by including CCR and BCC DEA scores as endogenous variables.

However, the standard Ordinary Least Squares (OLS) model is not suitable for such analysis, as the dependent variable is left and right censored, thus leading to inconsistent parameter estimates (Barassi 2006). Also, the predicted values of efficiency scores may not belong to the unit interval of the observed dependent variable.

To solve these problems, most of the reviewed studies (Fethi et al. 2000; Latruffe et al. 2004; Bravo-Ureta et al. 2007) that adopted a two-stage DEA approach used, for the second stage, a censored normal regression analysis such as the Tobit model (Tobin 1958), by assuming censoring at values of 0 and 1. The response variables (i.e. OTE_o and TE_o) are assumed in our hypothesis to be a linear, additive and separable functions of the k-farm observable animal welfare factors.

The general structure of the two-limit Tobit model (with both lower- and upper-tail censoring) can be formalised analytically as follows:

$$y_k^* = \alpha + X_k\beta + \varepsilon_k \tag{8}$$

where y_k^* is a latent endogenous variable that is observed for values greater than 0 and smaller than 1, and censored otherwise; α is the unknown intercept, $\varepsilon_k \sim iidN(0,\sigma^2)$, X_k represents the vector of covariates, and β is the parameter vector to be estimated, measuring the linear effects of animal welfare explanatory variables on the efficiency score.

The observed censored variable y_k, represented by the efficiency scores deriving from the first stage, can be defined as follows:

$$y_k = \begin{cases} y_k^* if 0 < y_k^* < 1 \\ 1 if y_k^* \geq 1 \\ 0 if y_k^* \leq 0 \end{cases} \tag{9}$$

Two Tobit models were estimated, respectively considering OTE_o and TE_o as dependent variables, by using the maximum likelihood procedure with White estimator to obtain robust standard errors. All the statistical analyses were carried out in Stata 12.

Before the estimation, a correlation analysis between the DEA inputs/outputs and the regressors was carried in order to prevent bias in the Tobit estimates (Coelli et al. 2005).

Moreover, several post-estimation tests were performed in order to check for multicollinearity between independent variables (variance inflation factors, VIFs) and to correct model specification (Link test; Pregibon 1980).

As β parameter estimates represent the marginal effects on the latent dependent variable y_k^*, two relevant non-linear marginal effects are suitable to be estimated to measure the effect on the mean value of the observed y_k in respect to a change in x_k (Wooldridge 2002; Hoff 2007).

In particular, the marginal effects on the expected value of y_k conditional on being uncensored, and the marginal effects on the unconditional expected value of y_k (McDonald and Moffitt 1980) were calculated in order to account for differences in the influence of animal welfare factors on efficiency scores between not fully efficient farms and the entire sample.

Results

Descriptive statistics of first stage: DEA variables

Descriptive statistics of the input and output variables of the sample are reported in Table 2. In relation to the considered outputs, on average, the 76 sheep farms produced 2618.31 kg of meat and 244.28 kg of wool per year. Both values were highly variable among sampled farms, as highlighted by the extent of the min–max range and the standard deviation values.

In relation to inputs, the mean flock size was 167.87 LSU, with a minimum of 6 and a maximum of 730 LSU.

To this regard, the relationship between the annual meat production and the LSU number (Figure 1) confirms the high degree of heterogeneity affecting the involved farms, which mostly show a limited size, as their high concentration near the axis origin highlights. As expected, a linear association between the two variables was observed.

With reference to labour use, the sampled farms employed on average 1.87 Man Working Units for the zootechnical activities, with differences associated with flock size, stable management and livestock housing choices. Regarding nutrition, the mean annual feed supply was 33.76 t of dry matter and ranged between 0.77 and 187.90 tons of dry matter, depending on the LSU number. The agricultural area used for the production reused in zootechnical activities was 97.84 ha on average and featured a high level of variability among sampled farms.

Descriptive statistics of second stage: Tobit regression variables

Variables entered in the Tobit regression models are reported in Table 1. As highlighted by the available data, on a total of 76 farms the prevailing farming systems were either semi-intensive or semi-extensive (n = 59, 77.6%), against the farms relying on a confined system (n = 17, 22.4%).

Regarding structural aspects, the infirmary area was absent in 46 out of the 76 farms, with the remaining 30 displaying an optimally managed infirmary. Data regarding biosecurity procedures highlighted a complete absence of access control and precautions for visitors in half of the sample (n = 38), and incomplete and unsystematic biosecurity protocols in the remaining half. A total of 28 farms showed sufficient housing and feeding space and 18 farms showed a more than adequate space dimension. Inadequate management of pre-lambing and lambing areas was found in 24 farms. Half of the sampled farms did not own a dedicated feed stocking area.

Most of the farms (n = 40, 52.6%) showed fairly clean premises for almost all breeding groups while cleanliness of bedding and housing premises resulted correctly managed for all breading groups in 20 farms. Moreover, most of the farms were characterised by an optimal cleanliness of livestock (n = 63, 83%) showing less than 20% of dirty individuals.

Veterinary assistance was completely absent in 14 out of the 76 sampled farms. Technical training of on-farm workers was better represented, with 26 farms employing workers with at least 7 years of working experience in addition to at least one farming course, although the majority of farms (n = 43, 56.6%) employed experienced workers with no history of training courses.

In relation to veterinary and health aspects, 11 farms relied on empirical vaccination programmes, whereas only 9 among the sampled population had a vaccination programme defined by the attending veterinarian.

The BCS data highlighted a prevalence of positive results: the majority of the sample (47 farms) showed less than 5% of animals having BCS beyond acceptable limits – less than 2 or more than 4 in a 5-point scale according to Munoz et al. (2019) – in relation to the physiological status of the sheep.

Regarding nutritional management, water availability was ensured by fully working water through in the majority of the farms (n = 46), while only 20 of them

Table 2. Descriptive statistics of the input and output variables of the sample (N = 76).

Inputs/outputs	Variable	Unit	Min	Max	Mean	Standard deviation
Output 1	Meat	Kg	118.80	11550.00	2618.31	2823.45
Output 2	Wool	Kg	0.00	1100.00	244.28	273.26
Input	Livestock Unit	LSU	6.00	730.00	167.87	176.80
Input	Labour	Man working unit	1.00	5.00	1.87	1.00
Input	Feed	Tons of dry matter	0.77	187.90	33.76	43.50
Input	Utilised agricultural area	Ha	0.00	610.00	97.84	131.91

showed *ad libitum* access to water. The feed ration formulation was found to be mainly empirical (50 out of 76 farms) and based on grazing and in-stable supplements of hay and unprocessed feeds (69 out of 76 farms). Feed was totally self-supplied by 16 out of the 76 farms. Grazing was widely applied; 48.7% of the farms let animals graze all year round with a rotational grazing technique, and the same amount adopted a rotational grazing model.

Replacement rate data showed a mean of 22% of replacement per year, moving from zero to a maximum of 49%.

DEA models

The results obtained by the DEA models by implementing Equations (1)–(7) are reported below. Table 3 shows summary statistical indices of farm efficiency scores in terms of overall technical efficiency (OTE), pure technical efficiency (TE), scale efficiency (SE) and super-efficiency (S-EFF). The absolute and relative frequency distributions of the sample in terms of OTE, TE, SE and S-EFF are shown in Table 4.

Focussing on CRS, a quite high level of overall efficiency performance was estimated, as shown by the average value of OTE of 0.80, varying within the range of 0.44–1. The frequency distribution revealed a high degree of variability in terms of OTE performance among the sample, since most of the farms were located in the upper part of the distribution. In fact, the overall fully efficient farms represented the most numerous class, accounting for 23.7% of the total; moreover, when the two upper classes were considered jointly, more than one-third of the entire sample showed an OTE-value of >0.9, revealing a high-performing production process. The remaining farms were equally distributed in the other classes (from 0.50 to 0.9), while only one farm had an OTE below 0.5. Under VRS, 27 farms out of the 76 (35.5%) were found to be fully technically efficient; the TE level varied from 0.49 to 1.0, with a standard deviation of 0.16, resulting in average TE-value of 0.85.

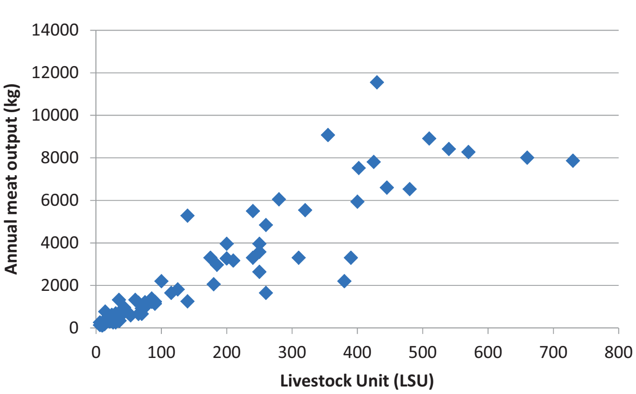

Figure 1. Annual meat output by Livestock Unit (LSU).

When comparing efficiency under the different scale assumptions through the SE scores, 17 farms (22.37%) showed a scale efficiency of 1.0, thus implying that they were operating at the optimal production scale. In terms of distribution, the vast majority of the farms (77.6%) performed with a scale efficiency greater than 0.9, with no farm showing an SE score below 0.6.

However, although a high SE was estimated, 56 farms (73.68%) exhibited IRS, thus showing potential benefits from increasing their farm size.

Scale efficiency showed a range of variation between 0.63 and 1.22, with an average value of 0.95 and a standard deviation of 0.08.

In Table 3, the results of super-efficiency DEA model are also provided. The overall technically fully efficient farms had a super-efficiency varying from 101.66% and 158.28%, with an average score of 126.83% and a standard deviation of 19.22. Hence, the worst super-efficient farm of the OTE-efficient ones showed an output surplus of 1.66%, while the extremely super-efficient DMU accounted for 58.28% over-performing productivity.

Tobit regression models

The results of the truncated regression analysis implemented in the second stage are provided in this paragraph. Before proceeding to a more in-depth characterisation of the model estimates, a brief description of the post-estimation tests results has to be analysed in order to check for potential model specifications.

The *F*-test of 2.98 and 3.14 for the OTE and TE models, respectively, and the *p* value of .000 in both cases confirmed that our model as a whole was statistically significant with respect to the null hypothesis with all zero-coefficient predictors. The VIF-test confirmed the absence of multicollinearity between the independent variables, as the test resulted in an average value of 2.53, with no variable showing VIF > 4.7. Moreover, for both Tobit models, the link test was passed, since the linear predicted value-squared terms were not significant, implying that the models were correctly specified, conditional on the specification of the dependent variable.

Table 5 reports the estimates of the Tobit models: two different equations were estimated, by considering OTE and TE as endogenous variables, respectively. The animal welfare factors selected above, representative of the different aspects of livestock management, were assumed to affect the efficiency performance and were hence included as regressors. Based on the coefficient estimates, in Table 6 the conditional and unconditional marginal effects for the significant variables are provided.

For both models, out of the 25 considered covariates six were found to be significant in explaining the postulated relationship, i.e. farming system, presence of access control structures, lower class percentage of animals with BCS beyond acceptable limits, presence of well managed birthing pens, replacement rate and the presence of dedicated feed stocking areas.

After comparing the two estimated marginal effects (MEs) for the two models, the ME for the unconditional expected value was only slightly larger, in absolute value, than the ME for the expected value of efficiency, conditional on being uncensored. This depends on the smaller variation in the range of y being considered in this latter case; however, no significant differences of censoring were detected in this regard. For this reason, only the ME for the unconditional expected value will be discussed below.

Regarding the farming system, a negative and significant effect on efficiency scores was estimated when a more extensive rearing system was adopted; in particular, the associated decreases in the unconditional expected values of TE and OTE were 0.113 and 0.101, respectively.

Among animal housing and structural aspects, providing the farm with biosecurity procedures involving access control and precautions for visitors was associated with remarkable 0.094 and 0.075 increases in OTE and TE, respectively. To a lower extent, the presence of birthing pens, appropriate use of birthing pens and sufficient bedding hygiene also resulted in positive MEs of 0.057 (OTE) and 0.054 (TE). Moreover, when feed was stored in a dedicated feed stocking area, the efficiency scores were positively affected, as the MEs of 0.096 (OTE) and 0.031 (TE) showed. In this regard, it must be noted that this is the only case where the two MEs were quite different, highlighting how the presence of feed stocking areas affected OTE by influencing mainly the SE. In fact, when the scale dimension was not taken into consideration (TE), its effect decreased significantly.

Regarding cleaning practices, no significant effects were estimated on efficiency for the cleanliness of both bedding and housing premises and that of the animals. Similarly, the effects of training activities and technical assistance were not significant in any of the regressions, as were veterinary services.

Concerning health and veterinary aspects, only the more restrictive level of BCS (i.e. less than 5% of

Table 3. Overall, technical and scale efficiency and super-efficiency of the sample (N = 76).

DEA indices	Overall technical efficiency (OTE)	Pure technical efficiency (TE)	Scale efficiency (SE)	Super-efficiency of overall technical efficient farms (S-EFF) (%)
Min	0.44	0.49	0.63	101.66
Max	1.00	1.00	1.22	158.28
Mean	0.80	0.85	0.95	126.83
Standard deviation	0.16	0.16	0.08	19.22
Efficient farms (%)	23.68	35.53	22.37	
No. of Constant Returns to Scale (CRS) farms		17 (22.37%)		
No. of Increasing Returns to Scale (IRS) farms		56 (73.68%)		
No. of Decreasing Returns to Scale (DRS) farms		3 (3.95%)		

Table 4. Frequency distribution of farms, by technical and scale efficiency estimates from the DEA models.

	Overall technical efficiency (OTE)		Pure technical efficiency (TE)		Scale efficiency (SE)	
Efficiency, θ	No. of farms	%	No. of farms	%	No. of farms	%
<0.5	1	1.32%	1	1.32%	–	–
$0.5 \leq \theta < 0.60$	11	14.47%	5	6.58%	–	–
$0.6 \leq \theta < 0.70$	13	17.11%	15	19.74%	1	1.32%
$0.7 \leq \theta < 0.80$	13	17.11%	9	11.84%	3	3.95%
$0.8 \leq \theta < 0.90$	12	15.79%	14	18.42%	10	13.16%
$0.9 \leq \theta < 1$	8	10.53%	5	6.58%	42	55.26%
$\theta = 1$	18	23.68%	27	35.53%	17	22.37%
$\theta > 1$	n.a.	n.a.	n.a.	n.a.	3	3.95%
Total	76	100%	76	100%	76	100%

Table 5. Tobit regression models estimates.

		Overall technical efficiency (OTE)			Pure technical efficiency (TE)		
Variable	Definition and measurement	Coefficient	Robust standard error	*p* Value	Coefficient	Robust standard error	*p* Value
FARMSYS	1 = semi-intensive/semi-extensive farming system; 0 = confined farming system	−0.137**	0.062	.030	−0.145**	0.069	.041
INFIRMARY	1 = presence of infirmary area; 0 = otherwise	0.046	0.039	.251	−0.021	0.045	.652
PRECACCESS	1 = presence access control structures, yet procedures for vehicles and visitors are incomplete and unsystematic; 0 = otherwise	0.114**	0.053	.035	0.106*	0.058	.074
SPACEADEQUACY1	1 = just sufficient housing space in the resting areas and/or feeding space just sufficient for the number of housed animals; 0 = Insufficient housing space in the resting areas and/or inadequate feeding space per animal	−0.053	0.093	.573	−0.041	0.100	.684
SPACEADEQUACY2	1 = more than adequate housing space in the resting areas and/or feeding space in excess of the required; 0 = Insufficient housing space in the resting areas and/or inadequate feeding space per animal	0.044	0.108	.686	0.158	0.111	.160
BIRTHMANAG	1 = presence of birthing pens, correct use of birthing pens and sufficient bedding hygiene; 0 = absence of birthing pens or incorrect use of birthing pens and inadequate hygiene of bedding	0.068*	0.038	.077	0.088*	0.047	.066
STOCKINGAREAS	1 = presence of dedicated feed stocking areas; 0 = otherwise	0.119**	0.048	.022	0.192***	0.049	.000
CLEANHOUSE1	1 = fairly clean premises for almost all breeding groups; 0 = dirty premises for almost all breeding groups	−0.052	0.068	.449	−0.081	0.072	.263
CLEANHOUSE2	1 = correctly managed, clean and dry premises for all breading groups; 0 = dirty premises for almost all breeding groups	−0.068	0.087	.442	−0.126	0.097	.199
CLEANLIVESTOCK	1 = less than 20% of dirty livestock; 0 = more than 20% of dirty livestock	−0.031	0.053	.559	−0.014	0.060	.817
VETASSIST	1 = presence of veterinary technical assistance; 0 = otherwise	−0.037	0.054	.501	−0.022	0.065	.738
WORKTRAIN1	1 = workers have at least 7 years of working experience with no training course or less than 7 years of working experience with attendance of at least one training course on farming; 0= less than 7 years of working experience and no training course	−0.064	0.061	.300	−0.037	0.078	.640
WORKTRAIN2	1 = workers have at least 7 years of working experience and a training course on farming; 0= less than 7 years of working experience and no training course	0.009	0.068	.897	0.080	0.085	.353
BCS1	1 = between 5% and 10% of animals with BCS beyond acceptable limits; 0 = more than 10% of animals with BCS beyond acceptable limits	−0.027	0.063	.667	−0.051	0.068	.462
BCS2	1 = less than 5% of animals have BCS beyond acceptable limits; 0 = more than 10% of animals with BCS beyond limits	0.141**	0.056	.015	0.143**	0.066	.034

(*continued*)

Table 5. Continued.

Variable	Definition and measurement	Overall technical efficiency (OTE) Coefficient	Robust standard error	*p* Value	Pure technical efficiency (TE) Coefficient	Robust standard error	*p* Value
VACCINSMANAG1	1 = presence of an empirical vaccination program; 0 = absence of a vaccination program	0.015	0.080	.853	0.098	0.094	.300
VACCINSMANAG2	1 = presence of a vaccination program defined by the veterinarian; 0 = absence of a vaccination program	0.056	0.082	.497	0.101	0.087	.253
WATERAV1	1 = presence of fully working water troughs for all groups; 0 = no access to water or not *ad libitum* access for one or more animals	0.079	0.068	.249	0.117	0.072	.111
WATERAV2	1 = *Ad libitum* access to water for all groups is available; 0 = No access to water or not *ad libitum* access for one or more animals	−0.038	0.066	.561	0.030	0.076	.692
RATIONMANAG	1 = specific ration for each breeding group (ewe-lambs, dry-off period, lactation) is adopted; 0 = empirical ration and no evaluation of nutritional requirements	0.017	0.043	.701	0.015	0.050	.760
FEEDMANAG	1 = grazing and in-stable supplement of hay and grains and other unprocessed feeds is provided; 0 = grazing and in-stable supplement of hay and processed commercial feeds (pellet, etc.)	−0.043	0.068	.529	0.014	0.079	.858
FEEDSELFSUFF	1 = feed is totally self-supplied; 0 = otherwise	0.076	0.070	.283	0.103	0.081	.210
GRAZING	1 = animals graze all year long; 0 = otherwise	−0.005	0.043	.904	−0.011	0.046	.810
ROTGRAZING	1 = rotational grazing is adopted; 0 = otherwise	−0.018	0.039	.649	−0.048	0.045	.286
REPLRATE	%	−0.003**	0.001	.014	−0.004**	0.002	.049
_cons		0.845***	0.126	.000	0.764***	0.162	.000
Log pseudolikelihood		17.084			3.007		
Number of obs		76			76		
F(25,51)		2.98			3.140		
Prob > F		0.000			0.000		
Number of censored observations		17 right censored observations			27 right censored observations		

*$p < .100$, **$p < .050$, ***$p < .001$.

Table 6. Marginal effects (MEs) of significant variables from the Tobit regression models.

		Overall technical efficiency (OTE)		Pure technical efficiency (TE)	
Variable	Definition and measurement	MEs for the expected value of OTE conditional on being uncensored	MEs for the unconditional expected value of OTE	MEs for the expected value of TE conditional on being uncensored	MEs for the unconditional expected value of TE
FARMSYS	1 = semi-intensive/semi-extensive farming system; 0 = confined farming system	−0.096	−0.113	−0.081	−0.101
PRECACCESS	1 = presence access control structures, yet procedures for vehicles and visitors are incomplete and unsystematic; 0 = otherwise	0.063	0.094	0.059	0.073
BIRTHMANAG	1 = presence of birthing pens, correct use of birthing pens and sufficient bedding hygiene; 0 = absence of birthing pens or incorrect use of birthing pens and inadequate hygiene of bedding	0.046	0.058	0.051	0.064
STOCKINGAREAS	1 = presence of dedicated feed stocking areas; 0 = otherwise	0.075	0.096	0.108	0.031
BCS2	1 = less than 5% of animals have BCS beyond acceptable limits; 0 = more than 10% of animals with BCS beyond limits	0.100	0.119	0.081	0.102
REPLRATE	Replacement rate (%)	−0.002	−0.003	−0.002	−0.002

animals with a BCS beyond acceptable limits) was found to affect positively the efficiency scores, with ME-values of 0.100 and 0.102 for OTE and TE, respectively.

None of the involved variables concerning feeding and watering practices, or grazing management, were found to influence significantly the efficiency scores for both models.

Lastly, a slight and negative coefficient was found with regard to replacement rate: increasing the replacement rate by 1% resulted in decreases in the OTE and TE scores by 0.003 and 0.002, respectively.

Discussion

Our study highlights a lack of specialised technical assistance and training, with the inadequacy of sanitary aspects, such as biosecurity measures and vaccination programs. This lack of technical assistance is common in the semi-extensive farming scenario in central Italy, due to the underlying social, historical and economic conditions(Rossi 2017).

The overall efficiency performance results concerning CRS implied that, on average, a potential increase of 20% in terms of output production would be feasible for the inefficient farms, by keeping stable the current level of inputs and assuming no change in production technology. Under VRS, results suggested that a potential gain of 15% in terms of output production could be possible if the inefficient farms were to adopt the observed best practices of efficient farms. These results indicate the improvement of the inputs management, rather than the optimisation of the farm-scale, as the main strategy to increase efficiency, as already suggested by other authors (Fousekis et al. 2001; Psychoudakis and Theodoridis 2006; Theocharopoulos et al. 2007; Dalgic et al. 2018).

The analysis of SE values confirms the limited effect of farm-scale optimisation. If all inefficient farms were to operate at the optimal scale, only a 5% potential increase in outputs production could be obtained without any change in input level.

The improvements in animal welfare indicators were not farm-scale-dependent in our study, suggesting that such improvements could be successfully applied to both small and large farms.

Regarding the farming system, our results confirmed the existence of a trade-off between efficiency and intensity of the livestock housing system, as pointed out in many studies involving different species, systems and study areas. However, pasture-based sheep systems are more environmentally sustainable than evolved farming systems (Rodríguez-Ortega et al. (2017). The adoption of extensive DEA models, able to provide a measure of farm environmental efficiency, could valorise the sustainability of sheep farming in marginal lands, finally increasing the value of their products.

Housing factors affect significantly the efficiency performance. Diversely, the presence of infirmary, as well as housing space in the resting areas and/or feeding space, did not seem to have any influence on OTE or TE. These results are probably due to the composition of our sample since the number of farms satisfying these requirements was low.

Significant effects were detected for the presence of access control structures, a well-known biosecurity measure. Biosecurity measures such as access control aim to contain the risk of infectious agents and parasites entering the farm. The presence of a dedicated feed stocking area implies better preservation of feedstuffs, which can prevent the formation of mould and the risk of mycotoxin ingestion, a threat to both animal and human health (Yang et al. 2020). All these measures contribute to the on-farm improvement of animal welfare and health, which can significantly enhance production performance while reducing losses (Dawkins 2016).

The significance of birth management can be explained by the fact that advanced perinatal care improves lamb survival rates (Douglas and Sargison 2018) and that good sanitary conditions reduce the risk of uterine infections associated with lambing, which adversely affect sheep health and fertility (Đuričić et al. 2016).

The results associated with the replacement rate confirm that increasing livestock longevity is an effective strategy to improve efficiency: these results are consistent with those estimated in different livestock systems by Allendorf and Wettemann (2015) and Lawson et al. (2004).

Body condition score, together with the farming system, was confirmed to be one of the most important driving factors for the efficiency performance of our sample, as it is widely regarded as a fundamental animal-based welfare indicator (Richmond et al. 2017; Phythian et al. 2019). It is conceivable to expect that optimal BCS scores, which are associated with better animal welfare, have a positive influence on animal health status, productive/reproductive performance and farm efficiency. BCS evaluation represents a simple and low-cost method of evaluating the adequacy of nutritional management and, more in general, animal welfare condition (Munoz et al. 2019).

The main limit of this study is the small sample size, which could affect the accuracy of estimation of the efficiency frontier. However, given the relatively small extent of the analysed study area, it can reasonably be assumed that the sample is sufficiently representative of sheep meat farming in central Italy. Another limit is represented by the deterministic approach of the DEA models in respect of efficiency assessment; in this regard, the impossibility of interpreting the results in a frame of statistical significance could limit their internal and external validity. Other strategies, as increasing sample size or performing bootstrapping techniques or sensitivity analysis, could address the uncertainty issue on data or sampling errors, finally improving the robustness of the estimates.

Conclusion

By focussing on the sheep farming sector in central Italy, this paper integrated DEA and Tobit models to test the hypothesis that farms which are high-performing in terms of animal welfare indicators are also more technically efficient.

We identified the lack of effective technical management as the main source of inefficiency, which depends, consequently, only to a less extent on the farm production scale. This finding should encourage farms to improve their production techniques and optimise their use of input, to reach the efficient ones along the frontier.

The Tobit estimates highlighted how implementing specific animal health-enhancing actions result in improved farm efficiency: a win-win scenario that can simultaneously meet both economic and social goals.

Our study provides indications to guide sheep farmers operating in marginal lands, as well as information for policymakers who may want to implement animal-welfare-related policy actions in these areas.

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Ethical approval

For this study economic and productive figures were used and the approval of the Ethical Committee of the University of Perugia was not required.

Author contributions

Conceptualisation: L.C. and M.C.; methodology: L.C.; formal analysis: L.C.; investigation: A.D.U., S.A.M., and L.V.; resources: M.C.; data curation: A.D.U., S.A.M. and C.F.; writing – original draft preparation L.C.; writing – review and editing C.F., L.V. and M.T.-M.; supervision C.M., M.C. and M.T.-M.; project administration: C.M.; funding acquisition: C.M.

Disclosure statement

The authors declare no conflict of interest associated with the paper. The authors are fully responsible for the content of the manuscript.

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