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A NOVEL EFFICIENCY ASSESSMENT OF DAIRY FARM SUSTAINABILITY

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SUMMARY

World food production must increase to meet greater future demand without exacerbating climate change and despite dwindling resources. More efficient dairy farm production is therefore essential if farms are to become- and remain- economically, socially and environmentally sustainable. This study introduced a novel Data Envelopment Analysis framework and demonstrated its superiority over the widely-applied, and so-called, radial models, by using data from a long-term dairy systems experiment comprising of four distinct systems. Not only was the novel model able to provide better measures of technical, environmental and cost efficiencies than radial models, but also it allowed for the disaggregation of efficiencies into resource-specific savings potentials, helping identify specific aspects in which each system could perform better. This exercise highlighted the invaluable contribution that robust modelling methods and data capturing technologies can make to dairy farm sustainability assessments and discussed opportunities for further research.

INTRODUCTION

Agriculture in the EU (and elsewhere in the developed world) aims for resource-use efficiency with policy increasingly focused on compliance with socio-economic and environmental sustainability standards and less on production controls. Wider definitions of efficient dairy farm production are therefore essential if dairy farms are to be and seen to be sustainable from an economic, social and environmental viewpoint.

The operational research method of Data Envelopment Analysis (DEA) has been used to measure dairy farm efficiency combining a range of performance criteria (e.g. Hansson and Öhlmér, 2008; Toma *et al*., 2013). Nevertheless, all studies identified in the literature have used models which not only ignore the substitutional nature of some of the dairy farms' resources, but also do not account for any potential resource/undesirable output excesses or output shortfalls when evaluating efficiency. Thus, the efficiency score is the only performance indicator and, consequently, it can only provide limited information value.

The aim of this study was to present a DEA framework which overcomes the limitations of models that have been used in past dairy farm efficiency studies. The demonstration of this framework was undertaken within an efficiency-based farm sustainability context, through the measurement of relevant indicators which can be of high information value to both farmers and policy-makers. The authors of this article did not identify any other dairy farm DEA assessments using the framework presented here and envisaged that its advantages will

significantly improve, and contribute to, (dairy) farm sustainability assessments.

MATERIALS AND METHODS

Modelling Framework

Data Envelopment Analysis (DEA) is a method for measuring the capacity of Decision Making Units (DMUs) to convert inputs into outputs. See Cooper *et al*. (2007). All DEA dairy studies identified in the literature have used radial models which have two well-known drawbacks. First, any input (output) reduction (improvement) is assumed to be equiproportional, i.e. they assume a given input (output) mix. Second, they do not account for the potential presence of input (output) excesses (shortfalls), i.e. slacks (Tone, 2001). This means that they are unable to indicate by how much the excess or shortfall of a particular resource has contributed to the efficiency performance of a specific DMU.

Tone (2001) proposed a non-radial, slacks-based model; the so-called slacks-based measure of efficiency (SBM). Because SBM accounts for slacks in the calculation of efficiency, it has been mathematically proven that it discriminates better than radial models (Tone, 2001). In this study, SBM variants were used to calculate the technical (TE) and environmental efficiency (EE) of dairy farms. The SBM scores were then used for the calculation of the farms' economic (cost) efficiencies (CE). The CE model used here is superior to the widely used Farrell-Debreu model (e.g. Hansson and Öhlmér, 2008) in that it does not assume identical input costs for each DMU (Cooper *et al*., 2007).

Suppose that there are n DMUs each having m inputs and s outputs represented by two vectors $\boldsymbol{x} \in \boldsymbol{R}^m$ and $\boldsymbol{y} \in \boldsymbol{R}^s$ respectively. Let us define the matrices $X = [x_1, \dots, x_n] \in \boldsymbol{R}^{m \times n}$ and $Y = [y_1, \dots, y_n] \in \boldsymbol{R}^{s \times n}$, with $X > 0$ and $Y > 0$. The SBM model is the following fractional programme:

$$\min_{\boldsymbol{s}^-, \boldsymbol{s}^+, \boldsymbol{\lambda}} \rho = \frac{1 - \frac{1}{m}\sum_{i=1}^{m} s_i^- / x_{io}}{1 + \frac{1}{s}\sum_{r=1}^{s} s_r^+ / y_{ro}}$$

subject to

$$\boldsymbol{x}_o = X\boldsymbol{\lambda} + \boldsymbol{s}^-$$
$$\boldsymbol{y}_o = Y\boldsymbol{\lambda} - \boldsymbol{s}^+$$

$\boldsymbol{s}^- \geq \boldsymbol{0}, \boldsymbol{s}^+ \geq \boldsymbol{0}, \boldsymbol{\lambda} \geq \boldsymbol{0}$,

where the vectors $\boldsymbol{s}^- \in \boldsymbol{R}^m$ and $\boldsymbol{s}^+ \in \boldsymbol{R}^s$ correspond to input excesses and output shortfalls (slacks) respectively, $\boldsymbol{\lambda} \in \boldsymbol{R}^n$ is a nonnegative vector and $\boldsymbol{0} \in \boldsymbol{R}^n$ is a vector of zeros. A linear equivalent of SBM can be found in Tone (2001). Once the SBM has been solved, the optimal slacks $\boldsymbol{s}^{-*}, \boldsymbol{s}^{+*}$ for DMU_o can be used to examine variable-specific patterns, e.g. input/undesirable output savings potentials, by calculating the ratio of each slack over its corresponding input/undesirable output. SBM can be modified to an input-oriented model representing TE or to account for the minimization of undesirable outputs, representing EE. See Cooper *et al*. (2007). Unlike radial models, SBM for EE allows for the simultaneous minimization of inputs and undesirable outputs, and for the maximization of desirable outputs. Also, it considers undesirable outputs as such, rather than transforming them into debatable forms, such as considering them as inputs, inverse outputs, etc. (Scheel, 2001).

After the TE scores have been calculated, the CE of DMU_o is calculated by the ratio C/C_o, where $C_o = \sum_{i=1}^{m} c_{io}x_{io}$ $(o = 1, \dots, n)$ is the actual (observed) input cost for DMU_o, and C can be calculated by the following linear program:

$$C = \min_{\boldsymbol{x}',\boldsymbol{\mu}} \boldsymbol{e}\boldsymbol{x}'$$
$$\boldsymbol{x}' \geq X'\boldsymbol{\mu}$$
$$\boldsymbol{y}_o \leq Y\boldsymbol{\mu}$$
$$\boldsymbol{\mu} \geq \boldsymbol{0},$$

where $X' = (x'_1, \dots, x'_n) \in \boldsymbol{R}^{m\times n}$, $x'_j = \left(x'_{ij}, \dots, x'_{mj}\right)$, $x'_{ij} = c_{ij}x^*_{ij}$, c_{ij} is the cost of input i for DMU_j, $\boldsymbol{x}^*_j$ represents the technically efficient input for producing $\boldsymbol{y}_j$, i.e. $\boldsymbol{x}^*_j = \boldsymbol{x}_j - \boldsymbol{s}_j^{-*}$ and $\boldsymbol{e}$ is a row vector with all elements being equal to 1.

Data

Data were obtained from Scotland's Rural College (SRUC) 7-year genetic line × feeding Holstein-Friesian dairy systems experiment (Pollott and Coffey, 2008). The so-called Langhill herd comprised of a select (S) line: selected for the highest fat+protein kg of predicted transmitting abilities (PTA) at the time of artificial insemination (AI); and of a control (C) line: selected to have the average genetic merit for fat+protein kg at the time of AI. The herd was managed with one group kept indoors on a low forage (LF) diet and the other group on a high forage (HF) diet with summer grazing. Thus, there were four distinct systems in the experiment, namely High Forage Control (HFC); High Forage Select (HFS); Low Forage Control (LFC); and Low Forage Select (LFS).The number of animals in each system was about 50 per year. In this study, as in Toma *et al*. (2013), each system was considered as a different DMU for each of the 7 years of the experiment, thus resulting in a total of (7 years) × (4 systems) = 28 DMUs.

For the calculation of TE, EE and CE of the 28 DMUs, the following data were used. Inputs: replacements (numbers), labour (h), land use (ha), nitrogen (N) fertilizer (t N) and dry matter (DM) of feed (t DM); outputs: milk (t energy-corrected milk) and animals sold (numbers); undesirable outputs: greenhouse gas (GHG) emissions (t CO_2 equivalents), N surplus (t) and phosphorous (P) surplus (t). All data except for labour were calculated by Toma *et al*. (2013) using data from the Langhill database. Regarding labour, data from DairyCo's (2012) *Milkbench+* report were used. The report provides labour data for three farm types, namely Cows at Grass, Composite and High-output Cows. In this study, labour data for Cows at Grass corresponded to HFC; Composite to LFC; High-output Cows to LFS; and the average of High-output Cows and Cows at Grass to HFS. Economic data (£/input) were obtained from the following sources: DairyCo's website (http://www.dairyco.org.uk/); the *Milkbench+* report (DairyCo, 2012); SAC Consulting, who publish an annual Farm Management Handbook (SAC Consulting, 2010); and, where available, from Langhill's own accounting data. In order to ensure consistency between data sources, data for the financial year 2010/11 (April 2010-March 2011) were used.

RESULTS

All calculations and visualizations were run in the programming language R. In order to demonstrate the differences between radial and SBM models, the radial, input-oriented, measure of technical efficiency (denoted as TE_R), see Cooper *et al*. (2007), was calculated and

compared to TE. Absolute differences between each inefficient DMU's TE_R and TE scores ranged between 0.04-0.19 and TE individual scores were, as expected, not greater than their corresponding TE_R scores. These observations indicated the drawbacks of radial measures in that they do not account for the potential presence of input slacks.

Appropriate statistics for the non-normally distributed efficiency scores TE, EE and CE were summarised in box plots (Figure 1).

The non-parametric Spearman's *rho* rank correlation coefficient was used to test correlation between TE, EE and CE (Table 1). TE and EE were strongly correlated, suggesting the hypothesis that more technically efficient farms were also more efficient in reducing their wastes. CE and EE were modestly correlated, i.e. there was not a clear relationship between cost reduction and reduction of wastes. Notably, correlation between CE with TE was weak. Therefore, farms able to best minimize their inputs, given their output production, did not always manage to reduce their costs to the lowest possible levels, in comparison with their peers.

Table 1: Spearman's *rho* correlation coefficient to test for correlations between TE, EE and CE

Efficiency score	TE	EE	CE
TE	1.000		
EE	0.834	1.000	
CE	0.189	0.415	1.000

The non-parametric Kruskal-Wallis (KW) test was used to test for differences (at 5%) in efficiency scores between the four systems. The test found significant differences between systems for CE (K statistic = 17.679) and therefore a post-KW multiple comparison test (Siegel and Castellan, 1988) was run to determine which systems were different. Significant differences were identified between the following pairs of systems: HFC-LFC (K = 11.786); HFS-LFC (K = 17.357); and HFS-LFS (K = 11.929). Box plots (Figure 1c) of the CE scores by system provided a way of 'ranking' the aforementioned significant differences: clearly, the HFC system was better than LFC and LFS; and HFS was better than LFS. These results suggested that HF systems were more cost efficient than LF; this could be one reason for the observed weak correlation between TE and CE.

Using the optimal slacks calculated by the SBM model for EE, mean undesirable output slacks were expressed as percentages of undesirable output levels (Table 2).

Table 2: Mean undesirable output slacks expressed as percentages of undesirable output levels

System	% of undesirable output levels		
	GHG	N surplus	P surplus
HFC	14.8	11.4	13.9
HFS	2.4	2.7	0.0
LFC	9.1	10.3	7.2
LFS	2.2	5.3	5.2

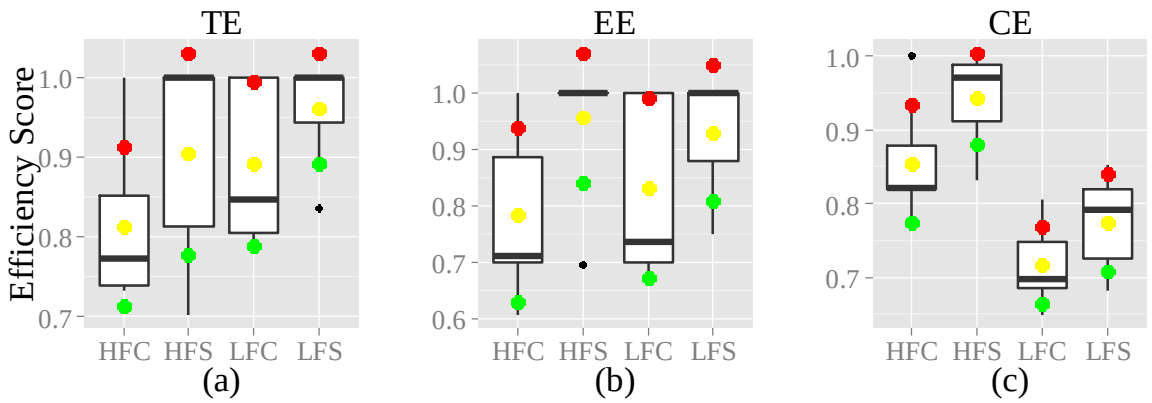

Figure 1: Box plots summarizing statistics for TE, EE and CE per system. Yellow dot: mean efficiency; red: mean efficiency + 1standard deviation; green: mean efficiency – 1standard deviation

HFC and LFC had the largest ratios for GHGs, N surplus and P surplus (Table 2). This could be attributed to the fact that C cows produce less milk per cow than S cows. The KW test found significant differences (K = 7.934) between HFC and HFS in terms of GHG savings potentials. This result could also indicate differences between the productivity of C and S animals, relative to their production of milk. Notably, HFS had very small ratios for all three pollutants, with the ratio for P surplus being equal to zero. While a savings potential equal to zero may look odd, it should be remembered that DEA is a relative measure and that this result indicates that HFS DMUs performed better than the rest regarding this particular pollutant.

DISCUSSION

This study presented a slacks-based DEA framework based on the SBM models of Tone (2001). The superiority of SBMs to radial DEA models, the latter having been extensively used in dairy farm efficiency assessments, was demonstrated through the measurement of a number of sustainability and resource-use indicators: technical efficiency (TE), environmental efficiency (EE), cost efficiency (CE), and undesirable output-specific savings potentials. The CE model presented here is not characterized by the unrealistic assumption of the widely-used Farrell-Debreu model that DMUs face identical input costs. Had TE and EE been calculated using radial models, it would have been impossible to achieve the depth of analysis presented here, for the following reasons. First, as radial models do not account for slacks, they tend to score higher, thus reducing the discriminatory power of DEA (as was the case with TE_R). Second, the calculation of slacks allowed for the measurement of variable-specific efficiencies (savings potentials), making it possible to compare farms in terms of specific aspects. Indeed, comparing the four systems' pollutant-specific savings potentials, rather than just comparing their EE scores, helped identify each system's ability to cope with each pollutant. Third, as mentioned above, a radial measure of EE would have unavoidably required the transformation of undesirable outputs into other, debatable forms (Scheel, 2001).

The advantages of the SBM framework could be of value to farm managers, policy-makers and, ultimately, society. On the one hand, decomposing efficiencies into variable-specific savings potentials can offer an in-depth comparison between different dairy farming systems. On the other, aggregating them into a single index (e.g. Despotis, 2005) can provide important

information at the policy-level. The latter could be a future step, as could also be the quantification of variability in the long-term performance of different systems. Given the robustness of the SBM framework in combination with an abundance of resource-use, environmental, and animal health data available in SRUC's Langhill database, there exist numerous opportunities for further research. Importantly, while Langhill was a controlled experiment, many of the data capturing technologies that were used to collect information are commercially available and increasingly being used by dairy farmers. Therefore, the suggested framework could soon be used for commercial dairy farm assessments.

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