Environmentally harmful by-products in efficiency analysis: An example of nitrogen surplus on Swiss dairy farms

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Abstract

Beside desirable outputs, farming generates environmentally harmful by-products. In this article, we include nitrogen surplus of farms in the representation of the production technology and assessed performance of farms. We measure environmental efficiency (EE) in the framework of a translog output distance function. EE shows by how much a farm can reduce its nitrogen surplus, given multiple inputs and multiple outputs. The study use bookkeeping data on dairy farms in the mountainous region of Switzerland. The analyses show that considering nitrogen surplus has a minor effect on the ranking of farms in terms of technical efficiency. Further, the results indicate relatively low average values for EE, suggesting a need for additional policy measures to reduce farm nitrogen surpluses.

Key words: efficiency analysis, environmental performance, nitrogen pollution, dairy farms

1. Introduction

In recent decades, significant efforts have been made to incorporate environmentally harmful by-products in traditional methods of farm productivity and efficiency analysis. The literature has pursued two main directions: incorporating by-products as additional input (Reinhard et. al., 1999; Fernandez et al., 2002; Ramilan et al., 2011) or as an undesirable output (Färe et al., 2005; Färe et al., 2006; Zhou et al., 2008). A few studies use additive or multiplicative inverse for transforming data on by-products such that the transformed data can be included as desirable output (Seiford and Zhu, 2002; Fleischman et al., 2009).

In this study, we employ stochastic frontier analysis (SFA) and incorporate the transformed by-product (1/by-product) as an additional output within the output distance function. We measure farm environmental efficiency (EE) and compare the obtained measure with other environmental indicators.

As an environmentally harmful by-product, we focus on nitrogen surplus of farms. Nitrogen pollution contributes to several environmental problems such as eutrophication, acidification, and climate change.

The remainder of this paper is structured as follows. Section 2 addresses model specification and illustrates the calculation of environmental efficiency. Section 3 describes the data used. We present and discuss the results in Section 4. Finally, Section 5 concludes.

2. Methodological framework

2.1 Output distance function and harmful by-products

We incorporate the nitrogen surplus as an additional output of production within a usual output distance function framework. An output distance function (ODF) is defined on the output possibilities set, *P(x),* as (Kumbhakar and Lovell, 2000: 30):

$$D_o(x, y) = \min\{\delta : (y/\delta) \in P(x)\}. \quad (1)$$

The ODF shows the minimum amount by which an output vector can be deflated (maximum possible expansion of outputs) and remain producible with a given input vector. The output distance function takes values between 0 and 1. The value of 1 lies on the boundary of the output possibilities set. The output distance function coincides with the measure of technical efficiency (TE).

To incorporate the by-product (b) as a usual output of production, we transform it using a multiplicative inverse: $b_{transformed} = 1/b$. After this transformation, a conventional ODF is used for the representation of the production technology.

2.2 Model specification

We specified the production technology using five inputs (x_1-x_5) and three outputs (y_1-y_3) as follows: (x_1) land (in hectares of farm area); (x_2) labour including both family and hired labour (in annual work units); (x_3) capital comprising of the depreciation costs of machinery and buildings plus interest on debt and on owned capital (in Swiss francs); (x_4) livestock (in standardized livestock units); (x_5) materials (in Swiss francs); (y_1) agricultural output including farm revenue from animal and plant production (in Swiss francs); (y_2) other output, including farm revenue from various activities, such as direct selling, agro-tourism, etc. (in Swiss francs) and (y_3) public services remunerated through direct payments (in Swiss francs). As a by-product (b), we used farm nitrogen surplus (in kg).

For the estimation of ODF, we choose a parametric estimation technique - SFA. We use the translog functional form, which provides a second-order approximation of the true production technology. Imposing homogeneity allows for the econometric estimation of ODF. We normalized all outputs by y_1. The stochastic ODF with three desirable outputs (y_1-y_3), one undesirable output (b) and five inputs (x_1-x_5) can be expressed as:

$$-\ln y_{1i} = \alpha_0 + \sum_{k=1}^{5} \alpha_k \ln x_{ki} + \frac{1}{2}\sum_{k=1}^{5} \sum_{l=1}^{5} \alpha_{kl} \ln x_{ki} \ln x_{li} + \sum_{m=2}^{3} \beta_m \ln\frac{y_{mi}}{y_{1i}} + \frac{1}{2}\sum_{m=2}^{3} \sum_{n=2}^{3} \beta_{mn} \ln\frac{y_{mi}}{y_{1i}} \ln\frac{y_{ni}}{y_{1i}}$$
$$+ \gamma_b \ln\frac{b_i}{y_{1i}} + \frac{1}{2}\gamma_{bb}\left(ln\frac{b_i}{y_{1i}}\right)^2 + \sum_{k=1}^{5}\sum_{m=2}^{3} \delta_{km} \ln x_{ki} \ln\frac{y_{mi}}{y_{1i}} + \sum_{k=1}^{5} \omega_{kb} \ln x_{ki} \ln\frac{b_i}{y_{1i}}$$
$$+ \sum_{m=2}^{3} \xi_{mb} \ln\frac{y_{mi}}{y_{1i}} \ln\frac{b_i}{y_{1i}} + \varepsilon_i, \tag{2}$$

where *i* is the farm index, *k* and *l* are indices for inputs (x), *m* and *n* are indices of desirable outputs (y), and b denotes the transformed by-product (1/nitrogen surplus).

The composite error term ε_i in expression 2 involves technical inefficiency (u_i) and a noise component (v_i). We assumed that both v and u are heteroscedastic and that they can be explained by several exogenous variables (Kumbhakar and Lovell, 2000).

Environmental efficiency measure

To derive the measure of environmental efficiency (EE), we follow the technique proposed by Reinhard et al. (1999). In this study, we derive the EE measure in the context of the output distance function (ODF) as follows:

$$\ln EE = \left[\begin{array}{c} -\left(\gamma_b + \sum_{k=1}^{5}\omega_{kb}\ln x_{ki} + \sum_{m=2}^{3}\xi_{mb}\ln y^*_{mi} + \gamma_{bb}\ln b_i\right) \pm \\ \left\{\left(\gamma_b + \sum_{k=1}^{5}\omega_{kb}\ln x_{ki} + \sum_{m=2}^{3}\xi_{mb}\ln y^*_{mi} + \gamma_{bb}\ln b_i\right)^2 - 2\gamma_{bb}\cdot u\right\}^{0.5} \end{array} \right] \Big/ \gamma_{bb}, \tag{3}$$

where y* denotes the normalized outputs, y_{mi}/y_{1i}.

Therefore, our measure of farm EE is defined as a non-radial single output-oriented measure of technical efficiency with respect to the by-product (nitrogen surplus). As the transformed by-product is used, higher values of such non-radial output-oriented efficiency indicate better environmental performance of farms. EE measures how much nitrogen surplus can be reduced given farm inputs and outputs.

3. Data

The data source for this analysis is the Swiss Farm Accountancy Data Network (FADN), which is managed by the Swiss Agricultural Research Station Agroscope Reckenholz-Tänikon (ART). The sample used in this study consists of 507 (389 non-organic and 118 organic) dairy farms in the mountainous region of Switzerland in 2010. The sample farms own 25 cows and cultivated 29 ha of agricultural land, on average.

We use nitrogen balance as an indicator of the environmental harm generated by the nitrogen use of a farm. In Switzerland - as in most other European countries - neither precise data on nitrogen use nor, more generally, environmental data are directly available in the usual micro-economic databases (e.g. FADN or farm-structure survey database). To overcome this data gap, we assess nitrogen surpluses of farms using the variables available in FADN data. The nitrogen balance is estimated according to the OECD soil-surface approach. All nitrogen input and output elements are indirectly assessed on the basis of accountancy and/or structural variables from the Swiss FADN using the approach specifically developed for that purpose by Jan (2012).

4. Results and discussion

4.1 Representation of technology, including by-products

First, we test whether the inclusion of by-products added statistically significant information to modeling the production technology of the sample farms. Using likelihood ratio test, we test the output distance function without by-products (restricted model) against the output distance function with by-products (full model). The likelihood ratio is 42.9, which is higher than the critical value (16.9), suggesting that the consideration of by-products in the representation of the production technology add statistical information to the model.

Table 1 shows that all the first-order parameter estimates for farm inputs and outputs are significant at the 1% level and have the expected sign.

Table 1. Estimated parameters of the first-order terms.

	Estimate	Significance	SE
Nitrogen surplus[1]	0.076	***	0.014
Agricultural output	0.360	---	---
Other output	0.054	***	0.006
Direct payments	0.506	***	0.018
Land	-0.126	***	0.016
Labor	-0.062	***	0.017
Capital	-0.073	***	0.012
Livestock	-0.391	***	0.026
Materials	-0.200	***	0.019

Note 1: Significant at 1% = ***.
Note 2: Parameters for agricultural output which is used for normilisation is not directly identifiable, but it can be recovered from the linear homogeneity restrictions: $\sum_m \beta_m = 1, m = 1, 2, \dots, M$.

[1] It denotes the transformed value (1/nitrogen surplus).

The estimated parameters can be interpreted as elasticities at the point of approximation (at the sample mean). The estimated elasticity of input land has the following interpretation: a 1% increase in this input would increase the distance function by 0.13% *ceteris paribus.*

4.2 Efficiency results

We find the mean technical efficiency (i.e. the *joint economic* and *environmental efficiency*) of sample farms to be 0.94 in both approaches. The range of efficiency scores is 0.65-0.99. The ranking of farms is less affected by the inclusion of by-product into the representation of the production technology.

We obtain the mean environmental efficiency (EE) of 0.47, indicating that an average farm may use the same inputs and produce the same marketable output with 53% less nitrogen surplus. We find high variability in EE across farms. Around 43% of the sample farms showed an EE of less than 0.40. Table 2 summarizes the results on EE of farms.

Table 2. Distribution of farms according to their EE.

Efficiency scores	Share of farms with regard to EE (in %)
> 0.00 and < 0.20	26.8
=> 0.20 and < 0.40	15.6
=> 0.40 and < 0.60	17.3
=> 0.60 and < 0.80	18.9
=> 0.80 and < 1.00	20.4

4.3 Comparison of EE with other indicators of environmental performance

We compare the obtained EE measure with other existing environmental indicators outside the field of the productive efficiency measurement: (i) nitrogen use efficiency (NUE), defined as nitrogen in outputs divided by nitrogen in inputs, (ii) nitrogen surplus per ha (N/HA), (iii) N-surplus per cow (N/COW) and (iv) nitrogen surplus per milk output (N/MILK). Table 3 presents results for the estimated rank correlations between these different indicators.

Table 3. Spearman correlation coefficients between EE and other environmental indicators

	EE	NUE	N/MILK	N/HA	N/COW
Environmental efficiency (EE)	1.00				
Nitrogen use efficiency (NUE)	0.10	1.000			
Nitrogen surplus per milk output (N/MILK)	-0.12	-0.67	1.00		
Nitrogen surplus per ha (N/HA)	-0.40	-0.68	0.40	1.00	
Nitrogen surplus per cow (N/COW)	-0.09	-0.82	0.68	0.65	1.00

5. Conclusion

In this study, we analyzed the environmental efficiency of 507 dairy farms located in the mountainous region of Switzerland for 2010. We used a multiplicative transformation of the by-product and incorporated it as an additional output of production within an output distance function. We derived the measure of environmental efficiency (EE) in the framework of the output distance function. EE measures by how much a farm can reduce its nitrogen surplus compared to the minimum nitrogen surplus given other inputs and outputs.

We can conclude that the modeling of by-products in the representation of production technology does not greatly affect the obtained technical efficiency scores, as the efficiency scores from models with and without by-products were rather similar. However, the modeling of by-products provides interesting insights into the environmental efficiency of farms.

We found a relatively low average value for environmental efficiency (equal to 0.47), indicating potential for improvement. These results suggest a need for additional policy to reduce nitrogen pollution from Swiss farms.

The comparison of EE and other indicators of environmental performance showed that the ranking of farms is very different depending on the choice of indicator. The EE investigation in this study looked at farms from a productive efficiency point of view by including all relevant inputs and outputs. This might provide a more comprehensive evaluation of the performance of farms.

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