Materials balance based modelling of environmental efficiency

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Abstract

A new method for analysing environmental efficiency, based on the materials balance, is proposed. With this method, an environmental allocative efficiency measure can be defined analogously to the more commonly used economic allocative efficiency. Nutrient surplus in pig fattening, a typical balance indicator, is used to illustrate the concept in a two input – one output case. The materials balance based efficiency analysis is elaborated using data envelopment analysis (DEA). Results are compared with those of more common, merely input or output oriented DEA approaches. A main conclusion is that, ignoring the balance feature of environmental issues such as nutrient surplus might be a main reason why traditional integral analyses of economic and environmental efficiency yield contradictory conclusions.

Key words: nutrient balance, data envelopment analysis, pig fattening, allocative efficiency

1. Introduction

Sustainability is one of the main guiding criteria for further development, innovation or diversification in agriculture. More in particular, in countries where agriculture reached a highly-industrialised level, environmental side-effects enter the core of public debate. To be able to distinguish between firms or production systems according to their environmental impact, environmental performance indicators are necessary. Moreover, these environmental indicators should be integrated with technical and economic performance.

The objective of the paper is to introduce a new environmental efficiency analysis method and to illustrate the concept with a simple case of nutrient surplus in pig fattening. The method is based on the materials balance concept and worked out with the DEA technique. In its most fundamental sense, the materials balance is the mass flow equation of raw materials used in the economic system and of the residuals disposed of in the natural environment (Field, 1994). The term is also used in a more restrictive sense for different types of materials such as water and used in clearly delimited, smaller systems or processes, where the material inputs must balance the outputs. An example is the materials balance model of a water treatment plant (Carlson & Bellamy, 2001). In the nutrient surplus case, the more restrictive connotation is used.

Whereas the link between technical and economic efficiency is well known as the allocative efficiency (see Farell, 1957, for the original concept), the link between economic and environmental efficiency is less clearly defined. The origin of this problem lies in the difficulty to describe the trade-offs between economics and ecology. Whereas the environmentally harmful effect is physically a bad joint output, in economic terms it may be considered as an increase of inputs to produce marketable outputs. When appropriately internalised, the environmentally harmful effect gives rise to private costs. In the case of pig fattening, environmental inefficiency is caused by the fact that not all nutrient inputs (feed, piglets) are completely transformed into fattened pigs, but are partly excreted through the manure.

The pig fattening case is an activity of feed transformation into meat starting from a 10 weeks old piglet and ending with a market hog of about 106 kg. Because of current juridical constraints on farm dimension, the farmers profit maximisation objective turns into a maximisation of gross margin per pig place. The pig fattening process can thus highly be simplified to one output, the marketable meat production, and to two variable inputs, feed and rotations. Phosphate is the most limiting factor in the nutrient flows in pig production. The feed input accounts for 92 % of the phosphate inputs. Only one third of the total phosphate input is incorporated in the marketable output “meat” (36%). Although the other two thirds (64%) have a potential manuring value, in the intensive pig production regions (Flanders, Brittany, the Netherlands), the excess phosphate is a waste product with an expensive disposal.

2. Theoretical framework

Environmental side-effects of the economic activity may be linked to the inputs, to the outputs or to both. Externalities are mostly seen as bad joint outputs (undesirable outputs or by-products) associated with the production of goods (desirable outputs).

Tyteca (1996) sees pollutants as undesirable outputs and considers them as a third factor, besides inputs and desirable outputs, to be taken into account in the scope of productive efficiency theory. Combustion of fuels, for example, yields energy as well as bad outputs such as SO_2 , CO_2 and NO_x emissions (Tyteca, 1996, 1997). On the other hand, combustion of the so-called environment friendly natural gas causes resource depletion that can be considered as a merely input-associated externality. The nutrient problem in agriculture is still more complex. Here, the emission is the result of a balance of what enters in the production process and what leaves as a good output.

So, with respect to measuring the environmental performance, different approaches of efficiency analysis are possible. Tyteca (1997) states that environmental performance models differ in the way they account for pollutants as undesirable outputs or for resources used as inputs. Overviews of environmental performance measures are given by Tyteca (1996) and Reinhard *et al*. (1999), mostly based on work of Färe *et al.* (1989, 1993).

More in particular for the environmental effects linked to balance variables, one can state that a tradition has emerged, both in parametric and in non parametric efficiency analysis, to incorporate the environmental damage as another input (Piot-Lepetit *et al.*, 1997) or as a bad output (Ball *et al*., 1994). In the case of nutrient emissions, the specific nature of the materials balance variable may cause difficulties for conventional efficiency modelling (Reinhard, 1999), but will also offer opportunities for a “third modelling way” based on behaviour optimisation (Lauwers *et al*., 1999).

In the case the bad output is the result of a materials balance, the isoquant “bad output - good output” graph under the constant returns to scale (CRS) assumption yields a linear production possibility curve: desirable outputs and pollution are perfect substitutes (Reinhard, 1999). In this case it is difficult to derive an efficiency measure in the conventional way (a move to the frontier): simply because of the balance condition, it is impossible to imagine input-output combinations situated beneath the frontier. The same applies for the input oriented approach. Similar to the isoquant production possibility curve, the isoquant factor substitution in the “nutrient input - nutrient emission” space is linear. Despite these observations most nutrient surplus modelling concerned merely input or output oriented approaches.

The idea of using the materials balance property in efficiency research originated from an empirical research on the nutrient emission efficiency in pig fattening (Lauwers *et al.*, 1999). Our approach is based on the analytical analogy of nutrient excretion with the gross margin: both are balance variables depending on inputs and outputs. The nutrient excretion is related to the physical quantities of inputs and outputs through the nutrient content coefficients, just as gross margin does through the prices. This opens the possibility to consider nutrient emission minimisation as a behaviour optimising approach in efficiency analysis and to define allocative efficiency from an environmental point of view.

Figure 1 gives an isoquant representation SS’ in a two-input space. Both inputs have a price and a per unit contribution to the nutrients flow. The economic optimum is point Q where the rate of technical substitution equals the slope of the isocost line (or that point on the isoquant where the isocost line is tangent). Similar to the isocost line CC’, an isonutrient input line NN’ is defined. The isonutrient input line is tangent to the isoquant at point Q’. Here, the input-combination minimizes the nutrient input per unit output, thus minimizes the nutrient emission. Using the same graph one can see that Q’ is not economic efficient. The economic efficiency of Q’ is obtained from the ratio:

$$EE = \frac{OE}{OQ'}$$

being the product of technical efficiency and the economic allocative efficiency (EAE). The term economic allocative efficiency is introduced in order to distinguish from the other allocative efficiency that will be defined from the environmental point of view. Analogously, the economic optimal point Q is not environmentally efficient. The environmental efficiency of Q is obtained from the ratio:

$$ME = \frac{OM}{OQ}$$

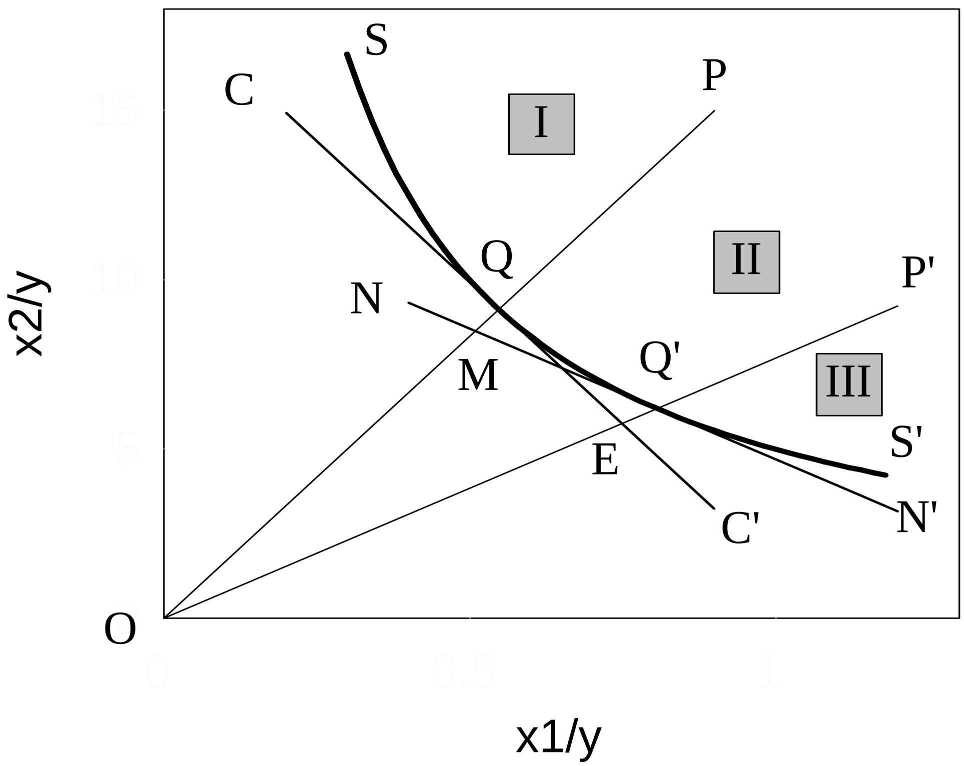
which, again, is the product of a technical and an allocative component. Here, the term environmental allocative efficiency (MAE) is proposed. The technical inefficient point P has the same environmental allocative efficiency as Q:

$$MAE = \frac{OM}{OQ}$$

The environmental efficiency of P is:

$$ME = MAE * TE = \frac{OM}{OQ} * \frac{OQ}{OP} = \frac{OM}{OP}$$

Figure 1. Definition of economic and environmental allocative efficiencies in the isoquant "input-input" space



Empirical results of an earlier application of these differential allocative concepts revealed a V-shaped link between economic and environmental allocative efficiency (Lauwers *et al.*, 1999). This particular form stems from the fact that the rays starting from the origin and passing through the economic and the environmental optimum divide the scatter of points into three subpopulations (figure 1, I-III). In the two outer parts, moving to one of the rays means improving the corresponding allocative efficiency, but also implies an improvement of the other allocative efficiency. Only between the two rays, moving away from one ray means coming closer to the other. Or, in efficiency terms, increasing one allocative efficiency means decreasing the other.

3. Non parametric modelling

A non parametric efficiency analysis method has been chosen based on following grounds: DEA is relatively easy to perform, does not require a priori knowledge on the functional form of the frontier and benchmarks to real existing firms (Gerber and Franks, 2001). Although this method may attribute stochastic noise to the inefficiency scores and thus may be more sensitive to outliers (Coelli, 1995; Reinhard, 1999), in our case this is a minor problem because of the highly-conditioned nature of the pig fattening production process. The choice for DEA is further supported by some earlier publications on efficiency analyses in the pig sector (Sharma *et al*., 1999; Piot-Lepetit *et al.*, 1997).

The constant returns to scale (CRS) assumption is maintained. This assumption not only allows for a simple illustration of the theoretical concepts developed in previous section, but can also be empirically verified in the pig fattening case. Another argument for using CRS is the possibility to compare output-oriented and input-oriented measures without disturbance from scale effects. Finally, radial efficiency measures in the CRS framework are preferred because farmers' technology choice concerns mainly the choice of the breed (genetic differences). Genetic progress within the range of current possibilities leads to a more or less homothetic shift in the isoquant and may thus be considered as Hicks neutral (Arnade, 1998).

The CRS input oriented technical efficiency for each farm is obtained from the well known optimisation problem as described in most textbooks. The economic efficiency is then derived from a cost minimising model (Coelli *et al.,* 1998; Sharma *et al*., 1999): the ratio of the costs associated with the economic efficient input vector to the observed costs on farm i gives the economic efficiency. The economic efficiency of a farm is a product of the technical and the economic allocative efficiency (EAE), so the latter is computed as

$$EAEi = \frac{EEi}{TEi}$$

Although the theoretical reflections in the previous section do not justify the use of either input or output oriented DEA-model for deriving an environmental efficiency measure, some of them are applied for comparison reasons. The first model is based on the radial expansion of both bad and good output, which is also the first mentioned by Ball *et al.* (1994). The second allows for a subvector radial expansion of the bad output, which is comparable to the first model given by Tyteca (1997). Finally, subvector radial expansion can also concern the good output, which yields a model comparable to the second Ball *et al.* (1994) model. The outcomes of these three output oriented models are notated as ROO, SBOO and SGOO.

For the input oriented approach, three model variants are used. The first considers the nutrient emission as a single input to be minimised for a given good output. The model is a non parametric operationalisation of the Reinhard (1999) definition of environmental efficiency. The second model considers the nutrient emission as one more input to be equiproportionally minimised just like the others. The third input oriented model aims at a subvector radial contraction of the nutrient emission given the other inputs and the good output. The outcomes of these input oriented models have already a higher environmental efficiency meaning than those of the output oriented models and are notated as SIO, RIO and SBIO.

Finally, these models are compared with a materials balance DEA model that exploits the analytic similarity of the economic and environmental objectives. The environmental efficiency is derived from an analogous model as for the economic efficiency measurement. The environmental efficiency of the i-th farm, ME_i is given, according to the derivation in section2, by the ratio of the nutrient flows associated with the ecologic efficient input vector to the observed nutrient flows on farm i. Similar to the economic allocative efficiency, the environmental allocative efficiency, MAE_i is then defined as

$$MAEi = \frac{MEi}{TEi}$$

4. Results for the simplified pig fattening case

The models are applied on a cross section of 175 pig fattening farms from the Belgian FADN (accounting year 1996-1997). The average technical efficiency score (0.87) and the average economic efficiency score (0.85) are almost the same, which indicates a very high economic allocative efficiency (0.98). Table 1 gives an overview of the main descriptive statistics of the DEA models' outcomes. The output oriented technical efficiency indicators are relatively high. The SGOO indicator coincides with the TE indicator. So, the extra "bad output" constraint is redundant with respect to the information in the original technical efficiency model. The high efficiency scores obtained with the ROO and SBOO-models could be interpreted in the sense that there is still room for "excretion expansion". But this has to be taken with care because if no scale effects occur, all points should be technically efficient and must lie on a linear frontier. Probably some remaining but minor scale effects are the reason behind these unexpected results.

Input-oriented measures have already a more sound environmental meaning. The more the environmental detrimental input is dominant to the other inputs in the model, the lower the efficiency scores are: the SIO score is lower than the SBIO score which is lower than the RIO score. The latter equals TE, which again proves that the materials balance information is redundant when the other inputs intervene. Finally, the average environmental efficiency score based on the materials balance DEA model is 0.769, which is between the average SBIO and the average TE score.

The correlation analysis shows a close link between the outcomes of the single input approaches (SIO, SBIO) and those of the materials balance approach. As these two are also conceptually the most explicitly oriented towards environmental efficiency, their link provides evidence about their usefulness for environmental efficiency analysis. The SIO efficiency measure yields, however, a too optimistic potential for emission reduction. The SBIO oriented efficiency measure has already an intermediate average value but its link with the balance based measure is less close.

Table 1. Descriptive statistics of the different efficiency scores obtained from the comparative DEA technical and environmental efficiency analysis of a 1996-1997 cross section of Belgian FADN pig fattening farms

	TE	TE – output oriented			ME input oriented			ME balance based
Average scores		ROO	SBOO	SGOO	SIO	RIO	SBIO	
	0.873	0.984	0.905	0.873	0.634	0.873	0.731	0.769
Pearson correlation coefficients								
TE	1							
ROO	0.451	1						
SBOO	- 0.771	0.011	1					
SGOO	1	0.451	-0.771	1				
SIO	0.802	0.166	-0.963	0.802	1			
RIO	1	0.451	-0.771	1	0.802	1		
SBIO	0.950	0.289	-0.868	0.950	0.894	0.950	1	
ME	0.808	0.243	-0.932	0.808	0.987	0.808	0.892	1

ROO : radial output oriented; SBOO : subvector bad output oriented; SGOO : subvector good output oriented; SIO : single input oriented; RIO : radial input oriented; SBIO : subvector bad input oriented

The main advantages of the materials balance approach lies in its potential to separate the overall environmental efficiency into a technical and an allocative component and in its interpretation as a behavioural outcome similar to the economic efficiency. This enables a more differentiated diagnosis of environmentally inefficient farms and possible solutions: by changing allocative behaviour or by a technology change.

The behaviour optimisation modelling for deriving economic and environmental efficiency also yields a cost and a nutrient input minimising vector. Whereas the efficiency score is derived from the ratio “cost (c.q. nutrient) input at this minimising vector over the actual cost (c.q. nutrient) input”, the difference between the two terms of the ratio gives an absolute estimate for the cost (c.q. nutrient) input reduction potential. In the pig fattening example our results indicate that at the Flemish level, a macroeconomic cost saving of about 162 million euro per year is possible and that the annual emission reduction potential is about 8 million kg of phosphate.

The materials balance approach also allows for a more dynamic analysis. Price shifts will guide the economic allocative behaviour and thus also influence the environmental one. In the case of pig fattening, the concentrated feed price decreases faster than the rotation price. So, theoretically, the economic optimum shifts to a higher feed input at the expense of the rotation number. This input allocation coincides with a higher endweight of the hog (slaughtering pig) and is confirmed by the observed endweight evolution during the last 25 years (from 95 to 106 kg). With this trend, the resulting economic optimum (Q in figure 1) shifts, however, further away from the environmental optimum (Q’ in figure 1).

Internalisation, which means turning the public costs of external effects into private costs, is another dynamic aspect. A better consideration of the social costs of input use may lead to a price ratio that gets closer to the nutrient content ratio. The farms that show a positive correlation between economic and environmental allocative efficiency, will further lose when internalisation proceeds. At first sight this seems to be a paradox. The reason behind this paradox stems from the fact that they belong to the subpopulation I in figure 1. With internalisation the axe OP will move towards OP’, lowering both their economic and environmental allocative efficiency. Farms belonging to subpopulation II (figure 1) have a negative correlation between economic and environmental allocative efficiency, but will be less affected by internalisation.

Finally, some observations with respect to the pig fattening case may illustrate a potential for incorporating life cycle accumulated externalities. Based on the nutrient input of feed and rotations (piglets), the number of rotations should increase drastically. In order to satisfy this increased piglet demand, piglet production has to be up-scaled. But more piglets also means a similar increase of the externalities (phosphate emission) associated with the piglet production. During piglet production the emission is about 1 kg P_2O_5 per produced piglet. Adding this amount to the actual nutrient content of the piglet will change the nutrient content ratio and shift the environmental optimum to a somewhat lower rotation number. On the other hand, when the feed input is a valorisation of a waste product from other production processes, the situation becomes even more complex. In the example of pig fattening, about 30 to 40% of the livestock concentrated feed is, in one way or another, a valorisation of by-products of the human food manufacturing. A question can be how to price and to incorporate this recycling of “otherwise unwanted” inputs in our models.

5. Conclusions

This paper has tried to find out the underlying reasons why conventional input or output oriented approaches with regard to environmental efficiency do not give satisfactory results. As illustrated, the choice for one of the possible approaches influences the link between economic and environmental efficiency. Whereas the output oriented approach under the weak disposability assumption leads to shadow prices (abatement costs) of externalities reduction, the input related approach starts from a cost saving viewpoint. The balance approach offers a much more differentiated picture of who might lose or win on one criterion when optimising for another. This approach therefore provides an appropriate framework for analysing apparently paradoxical conclusions obtained from a static or dynamic viewpoint. The method also has a potential for analysing internalisation actions and life cycle aspects of a production process.

The balance approach as presented in this paper can of course still be improved, in the first place with regard to CRS-assumption. Closely related to the VRS problem is the need to enlarge the cost and nutrient input minimisation approach to a profit maximisation and an emission minimisation approach. The balance based approach can also be extended for a wider range of environmental problems, provided the nutrient flow feature can be generalised to an externality flow.

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