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Eco-efficiency indicators: do they suffice for analyzing economic-environmental trade-offs?

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Abstract: The paper questions the value of eco-efficiency, as a ratio-indicator, for economic-environmental trade-off analysis and explores additional diagnostics that can be obtained by using production-theoretical principles. It is shown how the profit function and various emission functions can simultaneously be derived from the same physical production function. The materials balance principle that applies for environmental outcomes is taken into account, in order to comply with thermodynamic laws. The consistency of environmental information with the physical production process and economic outcomes allows for clarifying the conditions for pursuing economic-environmental win-wins and undergoing trade-offs. This paper illustrates that, for trade-off analysis in practice, one must be careful in choosing a functional form of the production function, as this functional form influences the resulting trade-offs pattern. Operational difficulties to distinguish between trade-offs and win-wins when multiple inputs come into play are demonstrated. The dataset and operational models that are used can be made available on request for verification and validation by Forum participants.

Keywords: eco-efficiency, materials balance condition, productive efficiency analysis, emission function, profit function.

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1. Introduction

Eco-efficiency encompasses the ambition to increase economic and social values while reducing environmental impacts [6]. It is about creating more value with less impact [8]. At the origin of the eco-efficiency concept is the World Business Council for Sustainable Development, who's intention was "sum up the business end of sustainable development" (Schmidheiny in his foreword to Lehni et al. [8]). With this business perspective in mind, it will be important that eco-efficiency measurement methods provide the necessary tools for monitoring and steering towards better business performances related to economic and social values and environmental impacts.

Basically, eco-efficiency stands for a ratio indicator, with the positively valued economic and /or social value as numerator and the negatively valued environmental impact as denominator. A vast number of eco-efficiency measures emerged from this concept, even from various disciplinary points of view [5]. Some of these measures aim at monitoring eco-efficiency, while others also aim at steering decisions towards performance improvements. Both aims are conditions of a good indicator. In this respect, production analysis techniques seem most promising among the eco-efficiency measuring methods, because they link production information with both the economic and the environmental outcomes.

The objective of this paper is to explore the contribution of production analysis techniques to analyzing trade-offs and providing concrete anchor points for business improvements strategies. We use productive efficiency methods to establish a frontier that serves as performance benchmark and allows for measuring performance inefficiencies of individual firms. As frontier-based models rely on production-theoretical principles, they have at least the potential for trade-off analysis. In practice, however, no consensus exists. Lauwers [7] distinguishes between three main groups of frontier-based methods: environmentally adjusted production efficiency models, frontier eco-efficiency models and materials-balance based methods. In particular the latter branch exploits the analytical power of treating the co-generation of economic added value and environmental burden as interlinked outcomes, as the materials-balance condition for environmental pressure is incorporated in the production function description in order to comply with thermodynamic laws.

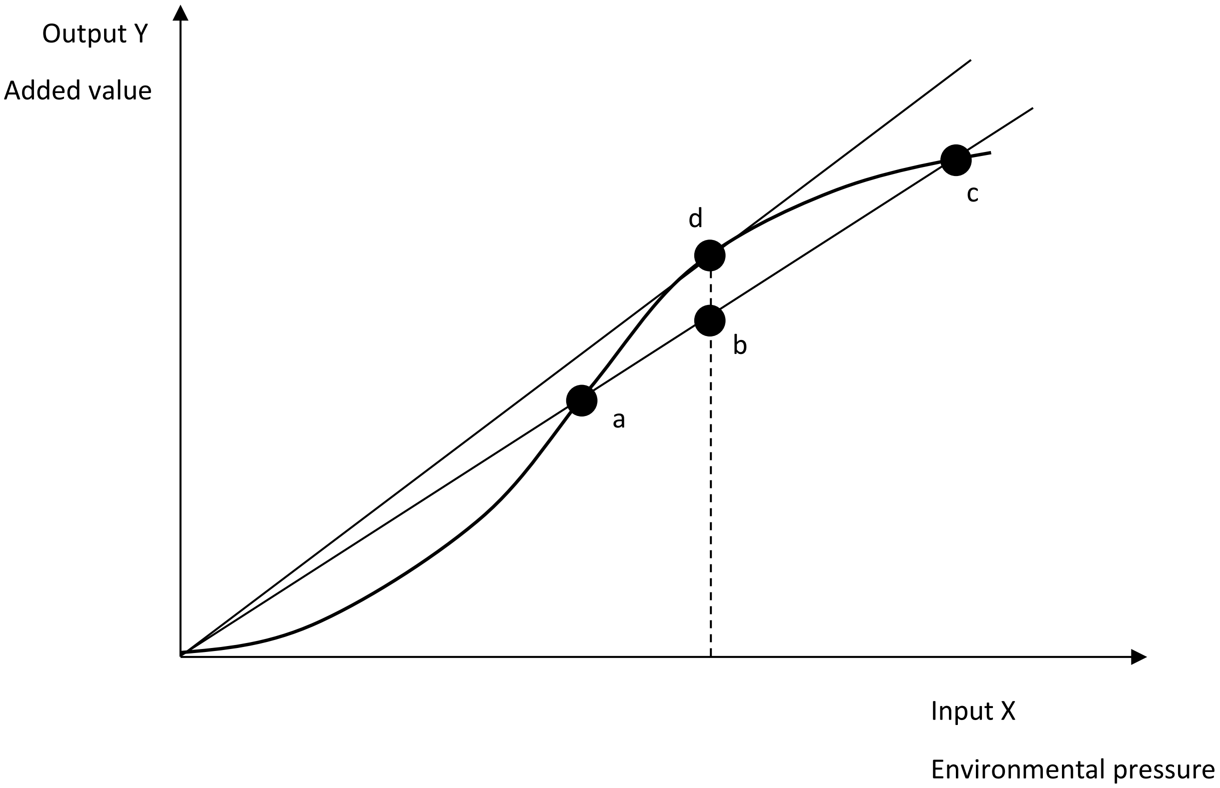
In section 2, the information value of eco-efficiency as a ratio-indicator is conceptually questioned by relating it to the production function. Section 3 then describes the linkage between the production function and economic and environmental outcomes. This is illustrated with a logistic production function. Section 4 matches our findings with a real-world dataset of pig farms. Based on our findings, Section 5 discusses implications for trade-off analysis in practice. Section 6 concludes. Throughout this story, the fact that the input-output transformations must satisfy the materials balance principle for environmental pressure plays an important role.

2. Ratio-indicator versus production function

Figure 1 presents a typically S-shaped production function with 1 input and 1 output. A production function represents the maximum amount of output that can be produced from a given amount of input. At low input levels, subsequent unitary increases in input result in higher increases in output (increasing returns to scale), while at higher input levels, subsequent unitary increases in input result in smaller increases in output (decreasing returns to scale). The amount of output produced divided by the amount of input used is a measure of productivity. Productivity is maximized where the straight line from the origin of the co-ordinate is tangent to the production function (point d). Although points a, b and c achieve the same productivity, they have to follow different improvement paths to maximize productivity. Points a and c are situated on the production function, this means that they are producing fully technically efficient. In order to maximize productivity, point a has to remain technically efficient and has to increase the amount of input used. Similarly, point c must decrease its input use in order to maximize productivity. Point b, on the other hand, is currently not producing efficiently. In order to maximize productivity, more output has to be produced with the same amount of input.

A similar reasoning applies when environmental pressure and added value are placed in respectively the X-axes and Y-axes. Let us assume that the S-shaped function presents the maximum amount of added value that can be obtained given the amount of environmental pressure. Maximum eco-efficiency is achieved where a straight line from the origin is tangent to the S-shaped function (point d). Points a, b and c have the same ratio of eco-efficiency. Nevertheless, in order to maximize eco-efficiency, they have to follow different improvement paths. These improvement paths can only be identified if the S-shaped function is known. Having only a notion of eco-efficiency as a ratio does not allow for these additional diagnostics.

Figure 1. Ratio indicator versus production function



Let us now conceptualize the relation between, on the one hand, input and output and, on the other hand, environmental pressure and added value. Input, or resource use, and environmental pressure can be considered as more or less the same, as environmental space is in fact a scarce mean. From a business point of view, however, pressure can also result from a materials balance. The materials-balance condition implies that, due to the first law in thermodynamics (law of conservation of mass), the transformation of material inputs into desired outputs can never be complete: some residual inadvertently arises as a by-product, and material input, desirable output, and residues are linked by the material balance [4]. Consequently, environmental pressure, as the denominator of the eco-efficiency ratio, is directly influenced by the transformation of input into output. Therefore, it can be considered as an outcome of the production function. A similar reasoning applies to added value, which is the numerator of the eco-efficiency ratio. Added value is created when social values (e.g. prices) are attached to the mere transformation of input into output. Therefore, added value can also be considered as an outcome of the production function.

The fact that both added value and environmental pressure can be considered as outcomes of the transformation of input in to output, provides us with a rationale to start from the production function and to derive eco-efficiency from this production function.

3. From production function to eco-efficiency function

In this section, a logistic production function with 1 input and 1 output is used to derive eco-efficiency. The following logistic function is considered:

$$y_i = \frac{1}{1+e^{-(x_i-b)}}$$

with y_i: output
x_i: input
a, b: parameters, a = 100 and b=6
i: case index

The coefficients a and b are chosen arbitrarily. Figure 2 shows graphically the logistic production function. From the production function, the revenue function can easily be derived by multiplying the output level with the output price ($P_y = 10$). The revenue function has the same shape as the production function. Also the cost function can be derived by multiplying the amount of input used with the input price ($P_x = 70$). The cost function is in fact the mirror image of the production function. Subtracting costs from revenues leads to the profit function. This function is convex at low input levels and becomes concave at higher input levels. The curvature of the profit function depends on the curvature of both the revenue (or production) and the cost functions. Similar to the profit function, an emission function can be constructed by applying the materials balance principle and calculating emission as a residual:

$$Emission_i = E_x * x_i - E_y * y_i$$

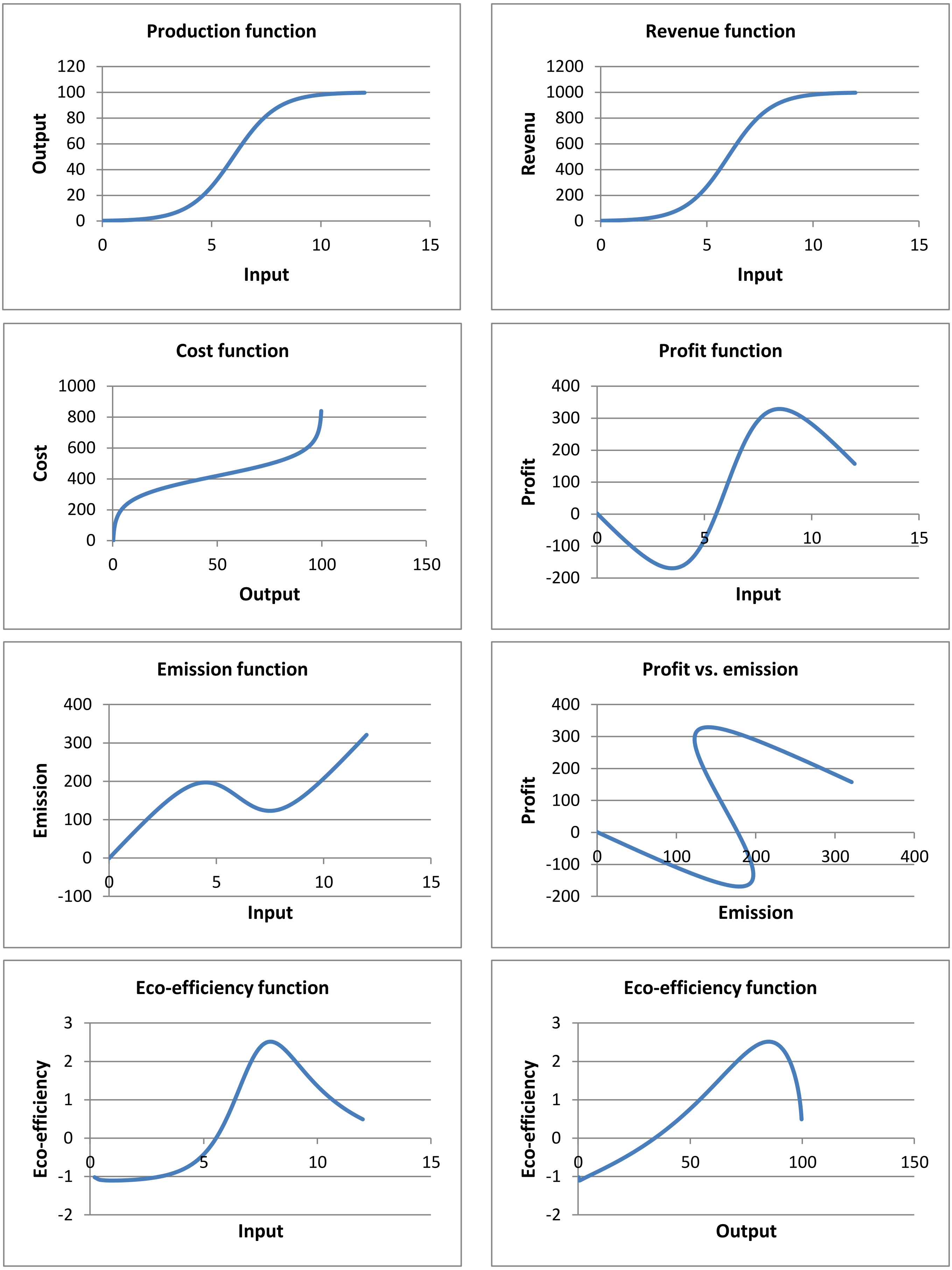
with $Emission_i$: emission
y_i: output
x_i: input
E_x, E_y: environmental coefficients, $E_x = 60$ and $E_y=4$
i: case index

Note that emission decreases as input increases between certain levels. This is in contrast with the findings of Baumgärtner [2], who proves that the thermodynamic law of mass conservation implies that the marginal product as well as the average product of a material input are bounded from above by the inverse of the resource fraction in the good produced. This means that an increase in input must result in a higher emission. The fact that we have chosen the coefficients of the production, profit and emission functions arbitrarily may result in the decreasing part of our emission function. In practice, however, production frontier analysis is restricted to the concave part of the production function, which will imply the convex part of the emission function.

We now have calculated both profit and emission. Positioning them together in one graph again results in a S-shaped function. The S-shaped function has a convex part, resulting from the part of the production function with increasing returns to scale, and a concave part, resulting from the part of the production function with decreasing returns to scale. Finally, we calculate eco-efficiency by dividing profit by emission. The eco-efficiency functions show how eco-efficiency varies depending on the amount of input used and the amount of output produced.

Based on this example, the contribution of production theory to economic-environmental trade-off analysis can be described. As the production function represents the maximum amount of output that can be obtained from a given input, the derived eco-efficiency function can be considered as the maximum eco-efficiency that can be achieved, given the amount of input or output. Firms may operate on or below the eco-efficiency function. Firms that operate below the eco-efficiency function can increase eco-efficiency through moving towards the eco-efficiency function. Firms that operate on the eco-efficiency function already achieve the highest possible eco-efficiency, given the amount of input they use or the amount of output they produce. These firms also operate on the initial production function, which means that they are also fully technically efficient. Nevertheless, they can further maximize eco-efficiency through moving on the eco-efficiency function, changing the amount of input used and output produced and remaining fully technically efficient. So, as the production function allows for identifying a point where productivity is maximized, the derived eco-efficiency function allows for identifying a point where eco-efficiency is maximized. The mere eco-efficiency ratio-indicator does not allow for identifying this point of eco-efficiency maximization. Therefore, knowledge about the production function gives additional information when it comes to identifying improvement paths for eco-efficiency.

Figure 2. Logistic production function and eco-efficiency



4. Matching our findings with a real-world dataset of pig farms

In this section, a real-world dataset is used to match our findings of section 3. The dataset consists of 62 typical Flemish pig-finishing farms. The output of pig-finishing farms consists of kilograms marketable pig. As we consider the short-run production function, only variable inputs are taken into account. The main variable inputs are feed and piglets. The finishing activity takes about 140 days, thus each pig place can be occupied by more than one piglet per year to finish as a marketable pig. Rotations (= number of start-ups per year) can be seen as an input factor instead of the mere piglet input. The rotation price then consists of the piglet price and the other costs linked to the starting-up process. The environmental pressure that is focused on is nitrogen emission, which can be assessed as the amount of nitrogen entering in inputs (feed and piglets) minus the amount bound up in marketable pigs (materials-balance condition).

Stochastic frontier analysis (SFA) is used to estimate a Cobb-Douglas production function. SFA was originally and independently described by Aigner et al. [1] and Meeusen and van den Broeck [9], and fits a parametric production frontier to given data, specifying a two-part error term that accounts for both random error and the degree of technical inefficiency. A Cobb–Douglas function is chosen because of its self-duality characteristic, which allows for deriving explicitly the cost function if input prices are known. Moreover, we follow the approach by Coelli et al. [3], who exploit the self-duality characteristic to derive besides the cost function also the emission function that complies with the materials balance condition (see also application by Van Meensel et al. [11]).

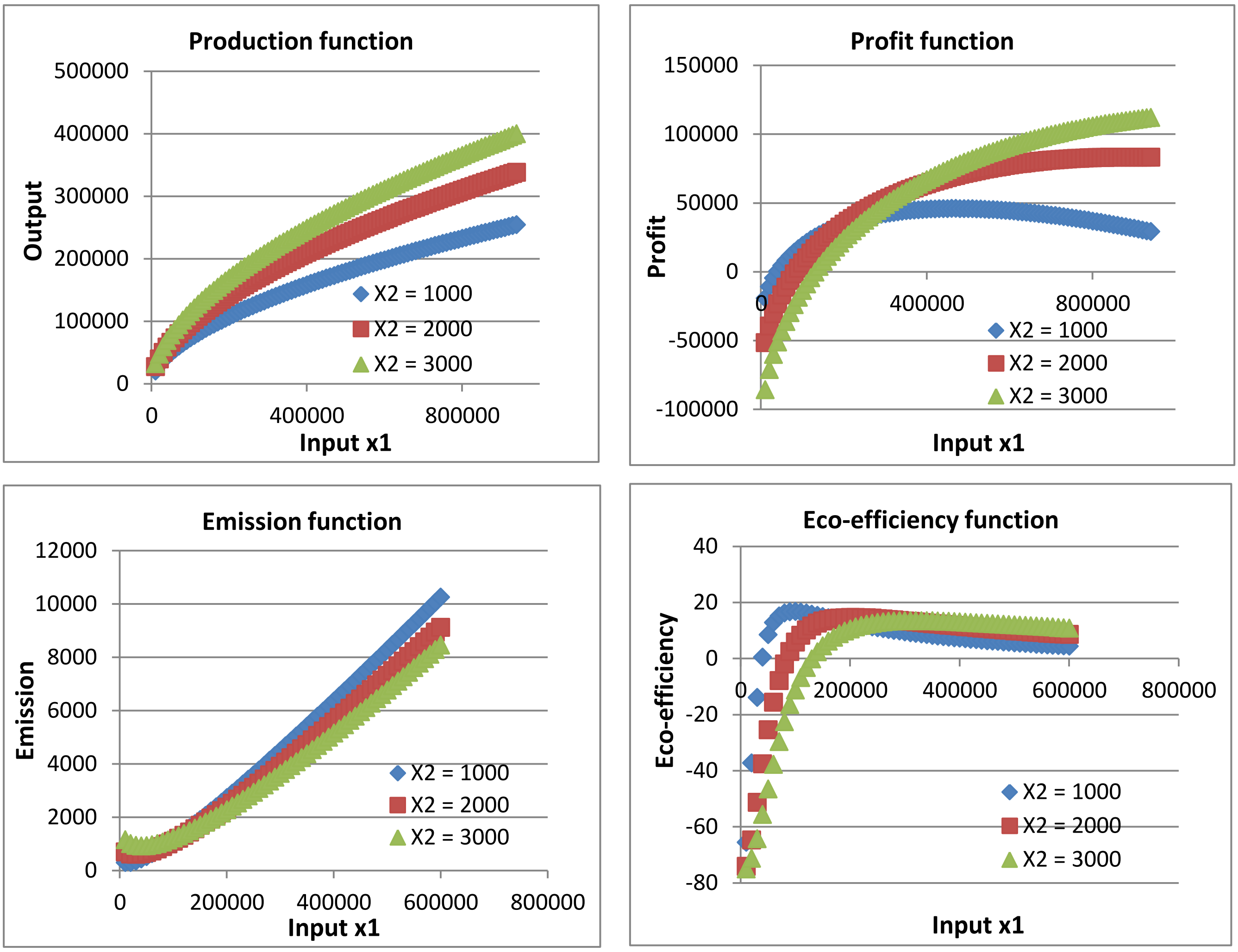
The following Cobb-Douglas production function is estimated:

$$y_i = A * x_{1,i}^{a} * x_{2,i}^{b} * e^{v_i} * e^{-u_i}$$

with: y_i: pig production (kilogram live weight)
$x_{1,i}$: feed use (kilogram)
$x_{2,i}$: number of rotations
v_i: random error
u_i: technical inefficiency
A, a, b: parameters
i: farm index

The estimated production function represents the maximum amount of output that can be produced with the given inputs. The corresponding profit function can be derived by multiplying this maximum amount of output with the observed output price and subtracting the observed input costs from it. The profit function then represents the maximum amount of profit that be achieved with the given inputs and prices. Similarly, an emission function can be derived that represents the minimum amount of emission with given inputs and environmental coefficients. Finally, the eco-efficiency function is assessed by dividing profit and emission. Figure 3 shows the different functions. A two-dimensional graph is presented, as we take 3 discrete values of the input x2 and let the other input x1 vary.

Figure 3. Profit, emission and eco-efficiency functions derived from the Cobb-Douglas production function

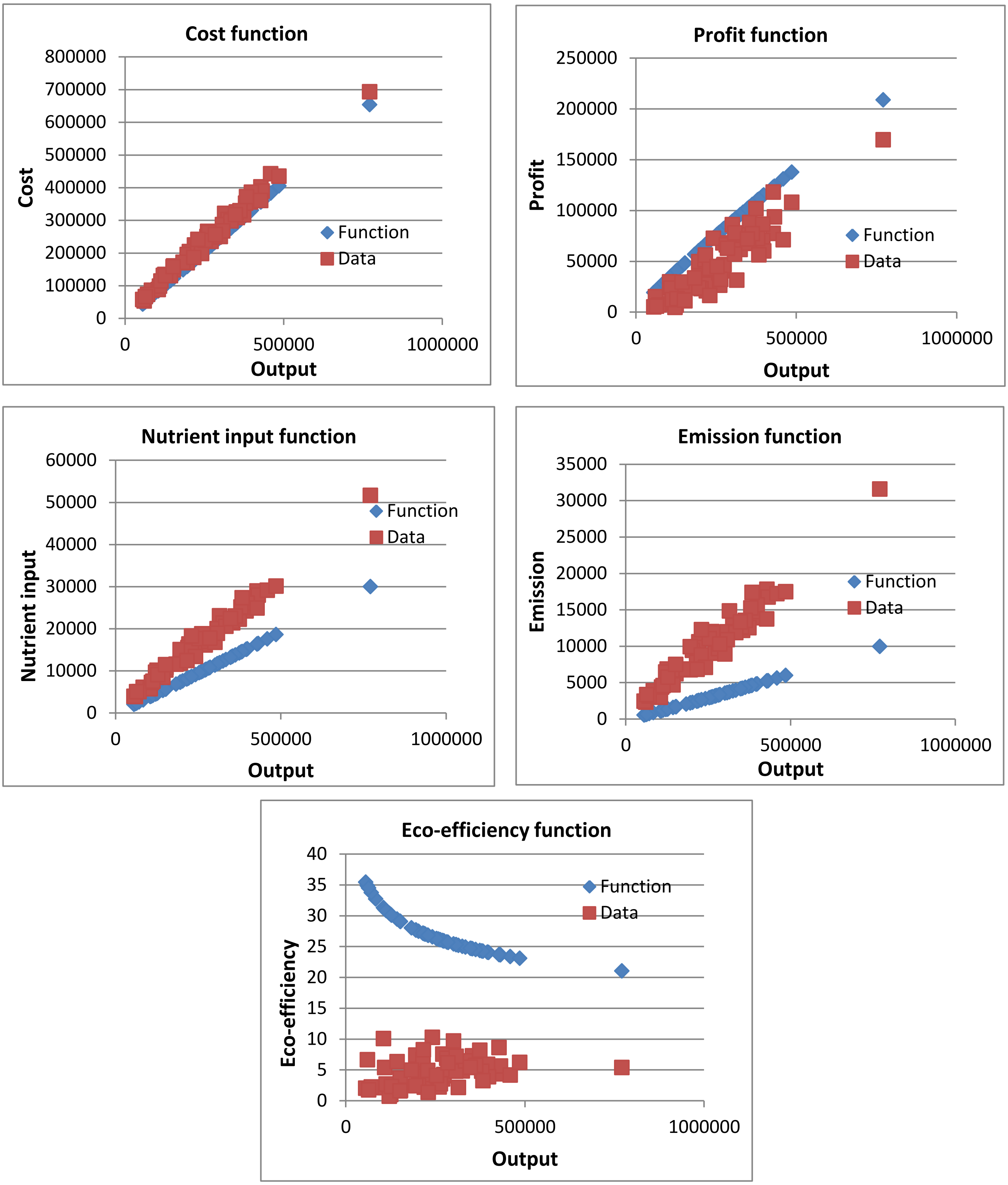


The estimated production function exhibits decreasing returns to scale. The profit function shows that increasing x2 results in less profit when small amounts of x1 are used. Contrarily, increasing x2 results in more profit if higher amounts of x1 are used. It shows that the proportion of used inputs influences the obtained profit. This can already be seen from the production function, which shows that, at low levels of x1, the same amount of output is produced when the amount of x2 increases. The proportion of inputs also influences the shape of the emission and eco-efficiency functions. Emission mostly increases as input x1 increases. Nevertheless, at the lowest levels of x1, increasing x1 results in less emission. On the production function, it can be seen that similar increases of x1, which are in fact changes in the proportion of inputs used, result in a higher increase of output at low levels of x1. Due to the materials-balance principle, changing input proportions therefore result in less emission at low levels of x1. The eco-efficiency function shows that eco-efficiency can be maximized. The maximum amount of eco-efficiency differs, depending on the combination of inputs that are used.

Using the self-duality characteristic of the Cobb-Douglas function, we can explicitly derive the cost and nutrient input functions from the estimated production function. The cost function represents the minimum costs that can be achieved, given input prices and observed output. The nutrient input function represents the minimum amount of nutrients that enter the production process, given environmental coefficients and observed output. From the cost function, a profit function can be derived that represents the maximum profit that can be obtained with given prices and observed output.

From the nutrient input function, an emission function can be derived that represents the minimum emission with given environmental coefficients and observed output. Again, the eco-efficiency function can be assessed by dividing profit and emission. Figure 4 shows the different functions, together with the observed data points.

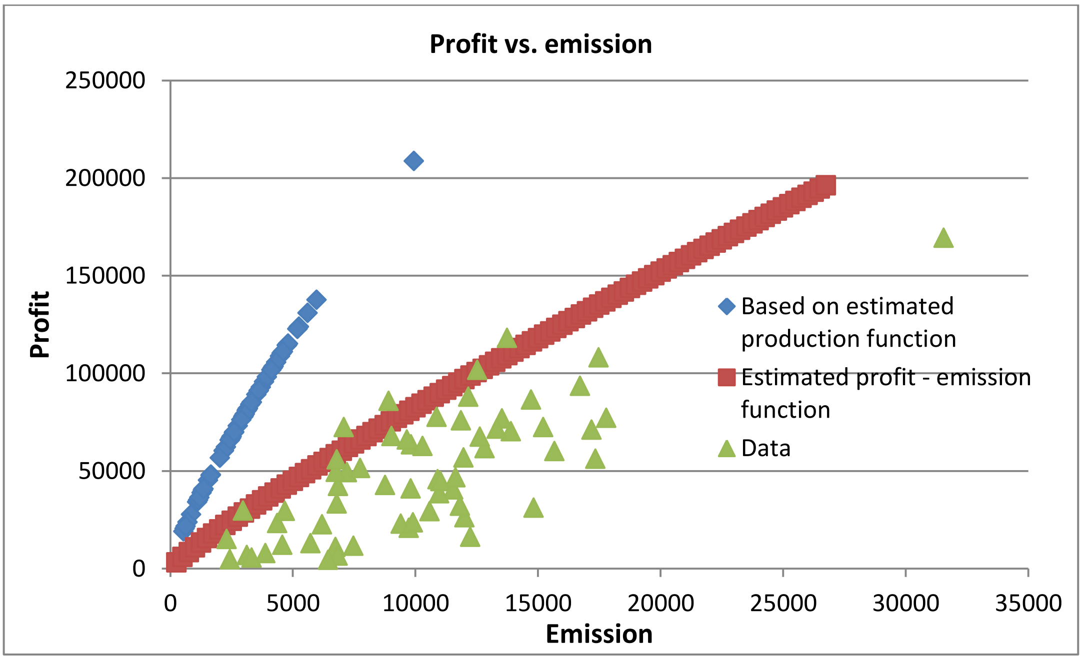
Figure 4. Using Cobb-Douglas duality characteristics to derive cost, profit, emission and eco-efficiency functions



The eco-efficiency function in Figure 4 shows that eco-efficiency is highest at low output levels. This can be explained by the decreasing returns to scale property of the estimated production function. Figure 4 also shows that the cost function, and to some extent also the profit function, envelop well the observed data points. Contrarily, both the emission and eco-efficiency functions are situated far away from the data points. This may have something to do with the restrictiveness of the Cobb-Douglas function. Another explanation may be that pig-finishing farms focus on minimizing input costs and maximizing profits, but they do not aim at minimizing nitrogen emission and maximizing eco-efficiency. This may be a result of a lack of penalization for creating environmental pressure or with other constraints preventing farms to reduce emissions and to become more eco-efficient.

According to Figure 4, pig-finishing farms have substantial improvement margins for reducing nitrogen emission and increasing eco-efficiency. We obtain this result since the estimated production function allows for the explicit derivation of both the emission and eco-efficiency functions. One could ask why we estimated the production function, and did not directly estimate the relation between profit and emission from the observed data. Figure 5 compares the relationship between profit and emission that is obtained from estimating the Cobb-Douglas production function and exploiting duality characteristics with the relationship that is obtained when a Cobb-Douglass function is estimated directly from the data about profit and nitrogen emission. The estimated profit-emission function envelops well the observed data points. Nevertheless, the function does not correspond to the function derived from the estimated production function. The estimated profit-emission function may well serve as a representation of best-performing farms. The derived function from the estimated production function, however, gives additional diagnostics about improvement possibilities of the whole group of farms. It provides starting points for discussing why farms are performing far from the optimum. Moreover, the production function-based relationship between profit and emission explicitly takes into account the materials-balance principle for emission.

Figure 5. Production-function-based versus outcome-based economic-environmental trade-off



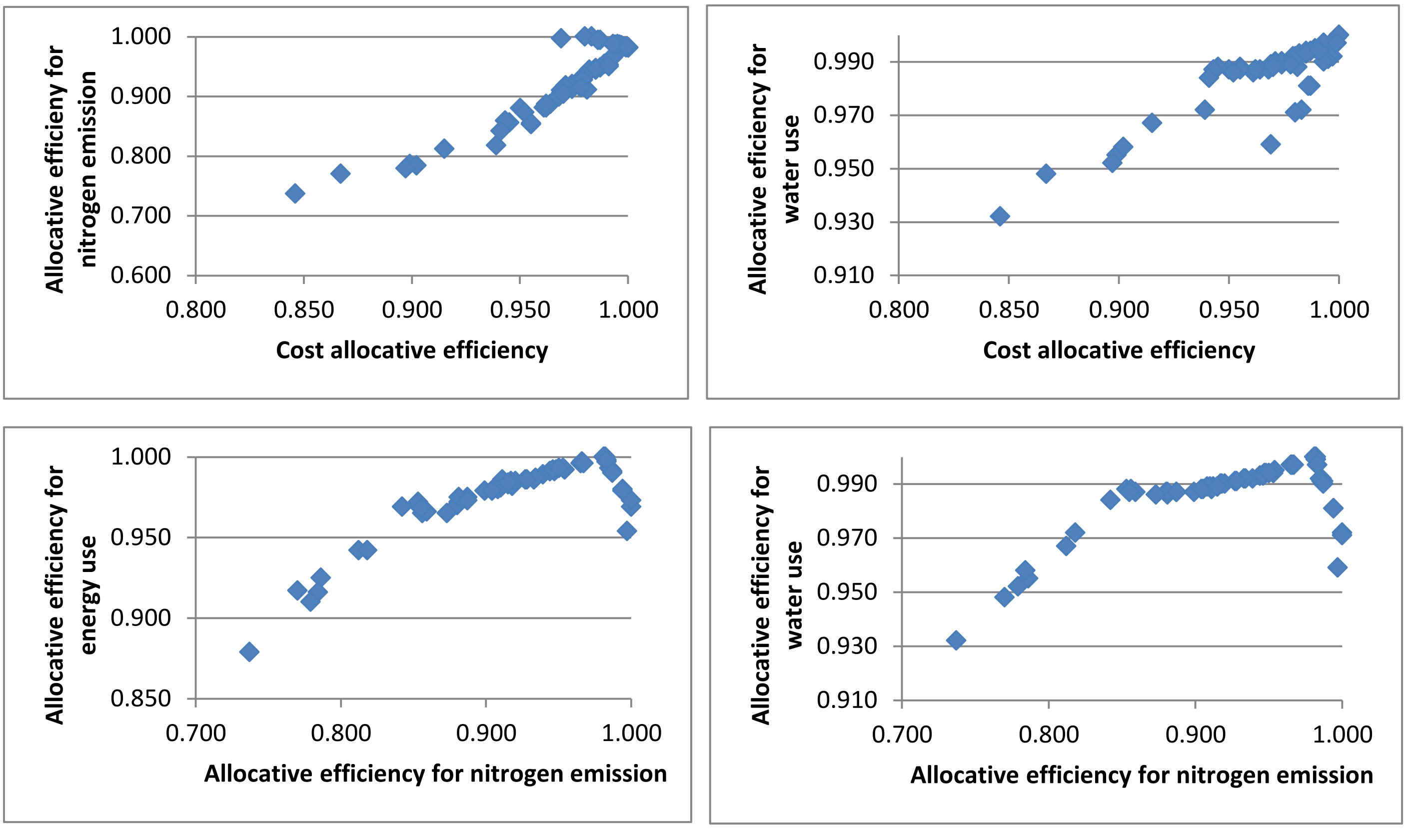
5. Implications for trade-off analysis in practice

Sections 3 and 4 illustrate how the production function provides additional diagnostics for analyzing economic-environmental trade-offs. Nevertheless, it is also shown that the choice of functional form of the production function (e.g. logistic, Cobb-Douglas) may influence the trade-offs pattern, as this functional form determines the shape of the derived profit, emission and eco-efficiency functions. In Section 4, we used a Cobb-Douglas production function. Although this functional form allows for exploiting duality characteristics, it is also known as a restrictive functional form. A translog function is more flexible, but does not have these self-duality characteristics. One could use a translog function, but then separate estimations of production, cost and emission functions would be required. This also requires the availability of data concerning outputs, inputs and prices.

Van Meensel et al. [10,11] provide examples of using the production function, duality characteristics and the materials-balance principle to analyze economic-environmental trade-offs for pig-finishing farms. They apply the findings of Coelli et al. [3], who show that both cost and environmental efficiencies can be decomposed into technical and input allocative components. They use SFA, with a Cobb-Douglas production function, and its deterministic nonparametric counterpart Data Envelopment Analysis (DEA) to illustrate that both technical efficiency improvements and changes in input allocations may result in economic-environmental win-win situations. They also focus on nitrogen emission as an example of environmental pressure.

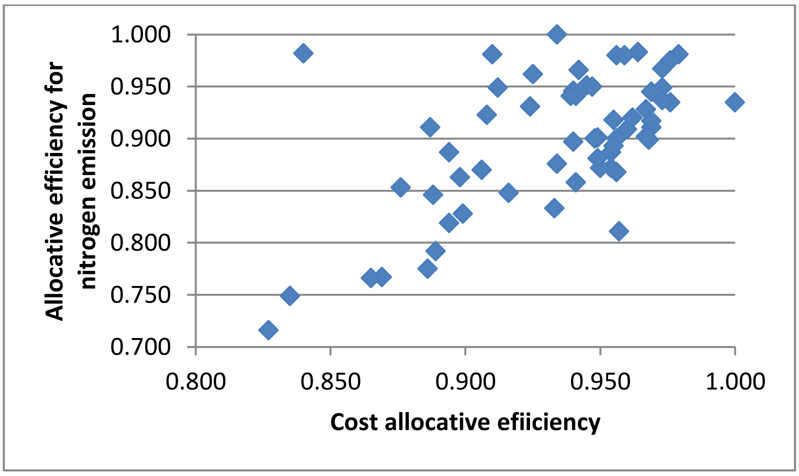
Using our dataset of 62 typical pig-finishing farms and considering 1 output (marketable pig) and 2 inputs (feed and rotations), we apply the DEA methodology from Van Meensel et al. [10,11] to assess efficiencies related to costs, nitrogen emission, water use and energy use. Figure 6 provides examples of obtained relationships between different input allocative efficiency scores. The examples show that changed input allocations may both lead to win-win situations and trade-offs, depending on the specific farm conditions.

Figure 6. Win-wins and trade-offs through changed input allocations



The above example uses 1 output and 2 inputs. Figure 7 shows the relationship between cost allocative efficiency and allocative efficiency related to nitrogen emission, in case of 5 inputs (feed, rotations, number of pig places used, labour, other costs). The clear pattern that shows the relationship between allocative efficiency scores is no longer obtained. Further research may focus on finding reasons for obtaining this more scattered pattern.

Figure 7. Allocative efficiencies in case of multiple inputs



The methodology by Coelli et al. [3] treats environmental efficiency in a similar way as cost efficiency. Nevertheless, firms may aim at maximizing profit, instead of minimizing costs. Therefore, further research may focus on exploring manners for linking profit efficiency and environmental efficiency. Directional distance functions may provide starting points for this exercise.

6. Conclusion

This paper explores the potential added value of using the production function, instead of the mere eco-efficiency ratio-indicator, for economic-environmental trade-off analysis. The production function provides additional diagnostics for steering firms towards economic-environmental win-win situations. It reveals underlying factors that may lead individual firms towards win-wins. For trade-off analysis in practice, however, still various issues have to solved. First, one has to be careful when choosing a functional form of the production function, as this functional form influences the obtained trade-offs. Further on, research must continue to focus on exploring the similarity between profit and environmental efficiencies. Existing methodologies to derive cost and environmental efficiencies in a similar way need fine-tuning in this respect.

Conflict of interest

The authors declare no conflict of interest.

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