Ecological Economics 142 (2017) 46–55

Contents lists available at ScienceDirect

Ecological Economics

journal homepage: www.elsevier.com/locate/ecolecon

Analysis

Cross-constrained Measuring the Cost-environment Efficiency in Material Balance Based Frontier Models

Ana M. Aldanondo-Ochoa, Valero L. Casasnovas-Oliva *, M. Carmen Almansa-Sáez

Universidad Pública de Navarra, Departamento de Gestión de Empresas, Pamplona 31006, Spain

ARTICLE INFO

Article history:
Received 17 July 2016
Received in revised form 12 April 2017
Accepted 7 June 2017
Available online 20 June 2017

Keywords:
Cross-constrained cost-environmental efficiency
Material balance condition
Nitrogen pollution
Greenhouse horticulture

ABSTRACT

Frontier models based on the material balance principle (MBP) constitute a major group of environmentally-adjusted efficiency methods that produce environmental and economic outcomes, but fail to integrate them with measures of allocative efficiency in order to perform a joint cost-environmental efficiency analysis. Drawing insight from the literature on multi-criteria analysis, the objective of this paper is to extend the MBP framework to new measures of cross-constrained cost and environmental allocative efficiency using data envelopment analysis (DEA). Cross-constrained measures seek for efficiency improvement in one of the two relevant criteria, cost and environment, consistent with given levels of both production and the outcome of the other criteria. The incorporation of these measures into the MBP framework provides an extra decomposition of allocative efficiency in efficiency gains that involve an economic- environmental trade-off and those that do not. The proposed approach is illustrated with an application geared to assessing the efficiency of a sample of greenhouse horticultural production units in Almeria, Spain. The results for this case show that it is possible to increase environmental allocative efficiency by up to 34% on average without incurring additional costs.

1. Introduction

The last decade has seen increasing application of efficiency frontier models taking the material[1] balance principle (MBP) into account to measure firm and regional level environmental performance and obtain both environmental information and economic outcomes (Coelli et al., 2007; Hoang and Coelli, 2011; Reinhard et al., 2000). The main acknowledged advantage of the MBP approach over other methods is that it is founded upon on the Law of the Conservation of Matter (Lauwers, 2009). According to this law, pollutant emissions from production activities are considered waste residuals (Ayres, 1995; Ayres and Kneese, 1969; Pethig, 2006), and are measured as the balance between the potentially pollutant materials that enter the production system (nutrients from agricultural fertilizers, for example) and the materials that are transformed into final goods (the nutrients that plants draw from the soil, for example). From this perspective, it is of significant importance to control the quantity and composition of inputs in the production process when dealing with the problem of environmental degradation, because the pollution generated in producing a given level of output will vary according to the quality and quantity of the inputs.

Following this logic, several authors (Lauwers, 2009; Van Meensel et al., 2010a; Welch and Barnum, 2009) have shown that the integration of the MBP into efficiency models also has major implications for decision makers. They show that a strategy for a more efficient management of inputs to reduce pollution generation may provide "win-win" outcomes, that conciliate the economic interest of firms with the environmental concern of society. For instance, reducing the overuse of inputs by improving technical efficiency has a twofold benefit, since it reduces both production costs and environmental pressure. Likewise, it is implicit in the MBP approach that part of the improvement in environmental allocative efficiency can be achieved while decreasing costs. For example, Lauwers (2009) and Van Meensel et al. (2010a, 2010b) measure environmental economic trade-offs in a sample of farms, and find half the sample able to achieve simultaneous improvements in cost allocation efficiency and environmental efficiency, by changing the proportions of their input factors to combinations that are both more environmentally friendly and less costly. Similarly, Welch and Barnum (2009), in a sample of electricity generation plants, find some that are able to achieve joint cost and environmental benefits, by moving from the technical efficiency point to the minimum cost point or to the point of lowest pollution. Evidence obtained by Nguyen et al. (2012) also suggests that there exists a positive economic–environmental trade-off path for allocative efficiency.

Despite this evidence, typical MBP measures of environmental allocative efficiency (Coelli et al., 2007; Nguyen et al., 2012) do not

* Corresponding author.
E-mail addresses: alda@unavarra.es (A.M. Aldanondo-Ochoa), valero.casasnovas@unavarra.es (V.L. Casasnovas-Oliva), carmen.almansa@unavarra.es (M.C. Almansa-Sáez).

[1] Some energy-efficiency studies (Hoang, 2014; Hoang and Prasada Rao, 2010) are also based on energy balances.

http://dx.doi.org/10.1016/j.ecolecon.2017.06.006
0921-8009/

integrate production costs; just as cost-efficiency measures do not consider environmental pressure. They compute the maximum potential reduction in environmental damage without considering cost and the maximum potential cost reduction irrespective of environmental performance. In this paper, we propose to integrate cost and environmental pressure into two alternative measures of cross-constrained allocative efficiency. We see this integration as beneficial from two perspectives. The first advantage of the cost-constrained approach, is that the proposed environmental allocative efficiency measure will seek pollution reduction input recombination consistent both with continued production of given outputs and with a given cost. This makes these measures particularly useful for assessing pollution-reduction potential in a setting where there is reluctance to compromise economic performance. The second benefit, from the environmentally-constrained perspective, is that the cost allocative efficiency measures will also show the maximum feasible improvement in cost allocative efficiency that can be obtained while maintaining given environmental standards. The value added of the cross-constrained method is that it will also bring into the analysis feasible intermediate options for efficient substitution of inputs between the minimum cost and the minimum pollutant material input that could potentially lead to environmental gains (economic gains) without detriment to the economic (environmental) outcome.

Moreover, by extending the standard MBP cost-environment efficiency model to include these measures, we are able to distinguish improvements in allocative efficiency that traditionally involve no detriment neither to the firm's cost performance nor its environmental performance (constrained measures) from those that involve a positive or negative trade-off. In this way, it provides information for environmental planning strategies. It allows a distinction between environmental objectives that could be achieved while safeguarding or improving economic competitiveness and policies that would restrict economic activity. The standard MBP model of cost and environmental efficiency do not provide this information.

To integrate costs and environmental in cross-constrained efficiency measures, we apply the constrained multi-objective optimization method, which is extensively used to map efficient solutions in multi-criteria analysis (Chankong and Haimes, 1983; Haimes et al., 1971; Marler and Arora, 2004). The advantage of this method is that it identifies efficient solutions without requiring ex ante specification of a utility function. Our work adapts the variation proposed by Mavrotas (2009) to find the optimal pollutant material input-to-cost ratio. The efficiency indices are computed from these optimal values.

To illustrate the usefulness of this method, we apply the efficiency measures to a sample of greenhouse horticultural farms in Spain. In doing so, we focus on the environmental pressure exerted by the use of nitrogen fertilizers. Our approach enables quantification of the potential reduction in nitrogen input that can be achieved with no increase (and even a potential reduction) in costs, by improving both technical and allocative efficiency.

The paper is organized as follows. In the next section, we describe the methodology. Section 3 presents the sample description and empirical results, and the subsequent sections contain a discussion of the results and the conclusions to be drawn from them.

2. Methodology

In this section we reproduce the standard MBP joint cost and environmental efficiency model (Coelli et al., 2007) and extend it to include some new cross-constrained allocative efficiency indicators. Our cost-constrained environmental allocative efficiency indexes are computed with given outputs and given costs. The environment-constrained cost allocative efficiency indicator is determined analogously. Finally, a decomposition of allocative efficiency makes a distinction between environmental (cost) allocative efficiency gains involving no economic (environmental) trade-off and those resulting in a cost increase (environmental degradation).

2.1. Standard MBP Cost and Environmental Efficiency Model

Consider a set of firms that use N inputs, $x \in R_+^N$ to produce M outputs $y \in R_+^M$ using a technology that may be represented by the feasible production set as:

$$T = \left\{(xy) \in R_+^{N+M} | x \; can \text{ produce } y\right\} \tag{1}$$

Assume that the production technology satisfies the standard axioms (Shephard, 1970), including convexity and free disposability of inputs and outputs.

The production activity also generates $z \in R_+^S$ pollutant emissions as by-products, and by the material balance equation:

$$z = a'x - b'y \tag{2}$$

where a and b are (N × S, M × S) vectors of constant coefficients, which represent the units of particular material compound or substance z_s contained in the input and in the output (it can be any particular material or a chemical element or compound as for example nitrogen, sulfur, carbon, etc.). The possibility exists that some inputs and outputs may contain a zero amount of substance z_s. For the sake of clarity, we consider that there is only one pollutant emission, $s = 1$, and are thus able to remove the subindex s.[2]

The standard MBP cost and environmental efficiency model present two separate overall cost (*CE*) and overall environmental (*EE*) efficiency measures. These measures are decomposed into a common measure of technical efficiency (*TE*) and two independent measures of allocative efficiency: cost allocative efficiency (*CAE*) and environmental allocative efficiency (*EAE*). In this section, we adhere very closely to the format used in Coelli et al. (2007), where the output y is fixed, and overall cost and overall environmental efficiency is referred to the minimum feasible cost and the minimum feasible amount of contaminants materials from inputs (material input), respectively. See Appendix A for details of the Coelli et al. (2007) specification. Here, we will comment only on the measures that constitute the basis of our own approach. Let us illustrate the efficiency measures mentioned so far with a simple diagram.

Fig. 1 depicts the very simple case of a technology involving two inputs, x_1 and x_2, the isoquant or frontier of technical efficiency, the isocost line, which shows all combinations of inputs that cost the same total amount, $w'x$, and the iso-material line which shows all combinations of inputs that contain the same quantity of material or potential pollutant substances, $a'x$.[3]

This diagram shows four decision making units: the least-cost unit, C*, the least-polluting unit, E*, and two inefficient units, I and I′. The *TE* of I is given by the quotient of Ot/OI; its *CE* is given by the Oc/OI; and its environmental efficiency, *EE*, is given by Oe/OI. Its cost allocative efficiency (*CAE*) is given by Oc/Ot; and its environmental allocative efficiency (*EAE*) is given by Oe/Ot. The efficiency measures for unit I′ could be shown analogously. However, there is an important difference between I and I′. The I technically efficient peer, t, lies on the portion of the isoquant between C* and E* that is considered efficient. At this point, it is worth specifying that the efficiency criterion used in this paper is similar in concept to that used by Shephard (1970) and Tone and Tsutsui (2010) to define technological efficiency, but applied to cost- environmental efficiency. We will consider a production unit to be efficient if within the input vectors of the feasible production set that yield at least its output rate there is no other allocation that is equally or less costly or equally or less pollutant, with one magnitude strictly smaller. Conversely, we consider a unit to be weakly efficient when there is no other feasible production alternative that can achieve the same or a greater

[2] Coelli et al. (2007) generalizes the model to various types of pollutants using pre-established environmental damage coefficients. This generalization is not included here.

[3] It is assumed that both inputs contain pollutant material. See Nguyen et al. (2012) for a depiction of the case in which only one of the inputs is potentially pollutant.