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Analysis

Analysis of environmental efficiency variations: A nutrient balance approach

Viet-Ngu Hoang [a,*], Trung Thanh Nguyen [b]

[a] Queensland University of Technology, Brisbane, Australia
[b] Bayreuth Center of Ecology and Environmental Research, Bayreuth University, Bayreuth, Germany

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ABSTRACT

Recent literature has argued that environmental efficiency (EE), which is built on the materials balance (MB) principle, is more suitable than other EE measures in situations where the law of mass conversation regulates production processes. In addition, the MB-based EE method is particularly useful in analysing possible trade-offs between cost and environmental performance. Identifying determinants of MB-based EE can provide useful information to decision makers but there are very few empirical investigations into this issue. This article proposes the use of data envelopment analysis and stochastic frontier analysis techniques to analyse variation in MB-based EE. Specifically, the article develops a stochastic nutrient frontier and nutrient inefficiency model to analyse determinants of MB-based EE. The empirical study applies both techniques to investigate MB-based EE of 96 rice farms in South Korea. The size of land, fertiliser consumption intensity, cost allocative efficiency, and the share of owned land out of total land are found to be correlated with MB-based EE. The results confirm the presence of a trade-off between MB-based EE and cost allocative efficiency and this finding, favouring policy interventions to help farms simultaneously achieve cost efficiency and MP-based EE.

1. Introduction

There are two important components in any type of empirical õenvironmental efficiency (EE) analysis, particularly in agricultural production (Reinhard et al., 2002). The first component estimates EE scores and variation in the EE scores across farms, the second identifies determinants of such variation. For the first component, several approaches to measuring EE exist (for an overview see for example Tyteca, 1996 and Callens and Tyteca, 1999). Recent literature favours the use of those EE measures which are based on the balances of materials, particularly in an agricultural sector (hereafter called MB-based EE) (Coelli et al., 2007; Hoang and Coelli, 2011; Lauwers, 2009). MB-based EE measures are preferred because the materials balance principle (MBP) regulates the transformation of materials in such closed systems of agricultural production; hence EE measures, in order to be reliable, should be adjusted to be consistent with the MBP. Moreover, the MB-based approach can lead to a more diversified analysis of EE and facilitate analysis of trade-offs between the economic and environmental performance of a given production technology (Lauwers, 2009; Van Meensel et al., 2010).

The MB-based approach has been applied in analysing the EE of several types of decision-making units (DMUs) in crop and livestock production in which the balances of nutrients such as nitrogen (N) and phosphorous (P) are considered as polluting emissions. Reinhard and Thijssen (2000) analysed Dutch dairy farms using a stochastic frontier analysis (SFA) technique. Coelli et al. (2007) investigated the environmental performance of 117 pig finishing farms in Belgium using a data envelopment analysis (DEA) technique. Van Meensel et al. (2010) applied both DEA and SFA techniques to the same data set used in Coelli et al. (2007) to analyse trade-offs between EE and economic efficiency. Hoang and Coelli (2011) and Hoang and Alauddin (2012) studied crop and livestock production in developed countries using the DEA technique. Nguyen et al. (2012) investigated the environmental performance of rice farms in South Korea. These studies found high variation in MB-based EE across decision-making units (DMUs) (i.e., countries and farms). For example, Nguyen et al. (2012) reported remarkably high variation of MB-based EE across 196 rice farms (e.g., a mean EE score: 0.309, the range: 0.055 to 1, and standard deviation: 0.179) (Nguyen et al., 2012).

With respect to the second component, the identification of determinants of variation, this type of analysis can provide decision makers with useful information about how to improve EE. Several analytical frameworks (for example two-stage DEA models or single-stage SFA models) to analyse efficiency drivers have been well developed and widely used in empirical studies (Battese and Coelli, 1995; Coelli et al., 2005; Greene, 2005; Simar and Wilson, 2007). Researchers have used these frameworks to investigate drivers of EE variation. Reinhard et al. (2002) appear to be one of the most cited empirical studies that investigate the determinants of EE variation in the

* Corresponding author. Tel.: +61 7 313 84325; fax: +61 7 3138 1500.
E-mail addresses: vincent.hoang@qut.edu.au (V.-N. Hoang), thanh.nguyen@uni-bayreuth.de (T.T. Nguyen).

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context of agricultural production; however, this study uses an EE model that is not adjusted for the MBP.

However, none of previous empirical studies of the MB-based EE approach performed the second component of the analysis. Hence, it is desirable to assess critically whether the existing analytical frameworks of analysing EE determinants can be appropriate in the context of MB-based EE analysis. The present article aims to fill this gap by using bootstrap truncated two-stage DEA models proposed by Simar and Wilson (2007) and estimating the stochastic nutrient frontier following the stochastic frontier model of Battese and Coelli (1995). Empirical applications of these models into a data set of rice farms in South Korea also illustrated the possibility of conducting a statistical hypothesis test for trade-offs between economic and environmental performance.

The remainder of the article is structured as follows. Section 2 provides a brief literature review on various approaches to measuring EE. Section 3 provides a mathematical illustration of the shortcoming of the EAPE model in relation to the MBP. Section 4 reviews the MB-based EE method and discusses potential uses of this method for trade-off and policy analysis. Section 5 introduces the use of SFA and DEA techniques to analyse variation in the MB-based EE. Section 6 presents an empirical analysis of rice farms in South Korea. Section 7 concludes the article.

2. Main Approaches to Measuring Environmental Efficiency: A Literature Review

Lauwers (2009) provides a review of three general groups of models used to measure EE: the environmentally adjusted production efficiency, the frontier eco-efficiency and the MB-based models. The environmentally adjusted production efficiency (EAPE) uses the production frontier to analyse a relationship between inputs and outputs. In EAPE's models, pollution is viewed as either environmentally detrimental inputs or undesirable outputs. Adding pollution as an extra input or output in conventional production models, technical efficiency (TE) measures can be estimated with input-oriented, output-orientated frameworks, or with hyperbolic or directional distance functions (Chung et al., 1997; Färe et al., 1996; Färe et al., 2007; Reinhard et al., 2002). An input-orientated framework minimises inputs given fixed output quantities. An output-orientated framework maximises outputs with fixed input quantities. The hyperbolic and directional distance functions allow the simultaneous expansion of outputs and the contraction of inputs. The proponents of these methods argue that these models credit farms for the contraction of pollution; therefore, TE can be interpreted as EE.

The frontier eco-efficiency (FEE) uses the frontier framework to model relationships between economic and ecological outcomes to derive eco-efficiency measures (Callens and Tyteca, 1999; Tyteca, 1999). The eco-efficiency measures relate the economic value of outputs to the environmental pressures involved in production processes (Picazo-Tadeo et al., 2012). Several empirical studies have applied this approach (Kortelainen, 2008; Kuosmanen and Kortelainen, 2005; Picazo-Tadeo et al., 2011). These applications can be seen as the frontier operationalisation of the eco-efficiency concept in the analysis of multidimensional sustainability (Lauwers, 2009). For example, Picazo-Tadeo et al. (2011), using a data set of 117 crop farms in Spain, assessed the opportunities of reducing five environmental pressures (tendency towards monoculture that has potential impacts on biodiversity, N balance, P balance, energy balance, and pesticide risks), given the value added of crop outputs.

There is a methodological distinction between EAPE and FEE models. The EAPE models are based on the conventional production relationship between inputs and outputs while the FEE models are grounded on a hypothesised relationship between economic values of outputs and environmental pressures. Often they are used in different research contexts. The primary use of the EAPE approach is to adjust efficiency measures to account for environmental pollution in the paradigm of costly environmental regulation. In this paradigm, efficiency analysis methods implicitly suppose that efficiency improvements imply cost reduction (Lauwers, 2009). The FEE approach is used mainly to provide relative assessments among DMUs in terms of environmental performance where there are many types of environmental pressures caused by production and consumption activities.

The third approach to measuring EE involves the use of the MB-based models firstly proposed by Coelli et al. (2007). The MB-based models view pollution as the balance of materials and attempt to minimise this balance. The MB-based EE measures are defined as the technically feasible minimum materials balance to the currently observed materials balance. The MB-based models are distinct from the EAPE and FEE methods because the materials balance does not appear as either an input/output in EAPE models or an indicator of environmental pressures in FEE models.

Note that the MB-based and EAPE models are grounded on the same production relationship between inputs and outputs; hence they are very useful in analysing economic–environmental trade-offs faced by DMUs (Lauwers, 2009; Van Meensel et al., 2010). However, the MB-based models are more suitable in situations where the MBP regulates the transformation of materials in production processes (Hoang and Alauddin, 2012; Hoang and Coelli, 2011; Nguyen et al., 2012).[1] The MB-based models are preferred because given the existing construction of EAPE models, measuring environmental inefficiency as the degree to which pollution (i.e., the materials balance) can be reduced with traditional inputs and outputs held constant is mathematically infeasible (Coelli et al., 2007; Hoang and Coelli, 2011; Lauwers, 2009). To provide further evidence of this shortcoming of the EAPE models, the next section investigates the model of Reinhard et al. (2002) in which emission is modelled as an input.

3. A Major Shortcoming of the EAPE Models: A Simple Mathematical Illustration

Consider the situation where farms produce a vector of M outputs, $\mathbf{q}\in\Re_+^M$, using a vector of K inputs, $\mathbf{x}\in\Re_+^K$. The production activity also produces an emission of polluting substances. The amount of emission is defined by the balance of nutrients:

$$u = \mathbf{ax} - \mathbf{bq} \qquad (1)$$

where **a** and **b** are the vectors representing nutrient contents of inputs and outputs. Some inputs, such as labour and machinery, could have zero contents of nutrients, suggesting that vector **a** may include zero values.

The MBP applies to individual flows of nutrients (e.g., N or P). In situations where there are many types of nutrients involved, one can use weights that reflect the polluting power of different nutrients in calculating the aggregate nutrient balance. For example, N and P are two main causes of eutrophication (i.e. oxygen depletions caused by excessive nutrient-induced increases in the production of organic matter) in water systems (Howarth et al., 2000). The analysis of eutrophication requires the use of a particular set of weights that reflect the eutrophying power of N and P in the context of a specific water system such that their aggregate effects can be analysed in empirical studies. Given an appropriate choice of N:P weights, the aggregate balance of nutrients can be calculated. Note that the eutrophying

[1] For example, in rice production not all N and P in seed, chemical fertilisers, organic fertilisers and land are transformed into rice outputs. In fact, N and P balances, defined as the differences of the total amounts of N and P in inputs and of the total amounts of N and P in outputs, will go to water and atmospheric environments. Scientifically, these balances have been identified as the main cause of eutrophication in lake, river, and ocean water systems (Smith et al., 1999). Therefore, in rice production, the balance of nutrients can be considered as potential polluting agents.