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Applying a network data envelopment analysis model to quantify the eco-efficiency of products: a case study of pesticides

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ABSTRACT

With the increasingly obvious constraint on resources and the environment that results from the growth of the population and the economy, promoting the eco-efficiency of products has become a critical component of achieving sustainable development. This research developed a network data envelopment analysis (DEA) combined with life-cycle environmental impacts of products for eco-efficiency evaluation. Taking pesticides as a case study, the eco-efficiencies of ten comparable pesticides were examined. The results show that Deltamethrin is the only eco-efficient pesticide and that Dichlorvos and Chlorpyrifos have lowest eco-efficiency scores. Pyrethroid pesticides are generally more eco-efficient than organophosphorus pesticides at the usage stage due to lower environmental impact. The results also find out that the network DEA method for evaluating eco-efficiency of products can distinguish differences in the eco-efficiency of products at the different stages which could provide a better discrimination among pesticides while compared to single-stage DEA model and present a relatively lower eco-efficiency score. Finally, since organophosphorus pesticides have a lower market price in China, new policies (such as subsidies or a pollution tax) should be designed to encourage the use of pyrethroid pesticides instead of organophosphorus pesticides.

1. Introduction

With the increasing strain on resources and the environment that result from economic and social growth, the current management philosophy regarding the choice between alternative products is gradually changing from an uni-dimensional pursuit of economic benefits to a recognition of the importance of sustainable development. It is essential to recognize the dual optimization of “the economy and the environment” as the target is imperative in product design. Eco-efficiency is recognized as an important measure in relation to the goal of sustainable development (Huppes and Ishikawa, 2005; Mudd and Diesendorf, 2008; Shonnard et al., 2003). Eco-efficiency has received significant attention in the sustainable development literature. The core idea of eco-efficiency is to emphasize the production of high-quality products with a minimum input of scarce resources and the smallest possible amount of pollution emission. This concept has also been expressed in terms of the ratio of production value to environmental load, environmental productivity, or growth-oriented eco-efficiency (Koopmans, 1951). The notion of eco-efficiency can be applied to the assessment of many different things such as products, enterprises, regions, societies, among others (Hahn et al., 2010; Huppes, 2009; Huppes and Ishikawa, 2009; Iribarren et al., 2011; Wursthorn et al., 2011; Zhang et al., 2008; Zhao et al., 2011; Zhu et al., 2011).

A number of alternative measures or indicators have been suggested (Glauser and Muller, 1997; Schaltegger and Burritt, 2000; Tseng et al., 2014), most of them being simple indicators such as “economic output per unit of waste” ratios that approach eco-efficiency from a very limited perspective (Kuosmanen and Kortelainen, 2005). The main problem that arises in the development of eco-efficiency indicators is the lack of adequate measures that correspond to market prices for undesirable outputs including waste products and pollution emissions (Pekka and Luptacik, 2004). To address this problem, some scholars have used data envelopment analysis (DEA) models to evaluate eco-efficiency or environmental efficiency (Coli et al., 2011; Halkos and Tzeremes, 2010; Zhao et al., 2006). DEA was originally developed as a general purpose performance evaluation method for situations involving multiple performance criteria, and it is widely employed in the comparative assessment of public sector and nonprofit organizations where price information is not readily available (Zhang

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et al., 2008; Zhang and Yang, 2007). The advantage of this method compared to traditional cost-effectiveness methods lies in its capacity to skip the steps of setting parameters to assess the influential monetization of the environment and its ability to avoid uncertainty during value assessment (Halkos and Tzeremes, 2010; Kuosmanena et al., 2009). A DEA efficiency score is based on weights that represent the optimal performance of the production unit that is to be evaluated compared to a sample of benchmark units. In practice, these optimal weights and eco-efficiency scores are calculated using linear programming techniques (Kuosmanen and Kortelainen, 2005; Tone and Tsutsui, 2009).

In addition, for the environmental impact of products, a comprehensive method is needed to assess the overall environmental impacts caused by all of the steps (including the system of production, the use of the product, and the disposal processes) that are necessary in connection with the relevant products. This series of steps is known as the value chain (Mirhedayatian et al., 2014) or the “product life-cycle” (Geisler et al., 2005). Life-cycle assessment (LCA) is applied to assess the environmental aspects and potential impacts associated with a product. Thus, researchers combine the DEA model with LCA by considering the life-cycle environmental impacts of products in the eco-efficiency evaluation (Michelsen et al., 2006). This approach has been applied to some home appliances (Barba-Gutiérrez et al., 2009), printers (Doyle and Green, 1991), cars (Papahristodoulou, 1997), and software (Herrero and Salmerón, 2005). In practice, however, eco-efficiency analysis that combines the DEA model and the product LCA approach usually applies only to a single-stage model that is unable to reveal the flow and structure of environmental impact of different stages of products (Lambert and Cooper, 2000; Mentzer et al., 2000; Papahristodoulou, 1997).

To comprehensively assess the eco-efficiency of products, the proposed network DEA model provides a powerful tool to solve the issues facing the eco-efficiency assessment at each stage of a product’s life cycle (Fare and Grosskopf, 2000; Mirhedayatian et al., 2014). The network DEA approach was developed to capture the underlying performance information found in the interacting divisions or sub-processes of a firm that would otherwise remain unknown to management (Färe et al., 2007). Wang et al. (1997) proposed a sequential two-node DEA efficiency assessment model, based on which Chen and Zhu (2004) conducted further research and proposed models that simultaneously consider the efficiency of each subsystem. Lothgren and Tambour (1999) demonstrated that the eco-efficiency of the network DEA model is lower than single DEA model. Based on this, Lewis and Sexton (Lewis and Sexton, 2004; Sexton and Lewis, 2003) proposed another assessment model and decided the frontline output of the intermediate product when the input of the first node is not changed by relying on the traditional DEA method. Bi et al. (2007a) discussed the fixed and unchanged sequential two-stage DEA model of the intermediate product. Tone and Tsutsui (2009) proposed a non-radial network DEA model based on a slacks-based measure (SBM) and the set weights among the modes. They also provide a thorough discussion regarding how the optimization direction is selected, among other issues.

Building on the research discussed above, this research applied the network DEA model instead of single stage DEA model (Zhang et al., 2008) to evaluate the eco-efficiency of products and used pesticides as the specific product that is to be examined. The key factors affecting the eco-efficiency of pesticides were identified through the design and application of a two-stage DEA model. The next section of this paper introduced the methods of the research and particularly the network DEA model. Section 3 reported the application of the model to pesticides as an example of how to construct a corresponding network DEA model and then explained the assessment results. Section 4 discussed the eco-efficiency evaluation results and the policy implications.

2. Method

2.1. System boundary

In the physical economy, people input material and energy and produce products (or value), but in the process, emissions and other undesirable outputs are unavoidable (Zhang et al., 2008). According the product life-cycle framework, different processes have different environmental impacts and economic value. Pesticides are consumables (i.e., they are disposed of through ordinary use) and thus, no treatment procedure is required after they have been used on farmland. The effect of pesticides on the environment consists primarily of the discharge of waste materials in connection with the production process and the ecological risk to farmers, consumers, animals and plants that is posed by the use of the pesticides (Geisler et al., 2005; Papahristodoulou, 1997). Therefore, the research scope is simplified to two processes: the process of producing the pesticides and the process of using the pesticides (see Fig. 1). The production stage for the pesticides involves the process of transforming the basic chemicals into pesticides, while the stage of using the pesticides involves the process of spraying the pesticides in the field. In the first stage, the production of pesticides yields economic benefit for enterprises, but it also generates pollution in the form of wastewater, hazardous solid waste materials, and so forth. In the next stage, using pesticides results in an increase in the volume of output of agriculture production, but the pesticide residue also results in harm to the ecosystem. The eco-efficiency of other processes relating to pesticides, such as the transportation, storage, and sales of pesticides, is not addressed in this research.

2.2. Case study and input–output index

In this research, pesticides were selected as the type of product for examination in a case study involving eco-efficiency analysis. Although it is generally profitable to use pesticides in agriculture, the pesticides that are used often have a greater environmental impact than what the users had intended (Pimentel, 2005). Pesticides are biocides that were designed to be toxic to specific types of organisms. They can have substantial adverse environmental effects in a wide variety of ways. Some of the adverse effects are fairly obvious, but others are extremely subtle and complex. Some pesticides are highly specific, and others have broad-spectrum effects. Both the specific and the broad-spectrum pesticides can affect terrestrial wildlife, soil, water systems, and humans (Belsey et al., 2011; Haith, 2010; Juraske et al., 2010; Sattler et al., 2007). Some

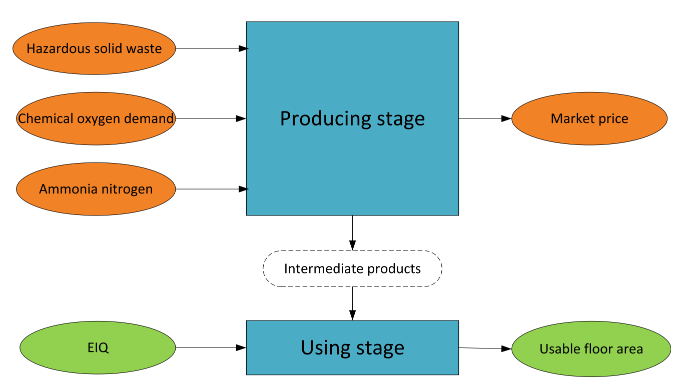

Fig. 1. Framework for analysis of two-stage DEA eco-efficiency model for pesticides.