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Measuring environmental efficiency of agricultural water use: A Luenberger environmental indicator☆

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ABSTRACT

Irrigated agriculture creates substantial environmental pressures by withdrawing large quantities of water, leaving rivers and wetlands empty and unable to support the valuable ecosystems that depend on the water resource. The key challenge facing society is that of balancing water extractions for agricultural production and other uses with provision of appropriate environmental flow to maintain healthy rivers and wetlands. Measuring tradeoffs between economic gain of water use in agriculture and its environmental pressures can contribute to constructing policy instruments for improved water resource management. The aim of this paper is to develop a modelling framework to measure these tradeoffs. Using a new approach – Luenberger environmental indicator – the study derives environmental efficiency scores for various types of irrigation enterprises across seventeen natural resource management regions within the Murray-Darling Basin, Australia. Findings show that there is a substantial variation in environmental performance of irrigation enterprises across the regions. Some enterprises were found to be relatively environmentally efficient in some regions, but they were not efficient in others. The environmental efficiency scores could be used as a guideline for formulating regional policy and strategy to achieve sustainable water use in the agricultural sector.

1. Introduction

The irrigated agricultural sector is creating substantial environmental pressures by withdrawing large quantities of water over a long period of time. The excessive water withdrawal for irrigation leaves rivers and wetlands unable to support ecosystems (Azad and Ancev, 2010; Grafton et al., 2010; Quiggin, 2001). A key challenge is to balance water extractions for agricultural production and other uses with provision of appropriate environmental flow to maintain healthy rivers and wetlands. Measuring tradeoffs between economic returns of water use in agricultural sector and its environmental pressures is crucial in constructing policy instruments for better water resource management. There are currently several methods described in the literature that can be used to measure these tradeoffs. Typically, these methods are adequate for an analysis of manufacturing sectors, but do not conform well to the specificities that are encountered in the agricultural sector due to the complexity of evaluating environmental impacts of agricultural activities. A recently developed method defined as 'environmental performance index' can measure the tradeoffs between environmental pressures created by irrigated agriculture and its economic performance (Azad and Ancev, 2010). This environmental performance index is a ratio-based approach, and thus the efficiency of the production activities depends on the estimated value of numerator (economic performance) and denominator (environmental pressure) of the index. Therefore, this index does not allow accurate estimation of the magnitude of environmental damage. To overcome this problem, in the present paper we propose a difference-based environmental performance measurement. This new approach can be used to estimate the actual level of efficiency and environmental damage of a production activity. The aim of the paper is to present a new modelling framework based on the Luenberger productivity approach to measure the economic and environmental tradeoffs in irrigated agriculture.

The Luenberger productivity indicator introduced by Chambers et al. (1996) is constructed based on directional distance functions, and it can be used to estimate productivity and efficiency changes of production units over a period of time. A number of studies have used the Luenberger productivity indicator to measure the change

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in productivity and efficiency for various economic units, (i.e., Epure et al., 2011; Williams et al., 2011; Barros and Peypoch, 2007; Boussemart et al., 2003; Guironnet and Peypoch, 2007; Managi, 2003; Nakano and Managi, 2008; Brandouy et al., 2010). The Malmquist-Luenberger productivity index — an index similar to the Luenberger index — was developed by Chung et al. (1997). This productivity index has also been widely used to measure performance of a range of decision making units (Oh, 2010). Several studies, such as Falavigna et al. (2013), Rodríguez-Rodríguez et al. (2012), Zhang et al. (2011), Kumar and Khanna (2009), Kumar (2006) and Färe et al. (2001) used the Malmquist-Luenberger productivity index for measuring environmentally adjusted productivity growth in various industries or countries. While both Luenberger and Malmquist-Luenberger productivity indices can be applied to measure environmental efficiency, a major difference between these two productivity indices is that the Luenberger indicator is a difference-based index, while the Malmquist-Luenberger is a ratio-based index. There are limitations of applying ratio-based productivity index especially when the key focus is in measuring differences in environmental impact. In addition, some empirical studies (i.e., Boussemart et al., 2003; Briec and Kerstens, 2004; Managi, 2003) showed that ratio-based productivity indices may overestimate productivity change compared to other productivity indicators. Due to these shortcomings of the ratio-based index we are proposing a difference-based index in the present study.

This study introduces a new methodological approach, which is developed based on the conceptual framework of the Luenberger productivity indicator for measuring environmental performance of agricultural enterprises. The merit and credibility of this approach is that it enables the researchers to compare the efficiency of irrigated enterprises across space rather than between the time periods. The Luenberger approach has so far been applied in various types of productivity and efficiency studies to estimate the productivity growth in a country, or to measure the efficiency change of enterprises over a period of time. In this paper we adapted the conventional Luenberger productivity indicator, and used it to measure environmental performance of irrigated enterprises using cross-sectional (regional data) instead of time-series data. We define this efficiency estimation method as the 'Luenberger Environmental Indicator' (*LEI*). The key criterion of this environmental indicator is that the production units (irrigated enterprises in the present case study) of various regions must be compared to a same reference unit. This enables comparing relative environmental performance of considered production units across regions.

Due to differences in the production environment (i.e. availability of resources, technology, management, etc.) there may be a substantial variation in productivity and environmental efficiency of agricultural enterprises across regions. There is a lack of adequate research in this area to develop appropriate methods and tools that can be used to measure the relative environmental efficiency of production units across space. Most of the empirical studies that focus on agricultural industries estimate the changes in environmental adjusted efficiency across time (i.e., Hoang and Coelli, 2011; Falavigna et al., 2013; Rodríguez-Rodríguez et al., 2012). In addition, a number of recent studies (i.e., Falavigna et al., 2013; Zhang et al., 2011; Oh, 2010; Bellenger and Herlihy, 2009) used directional distance functions to construct models for measuring environmental performance of production units, but they also consider changes in environmental efficiency across time. The Luenberger environmental indicator presented in the paper, which is based on directional distance functions, enables researchers to compare relative environmental performance of production units across space, rather than across time. To the best of our knowledge, this study is the first attempt to deal with the Luenberger approach in this alternative way.

2. Method and data

Chambers (1996) first introduced the Luenberger Productivity Indicator modelling with a set of directional distance functions. The advantage of using the directional distance function in an efficiency model is that it enables us to measure efficiency of a productive unit taking into account simultaneously desirable and undesirable outputs of a production technology. Put differently, it allows us to analyse production units while considering their ability to increase desirable outputs and to reduce undesirable outputs in a multi-output production process.

Suppose we have a sample of K production units each of which uses a vector of inputs $x = (x_1, ..., x_N) \in \Re^N_+$ to produce a vector of desirable outputs $d = (d_1, ..., d_M) \in \Re^M_+$, but as a consequence of the production process some undesirable outputs $u = (u_1, ..., u_j) \in \Re^J_+$ are also produced. The directional output distance function can be written as:

$$\vec{D}_o(x, d, u; g_d, -g_u) = \sup\{\beta : (d + \beta g_d, u - \beta g_u) \in P(x)\} \quad (1)$$

The directional vector is defined by(g_d, g_u). This directional output distance function seeks to achieve the maximum feasible expansion of desirable output in the g_d direction, but at the same time the largest possible contraction of undesirable output in the g_u direction.

While many studies use the time-variant directional distance functions to estimate productivity growth and efficiency change of production units, the present study constructs the directional distance function specified with an area or a region. To compare environmental performance of an irrigated enterprise between two regions, say region a and b, the area specific directional output distance function can be outlined in the following manner. For a given region a, it can be written as:

$$\vec{D}^a_o\left(x^a, d^a, u^a; g_d, -g_u\right) = \sup\left\{\beta : \left(d^a + \beta g_d, u^a - \beta g_u\right) \in P^a\left(x^a\right)\right\} \quad (2)$$

Subsequently the output-oriented Luenberger environmental indicator (*LEI*) can be formulated as:

$$LE^b_a = \frac{1}{2}\left[\vec{D}^b_o\left(x^a, d^a, u^a; g_d, -g_u\right) - \vec{D}^b_o\left(x^b, d^b, u^b; g_d, -g_u\right) + \vec{D}^a_o\left(x^a, d^a, u^a; g_d, -g_u\right) - \vec{D}^a_o\left(x^b, d^b, u^b; g_d, -g_u\right)\right]. \quad (3)$$

The output-oriented directional distance function for region b can be symbolized as $\vec{D}^b_o$, representing the reference technology constructed from data collected in region b. Equation (3) can be used to compare the performance of a production technology (irrigated enterprise for the present case study) between regions a and b.[1] If the value ofLE^b_a is greater than zero, it indicates that the environmental adjusted efficiency of a production technology in region b is greater than that of region a. Put differently, a production

[1] The term 'enterprise' is used throughout the text to denote an agricultural activity (e.g. cotton growing, or growing grapevines) in its entirety, comprising the technology, type of crops, and location in this case.