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Analysis of productive performance of crop production systems: An integrated analytical framework

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ABSTRACT

This article presents a new two-stage analytical framework to analyse the productive efficiency of crop production systems. In the first stage, crop growth and economic production models are estimated to calculate three measures of productive efficiency: (1) agronomic efficiency, as the ratio of actual yield to potential yield; (2) technical efficiency (TE), as the ratio of actual yield to best practice yield; and (3) agro-economic efficiency (AgEcE), as the ratio of best practice yield to potential yield. In the second stage, TE and AgEcE are analysed in relation to economic, institutional, social and technological factors that cause farm and spatial heterogeneity. The framework was illustrated through an empirical analysis of rice production in Sri Lanka.

1. Introduction

Measuring the productive performance of crop production systems at the farm level and identifying factors that determine their performance are important in both agronomy and economics. Farm and spatial heterogeneity have significant impacts on farm efficiency; hence, it is necessary to take them into account. In agronomy, many crop models incorporate location-specific physical conditions to estimate crop growth and potential yields for particular crop types, as well as for combinations of many crops (Bouman et al., 1996). These crop models are often developed using field and experimental data, thus providing reliable estimates of plant growth and potential yields. In fact, these models are a useful tool when designing agricultural systems for the maximisation of production outputs (de Koeijer et al., 1999; van Ittersum and Rabbinge, 1997). However, economic, institutional and social factors are not present in these models (de Koeijer et al., 1999), thus precluding their usefulness in socio-economic analysis.

On the other hand, many economic production models have been developed to estimate productive efficiency and identify efficiency determinants (Battese and Coelli, 1995; Greene, 2005). Empirical studies applying these models can provide meaningful information for farmers and policy makers to improve productive and economic performance. However, from an agronomic view point, these economic production models have several important drawbacks. Firstly, they fail to account for distinct impacts of differing inputs on the growth process of crops (Zhengfei et al., 2006). For example, fertilisers (or water) and labour (or machinery or pesticides) are considered to contribute to crop growth but fertilisers cannot be substituted by labour. Secondly, input–output relations are often based on historical data, which means that the latest technical development and biophysical insights are not incorporated (Chavas and Cox, 1995; de Koeijer et al., 1999).

The present article proposes a new approach that integrates the agronomic knowledge of crop production into socio-economic analysis of productive efficiency. A two-stage analytical framework is proposed. In the first stage, crop growth and economic production models are estimated to calculate potential and best practice output levels. The potential, best practice and actual output levels are used to derive technical efficiency (TE), agronomic efficiency (AgE) and agro-economic efficiency (AgEcE) measures. In the second stage, econometric techniques are used to analyse the determinants of variations in the scores of these efficiency measures.

The article is structured as follows. Section 2 reviews the relevant literature in agronomy and production economics. Section 3 describes the proposed analytical framework and its advantages in comparison with those in the existing literature. Section 4 discusses several potential applications of the framework for policy and decision making analysis. Section 5 provides an empirical study using a district-average dataset of rice production in Sri Lanka. Section 6 concludes the article.

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2. Literature review

2.1. Production ecological concepts

In agronomy, growth-defining, growth-limiting and growth-reducing factors are three groups of factors that determine the growth and output level of crops (van Ittersum and Rabbinge, 1997). Growth-defining factors, at the optimal supply of all other factors, determine potential growth of crops. They include seed or plant characteristics and weather conditions such as temperature, solar radiation and atmospheric CO_2 concentration. Growth-limiting factors comprise water and nutrients and in limited supply of either or both of these factors, a crop cannot achieve its potential growth. Growth-reducing factors, such as weeds, pests, diseases and pollutants, further reduce or hinder crop growth.

Also, three levels of outputs are distinguished: potential; attainable; and actual yields. The potential yield is determined by the growth-defining factors when the crop is optimally supplied with water and nutrients, and is completely protected against growth-reducing factors.[1] The attainable yield, also named water-limited and nutrient-limited yield, is lower than the potential level because of sub-optimal supply of water and nutrients. The actual yield is determined by the actual supply of water and nutrients and the degree to which the crop is protected against growth-reducing factors (van Ittersum and Rabbinge, 1997). Crop models have been used to estimate potential yield at scales ranging from a specific field to a region or country (Lobell et al., 2009).[2] Estimating crop growth in water-limiting or nutrient-limiting conditions can also be defined by the users of crop models.

Production ecological concepts, particularly crop models, have been useful for the biophysical analysis and design of crop production systems (van Ittersum et al., 2003; van Ittersum and Rabbinge, 1997). However, human behaviour, and other social and economic factors, are often neglected in these crop models (de Koeijer et al., 1999).

2.2. Economic analysis of productive performance

In measuring productive performance, economists generally quantify the relationship between inputs and outputs by estimating economic production functions. In a parametric framework, this empirical procedure starts with choosing a functional form (e.g., Cobb–Douglass, quadratic, translog, etc.) and then estimating the values of parameters of the chosen function so that the estimated equation fits "well" a particular set of data. Nonparametric estimation (e.g., using data envelopment analysis- DEA- technique) is also popular. Economic input and output data are often used to estimate economic production functions, and then to calculate farms' productive performance (Coelli et al., 2005). These studies have been useful in benchmarking the performance of an individual farm in relation to a sample of farms and identifying factors that determine variations in farms' productive performance. The results of these efficiency studies help farm managers or owners and policy makers make more informed decisions.

However, this traditional econometric approach has several drawbacks from the agronomic view point. Firstly, inputs such as water and fertilisers and other economic inputs (e.g., labour and machinery) are assumed to have similar impacts on the growth process of crops in economic production models (Zhengfei et al., 2006). However, water cannot be substituted by fertilisers and fertilisers cannot be substituted by labour in terms of agronomy; hence, the economic production model should be modified to impose further constraints of limited input substitutability. Secondly, input–output relations are often based on historical data, which means that future technical developments in crop science and changes in climate conditions are not incorporated (Chavas and Cox, 1995; de Koeijer et al., 1999). Often productivity predictions are done using efficiency measures derived from economic production functions (Coelli et al., 2005); hence, failure to capture changes in crop science and climate conditions are undesirable.

2.3. Links between production ecological concepts and economic production models

Several studies have attempted to link agronomic concepts with economic production models. Studies on damage control distinguish the damage-reducing role of pesticides from other inputs in economic models (Archibald, 1988; Lichtenberg and Zilberman, 1986). However, the differences between inputs in crop production are much broader than damage-reducing versus productive considerations. Few studies integrate agronomic knowledge into economic production modelling, those by Zhengfeit et al. (2006) and de Koeijer et al. (1999) being exceptions.

Zhengfeit et al. (2006) propose a conceptual framework that dichotomises economic inputs into growth and facilitating inputs. Growth inputs (e.g. seed, water, land, and nutrients) are directly involved in the biological process of crop growth whilst facilitating inputs (e.g. labour, capital, and pesticides) help create or alter growth conditions. The authors of this study acknowledge the presence of three different yield levels (potential, attainable and actual) but their model only distinguishes attainable and actual levels. The actual output is a product of a crop growth function (which relates the attainable yields with growth inputs) and a scaling function of facilitating inputs. The value of the scaling function is in the interval $[0,1]$. When the growth conditions are optimal, the scaling function equals 1, and output reaches its maximum level. When growth inputs are not in optimal supply, actual output is scaled down by the value of the scaling function. Zhengfeit et al. (2006) argue that their approach makes it possible to estimate crop growth functions using real farm data, thereby extending agronomic experiments into real-world agricultural production. In an empirical study of 323 potato farms in the Netherlands, this study estimated a translog crop growth equation and a quadratic form of the scaling function. The average value of the scaling function was estimated to be 94.7%, implying that ca. 5% of attainable yield has been lost. This study also linked this 5% yield loss to the concept of inefficiency used in the frontier production models.

De Koeijer et al. (1999) propose a conceptual framework to analyse the productive efficiency of crop production systems. This study acknowledges the three yield levels (i.e., potential, attainable and actual) and use the potential yield in their "agro-economic" framework. The authors identify three other output levels: normative, best practice and average. The normative output level is determined by the operational objective of farmers (e.g. profit maximisation rather than output maximisation), structural restrictions (e.g. resource endowment and legislation), and variability in the agro-economic complex. The best practice output level is determined by the best performers, while the average output level refers to the average performance of farms. Important details on

[1] Concepts of potential yields could be differentiated between rainfed and irrigated systems. For irrigated systems, potential yield (or yield potential) is commonly used term on the assumption that crop is often provided with adequate water supply throughout growth. For rainfed systems, water-limited potential yield could be a more precise term because most crops suffer water deficits at some point during the growing season (Lobell et al., 2009). For the sake of simplicity, the term potential yield is used throughout this article.

[2] In practice, potential yield can also be measured by using maximum yield from field trials, research experiments, or best yields from farmers' fields. Conceptually, potential yield estimated by crop models sets an upper bound for these alternative potential yield measures (Lobell et al., 2009). Hence, the present article focuses on model-based potential yield.