QUT School of Economics and Finance

Discussion Paper and Working Paper Series

Analysis of Productive Performance of Crop and Animal Production Systems: An Integrated Analytical Framework

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Working/Discussion Paper # 268
August 2011

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This article presents a two-stage analytical framework that integrates ecological crop (animal) growth and economic frontier production models to analyse the productive efficiency of crop (animal) production systems. The ecological crop (animal) growth model estimates “potential” output levels given the genetic characteristics of crops (animals) and the physical conditions of locations where the crops (animals) are grown (reared). The economic frontier production model estimates “best practice” production levels, taking into account economic, institutional and social factors that cause farm and spatial heterogeneity. In the first stage, both ecological crop growth and economic frontier production models are estimated to calculate three measures of productive efficiency: (1) technical efficiency, as the ratio of actual to “best practice” output levels; (2) agronomic efficiency, as the ratio of actual to “potential” output levels; and (3) agro-economic efficiency, as the ratio of “best practice” to “potential” output levels. Also in the first stage, the economic frontier production model identifies factors that determine technical efficiency. In the second stage, agro-economic efficiency is analysed econometrically in relation to economic, institutional and social factors that cause farm and spatial heterogeneity. The proposed framework has several important advantages in comparison with existing proposals. Firstly, it allows the systematic incorporation of all physical, economic, institutional and social factors that cause farm and spatial heterogeneity in analysing the productive performance of crop and animal production systems. Secondly, the location-specific physical factors are not modelled symmetrically as other economic inputs of production. Thirdly, climate change and technological advancements in crop and animal sciences can be modelled in a “forward-looking” manner. Fourthly, knowledge in agronomy and data from experimental studies can be utilised for socio-economic policy analysis. The proposed framework can be easily applied in empirical studies due to the current availability of ecological crop (animal) growth models, farm or secondary data, and econometric software packages. The article highlights several directions of empirical studies that researchers may pursue in the future.

JEL Classifications: D24, Q12, Q16

Keywords: agro-economic efficiency, agronomic efficiency, crop growth model, frontier production model, farm heterogeneity, spatial heterogeneity.

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1. Introduction

Measuring the productive performance of crop and animal production systems at the farm level and identifying factors that determine their performance are important in both agronomy and economics. The empirical studies in this field of research can provide meaningful information for both farmers and policy makers (Hoang and Nguyen, 2011). Individual farmers can not only learn more about their performance in relation to other farmers but also how to improve their productive performance. Policy makers can know more about the performance of farmers located in specific regions in relation to other regions and, more importantly, know what policies they should put in place to improve the overall performance of crop and animal production sectors. The reliability of these empirical studies, however, crucially depends on the accuracy of efficiency estimates.

Farm and spatial heterogeneity have significant impacts on farm efficiency; hence it is necessary to take them account. In agronomy, many ecological crop growth models incorporate location-specific physical conditions (e.g. climate conditions and soil characteristics) 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 growth models are often developed using field and experimental data, thus providing reliable scientific estimates of plant growth and potential yields. Similar ecological production concepts also have been applied to develop models that estimate potential growth for animals (van de Ven et al., 2003). These growth 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 preventing their utilisation in socio-economic analysis.

On the other hand, many frontier production models in economics have been developed to estimate efficiency and identify determinants of efficiency (Battese and Coelli, 1995; Greene, 2005). These models are able to incorporate farm and spatial heterogeneity when estimating productive performance. However, the bio-physical process of plant and animal growth is ignored in these econometric models (de Koeijer et al., 1999). In addition, the physical and weather conditions of locations where crops (animals) are grown, are treated asymmetrically to other economic inputs such as fertilisers, labour, pesticides and machinery (Sherlund et al., 2002). Hence, given the presence of location-specific physical heterogeneity, the economic frontier production models fail to provide accurate efficiency estimates; thereby rendering the analysis of efficiency determinants unreliable. This shortcoming hinders the usefulness of empirical studies for social and economic analysis.

A different approach is proposed in the present article: it integrates the knowledge of ecological crop and animal production into socio-economic analysis of productive efficiency for crop and animal production systems. The proposed analytical framework has two stages. In the first stage, both ecological crop growth and economic frontier production models are estimated. The estimated ecological crop (animal) growth model calculates “potential” output levels given the genetic characteristics of crops (animals) and the physical conditions of locations where crops (animals) are grown. The estimated economic frontier production model calculates “best practice” production levels, taking into account factors that cause farm and spatial heterogeneity. Three measures of productive efficiency are constructed: (1) technical efficiency, as the ratio of the actually observed to the “best practice” output levels; (2) agronomic efficiency, as the ratio of actually observed to “potential” output levels; and (3) agro-economic efficiency, as the ratio of “best practice” to “potential” output levels. Also in the first stage, the economic frontier production model identifies economic, institutional and social factors that determine variations in technical efficiency. In the second stage, the framework identifies determinants of agro-economic efficiency using various econometric techniques.

The proposed framework has several important advantages in comparison with existing proposals. Firstly, it allows the systematic incorporation of all physical, social and economic factors, that cause farm and spatial heterogeneity in the analysis of productive performance of crop and animal production systems. Secondly, the location-specific physical factors are not modelled symmetrically as other economic inputs of production. Thirdly, climate change and technological advancements in crop and animal sciences can be modelled in a "forward-looking" manner for socio-economic analysis of productive efficiency. Fourthly, knowledge in agronomy and data from experimental studies can be utilised for socio-economic policy analysis.

The article is structured as follows. Section 2 highlights the relevant literature in ecological agronomy and production economics. Section 3 describes the proposed analytical framework and its advantages in comparison with existing proposals in the literature. Section 4 discusses important issues related to the use of the proposed framework in empirical studies. Section 5 concludes the article.

2. Literature review

2.1. Ecological concepts of plant and animal production

In agronomy, there are three groups of factors that determine the growth and output level of crops: growth-defining, growth-limiting and growth-reducing factors (van Ittersum and Rabbinge, 1997). Growth-defining factors, at the optimal supply of all other factors, determine potential growth of plants. They include seed, or plant characteristics, and climate factors 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. According to these three groups of inputs, 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 growth-limiting factors (i.e. water and nutrients) and completely protected against growth-reducing factors. The attainable yield, also named water-limited and nutrient-limited yield, is lower than the potential level because of suboptimal 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).

For individual animals, analogous to crops, production factors can be classified into growth-defining, growth-limiting and growth-reducing factors (van de Ven et al., 2003). The growth-defining factors of animals comprise climate conditions (mainly temperature and day length) and animal genetic characteristics, including sex. These growth-defining factors determine the potential output levels. Growth-limiting factors such as the availability of drinking water and the availability and quality of feed regulate the animals' feed intake. If the animals are not supplied with the maximum requirements of water and feed intake, total output will be short of the potential level. Pollutants and diseases are typical growth-reducing factors.

Growth-defining factors are often beyond the direct control of farmers. However, farmers may have influence on growth-limiting and growth-reducing factors. In crop farming farmers can improve actual yield by increasing the use of water, nutrients or pesticides or by changing cultivation practices so that these inputs can be delivered to crops in a more efficient manner. Apart from weeds, diseases, pests and pollutants, factors like imperfect land preparation, non-optimal sowing and planting, and inconsistent input applications may affect how efficiently the crop uses light, water and nutrients and consequently make the crop more (or less) susceptible to diseases. Farmers can also influence the impact of these factors on yield with the proper use of machinery and labour. Similarly production output can be increased by improving the quantity and quality of water and feedstuff. Appropriate health care (e.g. phylactic vaccination and curative medicines), hygienic measures and other management practices (e.g. sufficient space for animals to move) are put in place to prevent or reduce the impact of growth-reducing factors on the production.

Obviously, production ecology emphasises the importance of the physical environment under which crops and animals are grown. The physical environment is location-specific and refers to climate factors (e.g. temperature, solar radiation level and humidity), soil characteristics (e.g. water retention characteristics, soil depth, texture, pH and organic matter content), and biotic factors in soil and atmosphere such as anaerobic conditions and air pollutants (van Ittersum and Rabbinge, 1997). Differences in the physical environment may affect potential, attainable and actual output levels (de Koeijer et al., 1999). For example, given the same crop characteristics, potential yields in locations with poor physical (i.e. soil and climate) conditions might be lower than potential yields in locations with good physical conditions. Consequently, at the same or even lower input levels, attainable and actual yields will be higher in the superior than in the inferior physical environment.

In agronomy, identification of optimal combination of inputs to realise a particular output level is referred to as a target-oriented or engineering approach in which inputs are quantified, based on agronomic knowledge of the physical, chemical, physiological and ecological process involved in crop and animal growth (van de Ven et al., 2003; van Ittersum and Rabbinge, 1997). Also, based on this knowledge, for each combination of physical environment and type of crops and animals, biophysical production possibilities can be estimated. These studies supply inputs into crop and animal growth simulation models that quantify biophysical production possibilities in different physical environments (Hengsdijk and van Ittersum, 2002). Many single crop growth models have been developed for many specific types of crops (e.g. potato, maize, peanut, rice, soybean, wheat, etc.) More complicated models also have been constructed to support the evaluation production systems with multiple crops (Jones et al., 2003). Production ecology concepts have been very useful for the biophysical analysis and design of plant, animal and plant-animal production systems at the farm level (van Ittersum and Rabbinge, 1997). However, human behaviour and other social and economic factors are neglected (de Koeijer et al., 1999). Therefore, the use of agronomic knowledge for socio-economic policy analysis in agricultural production is restricted.

2.2. Production economics

In modelling production, economists generally quantify the relationship between inputs and outputs by econometrically estimating production functions.[1] This empirical procedure starts

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[1] Nonparametric estimation (e.g. using data envelopment analysis - DEA - technique) of production possibilities is also popular (Coelli et al., 2005). The main advantage of DEA is that it does not specify a function form and the distribution of the inefficiency terms. However, DEA does not capture data errors and shocks (e.g. changes in climate conditions), which can be captured in a parametric framework. The parametric framework is preferred in empirical studies in agricultural production because of two reasons. Firstly, weather conditions are important factors in crop and animal production; hence it is important to capture changes in weather conditions. Secondly, the econometric production models may use statistical data, which may contain data errors.

with choosing a functional form (e.g. Cobb-Douglass, quadratic, translog, etc.) and then estimating the values of parameters in the chosen function so that the estimated equation fits "well" a particular data set. The econometric estimation of production functions often use input and output data measured in physical units (Coelli et al., 2005). Alternatively, dual forms such as cost, revenue, or cost functions, can be estimated when physical data are not available; duality theories can then be used to derive the primary production functions (Färe and Primont, 1995). However, the use of dual functions needs to be justified by the economic behaviour of farmers. If farmers are believed to minimise (maximise) production costs (revenues), cost (revenue) function should be estimated. In situations where farmers are profit-maximisers, profit functions can be used. These empirical efficiency studies have been very 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 and economic performance. The results are expected to help farm managers/owners and policy makers make informed decisions.

However, this traditional econometric approach has several important drawbacks from the agronomic view point. Firstly, inputs in production functions are normally treated symmetrically and this symmetric treatment of inputs fails to account for various biophysical roles of inputs in the crop and animal growth process (Zhengfei et al., 2006). For example, fertilisers (or water) and labour (or machinery or pesticides) are assumed to contribute to crop growth but fertilisers cannot be substituted by labour. Secondly, the input-output relations are often based on historical data, which means that the latest technical development and bio-physical insights are not incorporated (Chavas and Cox, 1995; de Koeijer et al., 1999). Due to these shortcomings, economic modelling of production has very limited use in designing agricultural production systems. More importantly, the results of such empirical studies are not reliable.

2.3. Linkages between ecological and economic production models

There are several studies that attempt to link agronomic production concepts with economic production models. Previous studies on damage control, for example, 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. Zhengfeit et al. (2006) and de Koeijer et al. (1999) are two rare studies that integrate agronomic knowledge into economic production modelling.

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) define the crop’s potential growth and limit it from this potential growth, whilst facilitating inputs (e.g. labour, capital, and pesticides) help create or alter growth conditions. Using agronomic production concepts, this study acknowledges the presence of three different yield levels (potential, attainable and actual) but their econometric model only distinguishes attainable and actual levels. In this framework, 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 the output reaches its maximum level. When the growth inputs are not in optimal supply, the actual output is scaled down by the value of the scaling function. The authors argue that their approach makes it possible to estimate the crop growth functions using real farm data, thereby extending agronomic experiments into realworld agricultural production. In an empirical study of 323 potato farms in the Netherlands, this study estimated a translog crop growth function and a quadratic form of the scaling function. The average value of the scaling function is estimated to be 94.7%, implying that over 5% of attainable yield has been lost. The authors also link this 5% yield loss to the concept of inefficiency used in the frontier production models. Note that no biophysical and experimental data are used in their crop growth model. Obviously, this modelling of crop growth differs vastly from common approaches in plant science (Bouman et al., 1996).

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. Obviously, normative, best practice and average yield levels are below the potential level. Since this study focuses its discussions on conceptual issues, important details on how the conceptual framework can be applied in empirical studies are not provided. In order to operationalise these concepts into empirical studies, various econometric models as well as estimation techniques need to be specified. To fill this gap, the present article takes a similar approach in combining agronomic and economic theories but provides a more practical framework that researchers can use to conduct empirical studies with useful implications for farms’ managers, owners and policy makers.

3. Integrated agro-economic framework

3.1. Efficiency, determinants of efficiency, farm and spatial heterogeneity

A conventional measure of economic efficiency (EE) has two components: technical efficiency (TE) and allocative efficiency (AE) (Farrell, 1957). TE refers to the contraction (expansion) of physical inputs (outputs) holding outputs (inputs) constant while AE is concerned with choosing cheaper combinations of inputs (or choosing combinations of outputs that generate higher monetary values of outputs). These definitions are based on the orientations in which optimization problems can be solved to calculate efficiency scores. For example, inputs will be contracted given fixed output quantities in an input-orientated framework whilst outputs will be expanded given fixed input quantities in an output-orientated framework. In a more generalized framework, one can contract inputs and expand outputs simultaneously. Dual functions allow not only the estimation of economic efficiency but also the decomposition of EE into TE and AE (Kumbhakar and Lovell, 2000). For example, one can use profit functions to calculate profit efficiency and decompose this efficiency into TE and AE. Discussions in this article focus on TE concepts only.

Agronomic efficiency is mainly concerned with gaps between actual (or attainable) and potential output levels (van Ittersum and Rabbinge, 1997). Hence, production economics and agronomy share a common interpretation of increases in efficiency: higher (or the same) output quantities can be achieved with less or cheaper inputs (de Koeijer et al., 1999). A potential to increase efficiency suggests that there is some degree of inefficiency. In empirical economic efficiency studies, calculating TE levels of individual farms are based on the production frontier: those farms that stay on the frontier are technically efficient whilst farms staying below the frontier have some degree of inefficiency. In agronomic analysis, inefficiency is present if actual output levels are lower than potential levels.

Analyses of determinants of efficiency (or inefficiency) are to provide meaningful information for farmers to learn how to improve their performance and for policy makers to know what policies to put in place to increase the overall efficiency of an agricultural sector. However, farm and spatial heterogeneity in terms of physical, economic, institutional and social conditions, challenge the accuracy of efficiency estimates and the reliability of analysis of efficiency determinants (Sherlund et al. 2002). Agronomic analysis neglects these factors; hence it fails to provide useful policy implications (de Koeijer et al., 1999; Heady, 1957). On the other hand, the frontier production model does not consider biophysical factors of crop and animal growth processes (de Koeijer et al., 1999; Greene, 2005). The present article integrates ecological crop (or animal) growth and frontier production models to provide a more reliable analytical framework. In addition, this analytical framework unveils a new efficiency measure that is not revealed by either agronomic or frontier models.

3.2. An analytical framework

Figure 1 presents an overview of factors that have influence on the potential, best practice and actual output levels of plant and animal production systems. For the sake of simplicity, following discussions focus on one crop. An identical analysis can be applied to the monoculture production system of animals. For polyculture crop, animal or mixed production systems, the economic frontier production models can be identically applied as shown in many empirical studies surveyed in Bravo-Ureta et al. (2007). However, the ecological growth models may need modifications in order to be applied to the polyculture production systems due to the complexity of biophysical interactions between crops, between animals and between crops and animals. Hence, the extension of the proposed framework depends critically on these polyculture ecological growth models. Several more complicated models have been constructed in the literature (Jones et al., 2003; Metherell et al., 1993). The analytical framework has two stages. In the first stage, all relevant efficiency measures (i.e. technical, agronomic and agro-economic efficiency) are defined and estimated, taking into account physical, social and economic heterogeneity across different farms and locations . In the second stage, the determinants of the agro-economic efficiency are quantified by using various econometric methods. The remaining discussions of this section will provide general descriptions of these two stages while the next section will highlight several practical issues related to model specification, estimation techniques and the relevance of empirical studies to socio-economic policy analysis.

Insert figure 1

Ecological production theories suggest potential output yield (Y_P, measured by kg per land unit, such as a ha) is a function of characteristics of seeds/plants (represented by a vector **s**) and the physical environment (represented by a vector **D**):

$$(1) \qquad Y_P = F_1(\mathbf{s}, \mathbf{D})$$

Note that even when the same type of crop is grown, Y_P can vary across locations because of spatial heterogeneity in the physical environment. Changes in seed or plant technologies, climate and soil conditions and the concentration of pollutants, can be easily incorporated when estimating the potential yield (de Koeijer et al., 1999). Hence, this approach overcomes the drawbacks of conventional modelling in production economics.

The actual yield is modelled as a function of growth-limiting inputs such as nutrients and water (represented by a vector **l**) and economic inputs such as labour, capital and pesticide (represented by a vector **x**). Due to farm and spatial heterogeneity, some farms are efficient in converting these inputs into outputs but others may be less efficient; hence the actual output level of an individual farm may be below the "best practice" output level. The "best practice" output level of a specific farm refers to the output level given the farm is technically efficient (i.e. staying on the production frontier). Note that for those farms that are technically efficient, their actual and "best practice" production levels are identical. For farms staying below the frontier, their inefficiency is represented by a distance to the frontier. Economic, institutional and social factors that determine efficiency levels are captured by a vector **z**. Hence, actual output level (Y) is defined as:

(2) $\mathrm{Y} = F_2(\mathbf{l}, \mathbf{x}, \mathrm{u})$, where

(3) $\mathrm{u} = F_3(\mathbf{z})$

Note that equations (2) and (3) should be estimated simultaneously (Battese and Coelli, 1995) and consequently, a traditional measure of TE can be defined as:

$$(4) \qquad TE = u = \frac{Y}{Y^*},$$

where Y is the actually observed output level and Y^* is the “best practice” output level in (2) when the inefficiency term (i.e. u) is zero. TE taking a value between zero and one measures the output of a farm relative to the output that could be produced by a fully-efficient farm using the same (economic) input quantities. A value of 0.8, for example, suggests that the farm can increase output levels by 20% without any increased consumption of economic inputs.

Agronomic efficiency (AgE), defined as the ratio of actual to potential output levels, can be decomposed:

$$(5) \qquad AgE = \frac{Y}{Y_P} = \frac{Y}{Y^*} \times \frac{Y^*}{Y_P} = TE \times AgEcE,$$

Note that the value of AgE is also bounded between 0 and 1. Decomposition in equation (5) identifies two sources of agronomic efficiency: technical efficiency (TE) and agro-economic efficiency (AgEcE). Statistically significant factors of **z** in (3) are interpreted as determinants of TE. The second stage of the framework is to identify determinants of AgEcE.

Apart from those factors that affect TE, several other important factors can affect AgEcE. Intuitively, any changes in Y^* or Y_P will lead to changes in AgEcE; hence factors that affect Y^* and/or Y_P will have impacts on AgEcE. , Those socio-economic factors that drive changes in the genetic characteristics of the crop and location-specific biophysical conditions will affect Y_P and need to be incorporated. Examples of those factors are research and development (R&D), technological and capacity diffusion in crop and crop protection sciences, and environmental management (e.g. pollution abatement). An increase (or decrease) in Y^* refers to an upward (or downward) shift in the "best practice" production frontier, which in efficiency literature, is commonly referred to as technological change (TC) (Coelli et al., 2005). Hence, researchers can investigate the relevant factors by looking into those empirical studies that have been done in the literature. Bravo-Uretav et al. (2007) provide a comprehensive list of these empirical studies. AgEcE is econometrically analysed against these economic, institutional and social factors (presented by a vector **c)**:

$$(6) \qquad \text{AgEcE} = \frac{Y^*}{Y_P} = F_4(\mathbf{c})$$

In a special situation where Y_P is fixed, Y^* is the only cause of changes in AgEcE; therefore, factors in **c** can be interpreted as determinants of technological change. In a general context, this analysis provides policy makers with useful information regarding how policies should be designed to bridge gaps between best practice and potential output levels.

The proposed framework is the first which integrates the ecological crop growth models with economic frontier production models to analyse socio-economic aspects of productive efficiency in crop production. However, it is important to distinguish this new approach with existing proposals in the literature. Firstly, the proposed framework uses the ecological crop growth models constructed from experimental data to estimate the potential yield whilst Zhengfeit et al. (2006) proposed to use farm data to estimate the potential yield. Farm data are historical data which reflect the actual farms' performance in response to variety of market and weather conditions (de Koeijer et al., 1999). The "forward-looking" nature, however, is not captured by historical data. On the other hand, the crop growth models are "forward-looking" in two aspects: (1) the impacts of climate change on crop or animal production can be easily simulated in the ecological crop growth models and (2) any innovations in plant and animal sciences can be incorporated in the crop growth models.

Secondly, unlike other existing studies, the proposed framework captures location-specific environmental conditions in the ecological crop growth models but not in the economic frontier production models. These studies have proposed to take account of environmental conditions in a way similar to economic inputs (i.e. labour, capital, pesticides, etc.) included in frontier production models (Sherlund et al., 2002; Zhang and Carter, 1997). As clearly documented in the agronomic literature, the roles of the environmental conditions in the ecological growth processes of crops or animals is distinguished from those of economic inputs: the former are growth-defining factors whilst the latter are growth-reducing factors; hence, considering environmental inputs symmetrically to other economic inputs is not adequate.

The third important advantage of the proposed framework is related to seed (baby plant or animal) qualities and varieties. Note that seed qualities and varieties are the core determinants of potential and actual yields; hence changes in seed qualities and varieties greatly affect farms' performance. The impacts of seed improvement on yield growth are very different from the impacts of other inputs (i.e. waters, fertilisers, pesticides, machinery or labour): improvements in seed not only increase yield but also result in lower consumption of other inputs. In addition, the driving force for seed innovations has evolved mainly from yield enhancement into multiple objectives (i.e. yield enhancement, less input consumption and less pollution) (de Koeijer et al., 1999). Therefore, it is not reasonable to consider seeds similar to other inputs (Kaneda, 1982) as is commonly done in existing frontier production models. However, seed improvements and innovations are handled quite differently in the proposed framework: all changes in seed qualities and varieties are taken into account by the ecological crop growth models in equation (1) whilst other inputs are included in a separate model in equation (2).

4. Discussion

The proposed framework can be easily applied in empirical studies for three reasons. Firstly, there is an increasing number of crop and animal growth models developed from experimental studies (Bouman et al., 1996; Cacho et al., 1995; Cros et al., 2003; Jones et al., 2003; Stöckle et al., 2003). Meta analysis from these experimental studies can be done and the results of these studies used in many geographical locations of production systems (Lean et al., 2009). These developments in crop and animal sciences allow the estimation of potential output levels for many mono- or polyculture production systems in many locations. Secondly, farm-level data also have been well collected, which make estimation of inefficiency frontier models possible. Thirdly, econometric estimation techniques and software have been well developed (Battese and Coelli, 1995; Greene, 2005). These three factors make it easy and cost-effective to apply the proposed framework into empirical studies. By conducting these empirical studies, this proposed framework extends the agronomic field and experiment studies into a socio-economic analysis. The following sections highlight several important considerations related to the applicability of the proposed framework in empirical studies. Before discussing possible implications for decision making processes of farmers and policy makers, several possible specifications of the models in empirical studies are proposed

4.1 Econometric specifications of models

Note that in order to conduct empirical studies, function forms of equations (1)-(3) and (6) need to be specified. There are many crop growth models that have been well documented in the literature (Bouman et al., 1996; Jones et al., 2003; Matthews et al., 2002) and these models can be used in (1). A translog function can be used in equation (2) because of three reasons: firstly, the translog form is second-order flexible, which is preferred to first-order flexible forms such as linear and Cobb-Douglass forms (Coelli et al., 2005; Sauer, 2006); secondly, the translog is linear in the parameters, which is easy to estimate; and thirdly, the translog form has been extensively used in agricultural empirical studies (Zhengfei et al., 2006). F_3 in (3) follows a linear form as conventionally used in the inefficient frontier models (Battese and Coelli, 1995; Greene, 2005).

Equations (2) and (3) are estimated simultaneously for panel data using the method proposed by Battese and Coelli (1995), which has also been used in many agricultural efficiency studies (Bravo-Ureta et al., 2007; Coelli, 1996; Tipi et al., 2009). For crop production systems, using vectors **l** (water and nutrient) and **x** (labour, pesticide and machinery including energy) and vector **z** of explanatory variables (i.e. farm size, farm manager/owner's gender and education, etc.) that determine efficiencies, the stochastic frontier production models in equations (2) and (3) for n-th farm in t-th period are:

$$\begin{aligned}(7)\qquad \mathrm{lnY_{nt}} = \;& \alpha_0 + \sum_{i=1}^{2}\alpha_i \mathrm{lnl_{int}} + \sum_{j=1}^{3}\beta_j \mathrm{lnx_{jnt}} + 0.5\sum_{i=1}^{2}\sum_{j=1}^{2}\alpha_{ij}\mathrm{lnl_{int}}\mathrm{lnl_{jnt}} + \\ & 0.5\sum_{i=1}^{3}\sum_{j=1}^{3}\beta_{ij}\mathrm{lnx_{int}}\mathrm{lnx_{jnt}} + 0.5\sum_{i=1}^{2}\sum_{j=1}^{3}\delta_{ij}\mathrm{lnl_{int}}\ln x_{jnt} + \mathrm{u_{nt}} + \mathrm{v_{nt}}\end{aligned}$$

$$(8)\qquad \mathrm{u_{nt}} = \gamma_0 + \sum_{i=1}^{N}\gamma_i \mathrm{lnz_{int}} + \mathrm{w_{nt}}$$

where $\mathrm{v_{nt}}$ refer to random errors with zero mean, $N(0,\sigma_v)$, independently distributed of the non-negative random inefficient term (i.e $\mathrm{u_{nt}}$) and $\mathrm{w_{nt}}$ is defined by the truncation of the normal distribution with zero mean and variance, σ_w^2, such that $\mathrm{w_{nt}} \geq -\,\mathbf{z}_\mathrm{nt}\boldsymbol{\delta}_\mathrm{w}$.

Note that growth-limiting inputs (vector **l**: water and nutrients) and other economic inputs (vector **x**: labour, pesticide and machinery) in the translog form as in equation (7) are treated symmetrically with an assumption that there is a certain degree of economic substitutability between them. This assumption does not conform to the bio-physical growth processes of crops or animals but are useful for socio-economic analysis. For example, given budget constraints, farms may have to balance the expenditures between water and labour: if water is relatively more expensive than labour, farms may underuse water, which would affect crop growth. Relative analysis in terms of the affordability for water and labour, then, can guide policy makers to tackle this problem. A common policy option is to provide subsidies for water so that water cost becomes relatively cheaper than labour cost so that farmers can afford to supply more to crops. For this reason, all relevant economic inputs should be present in the frontier production model.

There are several methods that can estimate equation (7) (such as ordinary least squares, maximum likelihood or Bayesian method). Discussions on the advantages and disadvantages of these estimation methods are in the literature (Coelli et al., 2005; Kumbhakar and Lovell, 2000) and will not be covered in this article. Once equation (7) has been estimated, for each farm in each period, its “best practice” output level can be calculated given input quantities as well as its TE level. Combining potential and “best practice” output levels, agronomic efficiency (AgE) can be measured as in equation (5); then agro-economic efficiency (AgEcE) can be estimated.

In the second stage, F_4 in equation (6) is assumed to have a (log) linear relationship with variables that determine variations in AgEcE. As shown in Figure 1, possible variables in vector **c** are local R&D expenditure, governmental subsidies, conditions in the markets of inputs, outputs and finance and so on. This relationship becomes:

(9) $$\text{AgEcE}_{nt} = \chi_0 + \sum_{i=1}^{M} \chi_i \ln c_{int} + o_{nt}$$

where o_{nt} refer to random errors with zero mean, $N(0, \sigma_o)$. Note that equation (9) can be estimated using the conventional ordinary least squares method or a limited dependent variable technique such as Tobit. An alternative specification, however, can be estimated using the quartile regression method (Koenker and Hallock, 2001):

(10) $$\text{AgEcE}_{nt} = \chi_0^{(p)} + \sum_{i=1}^{M} \chi_i^{(p)} \ln c_{int} + o_{nt}^{(p)}$$

where $0<p<1$ indicates the proportion of all AgEcE scores whose values are below the quartile at p. This quartile regression model is particularly useful when the assumption of normal distribution of the error term o_{nt} in (9) does not hold and there are many outliers in the distribution of AgEcE scores. The quartile regression is also useful when the effects of determinants (i.e. variables in vector **c**) on AgEcE vary across various levels of AgEcE.

4.2 Implications for decision making processes

This section highlights several important hypotheses about the possible effects of farm and spatial heterogeneity factors, including local policies, on farms' efficiency. These hypotheses are not empirically tested in the present article but were investigated in many previous empirical studies (see Bravo-Uretav *et al.* 2007 for a comprehensive list of these studies). In many instances, these empirical studies give conflicting conclusions. These hypotheses are thus selected to be discussed here not only to demonstrate the use the proposed framework to address important issues but also to motivate other researchers to revisit these hypotheses using this new framework, in order to provide more reliable empirical results.

Famers look for ways to improve their productive performance, and a typical empirical study following the proposed framework can give them useful information to do so in two important ways. Firstly, an individual farmer can benchmark his/her performance in relation to that of their peers. Farmers, therefore, are able to learn lessons from their peers in order to improve their future production. For example, a farmer can compare his/her farm's consumption levels of various inputs with those of a "best practice" farm in the same location to see if their input combinations are "optimal" yet. Secondly, by analysing determinants of productive efficiency, farmers can learn how to improve their future performance. For example, if the estimation results show that farming experience is statistically positively related to efficiency levels, those farmers with less experience should look at ways to enhance their knowledge in order to improve their performance.

Governments play an important role in agriculture and they can affect both technical and agro-economic efficiency of each and every farm. Interventions via subsidy or tax policies affect input and output prices, hence the levels of input consumption and production outputs. Other types of interventions (such as pollution clean-up or supports in relation to R&D in plant and animal sciences) can affect the bio-physical environment and crop (or animal) genetic characteristics, which in turn determine crop (animal) growth and output levels. Therefore, it is crucial that policy makers be provided with reliable analysis to design good agricultural policies in order to support farmers in achieving higher technical and agro-economic efficiency. Depending on the scale of analysis, empirical studies can support policy makers with useful information.

In a typical location-wide study, one can analyse efficiency (including TE, AgEcE and AgE) in the production of a particular crop (i.e. rice) across farms located in different locations (i.e. counties, provinces, states, countries or regions). It is also possible to apply the framework to more aggregated (secondary) data, such as county-level data which are readily available in national official statistics, but the use of more aggregate data often comes at the cost of less in-depth analysis. The study needs to use a crop growth model for this particular crop type, such as the ORYZA rice model (Bouman and van Laar, 2006). Identifying important factors that determine efficiency variations give local policy makers insight in of how to improve productive efficiency in their locations. For example, one can argue that high financial costs may prohibit farmers from using efficiency-enhancing equipment. If this hypothesis is statistically tested to be true, then local governments should investigate financial sectors to find ways that will make funds more accessible to farmers.

A typical crop-wide study can investigate efficiency variations across farming systems (or across locations in cases where more aggregate data are used) that grow different types of crops, such as rice, wheat or maize. The study can use a multiple-crop growth model such as DSSAT (Jones et al., 2003) to estimate potential yields. Analysis of determinants of efficiency can have useful policy implications. For example, one is able to test if governmental support programs (e.g. training provided by scientists to farmers in developing countries) are positively related to efficiency. Reliable answers to this question will provide supportive evidence to the local government to continue such support programs.

In a country, there can be many crop varieties that farmers use as a result of past and current development in the crop science. For example, there were more than 390 major rice varieties used across China in 1995 (Jin et al., 2002). Given many varieties, farmers have more choices of seeds but it may not be easy for farmers to choose the variety that best suits land and climate conditions. Obviously, if the diffusion of seed science to the farmers is effective, farmers should use varieties that produce high technical efficiency and also high agro-economic efficiency. An empirical crop-wide study that benchmarks the efficiency performance across seed varieties could shed lights on this issue and give useful information for policy makers to promote technological diffusion. This topic is closely related to the impacts of technological spillover and research and development on agricultural efficiency and productivity, which needs more empirical research (Hoang and Coelli, Forthcoming).

It is also possible that agronomic efficiency levels vary across different crops. For example, Jin et al. (2002) reported significant differences in yield gaps between rice, wheat and maize in China. One can use the proposed framework to investigate if these AgE variations are caused by TE or AgEcE variations. If the main cause is AgEcE but not TE then analysis of the determinants of TE variation does not have useful policy implications. However, determinants of AgEcE, which can be analysed in the second stage of the framework, would provide policy makers with more useful information.

5. Conclusion

This article has proposed a new analytical framework in which farm and spatial heterogeneity in terms of physical, social, institutional and economic factors all are included to analyse productive efficiency in crop and animal production systems. Its innovation lies in the integration of agronomic knowledge into economic stochastic frontier production analysis. The framework has two stages. In the first stage the ecological crop (animal) growth and frontier production models are used to estimate potential and best practice output levels. In relation to actually observed output level, three productive efficiency measures are defined: agronomic efficiency (AgE), technical efficiency (TE) and agro-economic efficiency (AgEcE). Determinants of technical efficiency also are identified in the first stage. In the second stage, agro-economic efficiency- firstly developed in this article as the ratio of “best practice” to potential output levels- is analysed econometrically against a set of farm-specific and location-specific social, institutional and economic factors. This analysis reveals determinants of variations in the agro-economic efficiency across farms and locations.

Using this framework, knowledge and innovations in agronomy and efficiency literature can be integrated to provide more useful information to farmers and policy makers. In static analysis, improvements in TE and AgEcE are two general sources of output expansion and the determinants of these improvements can be identified systematically and reliably. Hence, farmers can learn more about their farm's performance relative to other farms, and possible ways to improve it. Similarly, policy makers identify components of good policies to improve the productive performance of all farms. In a more dynamic analysis, climate change and innovations in crop and animal sciences can be easily incorporated into this framework.

This article highlights several possibilities for empirical studies to investigate important issues related to determinants of productive performance in farming, which have been investigated by many other empirical studies. Although these issues have been investigated in many other empirical studies, they suffer several important shortcomings due to their ignorance of bio-physical processes of crop and animal growth and the nature of historical analysis; therefore their results lack a high degree of reliability. This article expects to provide a new approach for future empirical studies.

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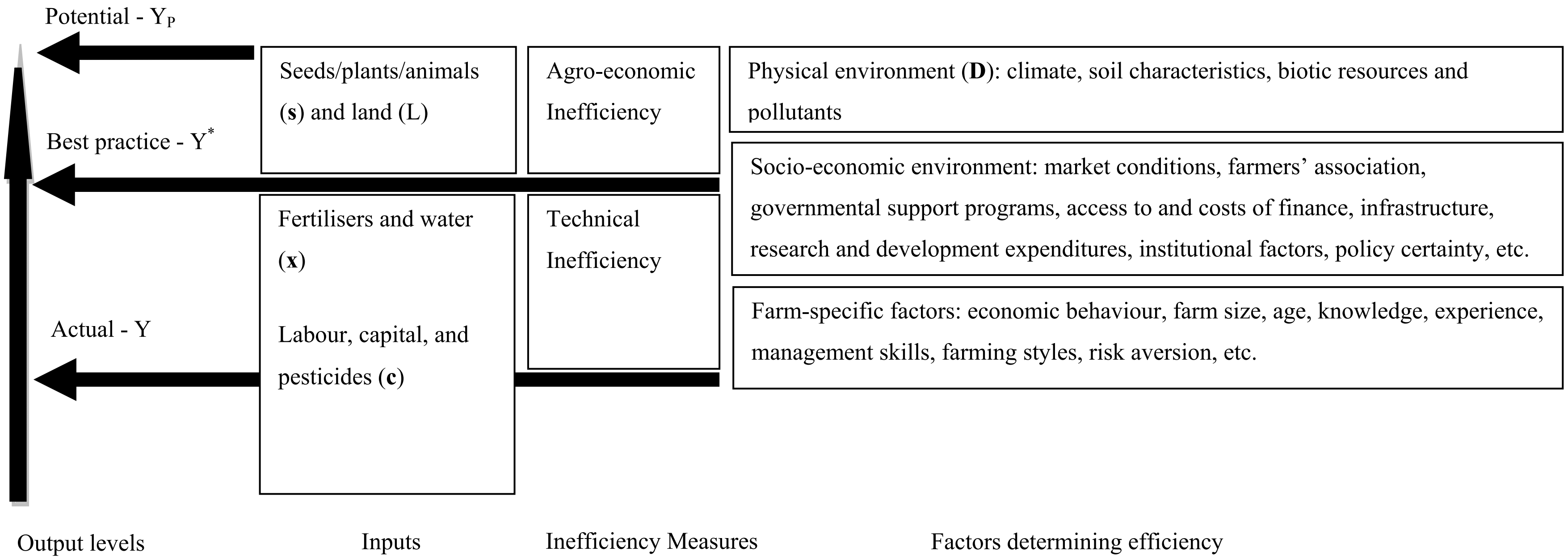

Figure 1: Factors that affect technical, agro-economic and agronomic efficiency of crop or animal production system