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INCORPORATING ENVIRONMENTAL FACTORS: A NUTRIENTS BALANCE
APPROACH

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**MEASUREMENT OF AGRICULTURAL TOTAL FACTOR
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by

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Abstract

This paper develops a new measure of total factor productivity growth in agricultural production which incorporates environmental effects. The new measure is called the Nutrient-oriented total factor Productivity (NTFP) Index, and incorporates a materials balance condition. NTFP measures changes in nutrient-orientated efficiency and can be decomposed into efficiency change (EC), technological change (TC) and nutrient-orientated allocative efficiency change (NAEC) components. An empirical analysis, involving country-level data from OECD countries during 1990-2003, is provided using DEA methods. Estimates of mean technical and nutrient-orientated efficiency are 0.798 and 0.526, respectively. Estimated mean NTFP growth is 1.5% per year, with nutrient-orientated technological progress contributing 0.8%.

Keywords: Total factor productivity, environment, nutrient balance, DEA

1. Introduction

During the past three decades, the environmental side effects of economic activities have received increasing attention in public and political debate. This raises the need to adjust traditional methods of measuring efficiency and productivity in order to take into account environmental effects.

Significant efforts have been made to integrate environmental concerns into traditional technical and economic performance measures (Scheel 2001; Tyteca 1996). Generally, these environmental performance measures are derived by making adjustments to standard parametric and non-parametric efficiency and productivity analysis techniques (Coelli, et al. 2007). The traditional approach that the majority of these studies have taken is that the environmental effect is modeled as either a bad output or an environmentally detrimental input in production models (e.g. Ball, et al. 1994; Färe, et al. 1989; Reinhard, et al. 2000; Shaik and Perrin 2001; Tyteca 1997). These methods, however, face two criticisms. First, they fail to allow for both increasing desirable output and reducing undesirable output at the same time (Chung, et al. 1997). Secondly, Coelli, et al. (2007) shows that these methods often do not satisfy the materials balance condition.

Chung, et al. (1997) proposed the use of a directional distance function which allows for simultaneous expansion of desirable output and contraction of undesirable output. While this method overcomes the first criticism, this approach also fails to satisfy the materials balance condition, which we show later in this paper.

Recently, Coelli, et al. (2007) suggested the use of an alternative modeling approach that uses the materials balance condition in deriving an environmental efficiency measure². They consider the situation where the environmental pollution is caused by the balance of nutrients, equal to the difference between nutrients in inputs and nutrients in outputs. In order to reduce pollution, one could reduce the nutrients balance by, for example, reducing the nutrient amount contained in the input vector. Compared with the traditional approach, this method does not involve the introduction of any extra variables into the production model and satisfies the materials balance condition.

² Lauwers et al (1999) and Reinhard and Thijssen (2000) also proposed efficiency measurement methods that incorporated the use of the materials balance condition. The former study estimated efficiency scores using DEA technique while the latter study involved the econometric estimation of a shadow cost system.

In their study, the materials contents of inputs is treated in an analogous way to the way in which input prices are used in a standard cost efficiency calculation, and hence existing parametric and non-parametric techniques can be used to estimate the efficiency scores. Given a fixed output vector, the environmental efficiency is defined as the ratio of the smallest technically feasible nutrient balance over the observed nutrient balance. The environmental efficiency can also be decomposed into technical efficiency (TE) and allocative efficiency (AE) components.

In this paper, we use this nutrients balance approach to measure the environmental efficiency of the national agricultural sectors in OECD member countries in terms of both nitrogen and phosphorous balance. We term this environmental efficiency measure as nutrient-orientated efficiency (NE) which is then decomposed into TE and nutrient-oriented allocative efficiency (NAE). We also construct a nutrient-oriented total factor productivity (NTFP) index. This index is an environmentally adjusted Malmquist productivity index which incorporates the traditional total factor productivity (TFP) information along with environmental factors.

The paper is structured as follows. Literature on the nutrients balance approach and existing methods of measuring environmental performance is reviewed in Section 2. The development of the nutrient-oriented total factor productivity (NTFP) index is presented in Section 3. The empirical analysis of agriculture in OECD member countries for the years of 1990-2003 is discussed in Section 4, followed by concluding comments in Section 5.

2. The nutrients balance approach and existing methods

The nutrients balance condition in agricultural production

The nutrients balance condition is a particular form of a materials balance condition which is ruled by the law of mass conservation or the first law of thermodynamics (Daly 1987). This law states that the materials in a production system are not lost and that material inputs end up in either stock accumulation or material outputs. In other words, the material inputs are transformed into desirable and undesirable outputs. This law has been used widely for the purposes of economic analyses (Daly 1987; 1992; Georgescu-Roegen 1971; Kneese, et al. 1970) and especially in agricultural production (Coelli, et al. 2007; Hartmann, et al. 2007; Parris 1998; Reinhard, et al. 1999; Reinhard and Thijssen 2000).

In agricultural production, economic agents (i.e. farmers) use many different inputs which contain a variety of nutrients (e.g. nitrogen, phosphorous and sulphur) to produce crop and livestock products. These nutrients are needed for crop and livestock production. They are present in various inputs such as feed, seed, planting material, fertilizers, purchased animals, manure, soil, underground water, and even in air. The materials balance condition implies that the balance of nutrients equals the nutrient input minus the nutrient output. If the nutrient balance is positive, it goes into the environment through land, air or water and (potentially) causes pollution.

As part of an ecosystem, agricultural production activities are regulated by the law of mass conversation, implying that the nutrients balance condition holds true. This suggests that measures of efficiency and productivity growth in agricultural production have to satisfy the test of the materials balance condition.

Methods of measuring environmental performance

Historically, undesirable outputs have often been ignored in production economics. However, recently there has developed a growing literature proposing different indicators linking environmental and economic performance of production activities. Tyteca (1996) provides a detailed literature review of the different methods that have been used to measure environmental performance of organizations. His paper raised a variety of issues relating to the development of environmental performance indicators, including concerns about aggregation, normalization, standardization and accounting. The author also stresses the potential usefulness of the efficiency measurement literature in dealing with these issues.

Pittman (1983) was one of the first to attempt to incorporate pollution into conventional productivity measures. He proposed an index number methodology that was derived from a theoretical model where the objective was the maximal radial expansion of desirable outputs and contraction of undesirable outputs, holding the input vector constant.

Färe, et al. (1989) used non-linear programming techniques to construct hyperbolic efficiency measures allowing for the expansion of desirable output and the reduction of pollution as an environmental detrimental input at the same time. This approach was used by Yaisawarng and Klein (1994) and Tyteca (1997) in industrial applications. Färe, et al. (1993) extended the work by Färe, et al. (1989) using parametric output distance functions to permit easier measurement of the shadow prices of the bad outputs.

Färe, et al. (1996) proposed an input distance function approach that could be used to decompose productive efficiency into input efficiency and environmental efficiency. More recently, Chung, et al. (1997) have used a directional distance function to estimate environmental efficiency and productivity measures.

In Färe, et al. (1996), for each firm two input-orientated DEA models were run. The first model allowed for the conventional proportional contraction of all inputs given the level of desirable and undesirable outputs, with strong disposability assumed for all variables. The second model did the same thing, except it imposed weak disposability on undesirable outputs. The environmental indicator was then defined as the ratio of the efficiency scores obtained in the first and second models. Tyteca (1997) then further adapted the Färe, et al. (1989) to derive environmental efficiency scores by measuring the degree to which the pollution variable could be reduced given the fixed levels of inputs and desirable outputs.

In contrast to an output distance function which seeks to increase both desirable and undesirable outputs simultaneously, Chung, et al. (1997) proposed the use of a directional distance function which seeks to increase desirable output and reduce undesirable output at the same time. The authors suggested scaling the output vectors according to a vector of directions which could be flexibly selected. The direction vector they proposed was to increase desirable outputs and decrease undesirable outputs, in a manner proportional to the observed values for that firm. The paper also illustrated how one could decompose a total factor productivity change measure (that includes undesirable outputs) into efficiency change and technical change.

In an agricultural example, Reinhard, et al. (2000) studied the effects of nitrogen pollution on dairy farms in the Netherlands. The nitrogen balance calculated using the materials balance equation was the pollution variable of interest. This pollution variable was modeled as the environmental detrimental input variable in the production function. The first model involved the contraction of the pollution variable holding the conventional inputs and outputs constant. The second model allowed for the radial expansion of the outputs with the both the conventional inputs and pollution variable held constant. The third model was the input-orientated version of the second model, which scaled down the conventional and pollution input variables given the fixed level of outputs. These three models produced three types of efficiency scores: an environmental efficiency score, an output-orientated technical efficiency (TE) score and an input-orientated TE scores.

Satisfaction of the materials balance condition

Coelli, et al. (2007) show that most of efficiency measures described above do not satisfy the materials balance condition. This was done for groups of environmental efficiency measures which are based on input or output distance functions (i.e. Färe, et al. 1989); Färe, et al. (1996); Reinhard, et al. (2000)). In the following section we also show that the directional distance function proposed by Chung, et al. (1997) also fails to satisfy this condition.

We first define some notation. Consider the situation where there is a firm that produces a vector of $m = 1, 2, \dots, M$ outputs, $\mathbf{q} \in \mathfrak{R}_+^M$ using a vector of $k = 1, 2, \dots, K$ inputs, $\mathbf{x} \in \mathfrak{R}_+^K$. The production activity also produces emission of possibly polluting substances as a by-product. The amount of emission is defined by the nutrients balance condition

$$\mathbf{z} = \mathbf{ax} - \mathbf{bq} \quad (1)$$

where \mathbf{a} and \mathbf{b} are vectors of known non-negative constants. Following Coelli, et al. (2007), we allow the possibility that some of inputs could have zero amounts of the nutrients of interest, for example labour and machinery.

Chung, et al. (1997) define the production technology by the output set in which input vector \mathbf{x} is used to produce good output \mathbf{q} and undesirable output \mathbf{u} :

$$P(\mathbf{x}) = \{(\mathbf{q}, \mathbf{u}) : \mathbf{x} \text{ can produce } (\mathbf{q}, \mathbf{u})\} \quad (2)$$

The authors define the directional distance function

$$\bar{D}(\mathbf{x}, \mathbf{q}, \mathbf{u}, \mathbf{g}) = \sup\{\beta : (\mathbf{q}, \mathbf{u}) + \beta\mathbf{g} \in P(\mathbf{x})\} \quad (3)$$

where \mathbf{g} is the vector of directions in which good output is increased and undesirable output is decreased.

The directional distance function of Chung, et al. (1997) is illustrated in Figure 1, where we depict the simple case of one desirable output and one undesirable output. The production frontier is defined by the line $0Y$, which corresponds to a particular quantity of input. The direction vector $\mathbf{g} = (-\mathbf{u}, \mathbf{q})$ is used to project point A (the observed data point for firm A) to point

B (which is technically efficient). This involves expanding the desirable output (q) and contracting undesirable output (u).

From the diagram, it can be shown that $\frac{q_2}{q_1} = \beta$ and hence $\frac{u_2}{u_1} = 2 - \beta$.³

The materials balance condition applied in this model indicates that at points A and B, respectively, we have⁴

$$u = ax - b\beta q \quad (4)$$

and

$$(2 - \beta)u = ax - b\beta q. \quad (5)$$

Then combining (4) and (5) we obtain

$$(ax - 2bq)(\beta - 1) = 0. \quad (6)$$

Equation (6) has two solutions: $\beta = 1$ and $ax = 2bq$. The first solution ($\beta = 1$) means that only efficient firms satisfy both the directional distance function measure and the materials balance condition (i.e. any interior point in the production technology such as point A in Figure 1 is not feasible). The second solution indicates that the amount of nutrient in the input vector must always be exactly equal to double the amount in the output vector. Neither of these solutions are a desirable feature of a directional distance function.

3 This is because $\text{tg}\alpha = \frac{BC}{CA} = \frac{q_2 - q_1}{u_1 - u_2}$ and $\text{tg}\alpha = \frac{OD}{DE} = \frac{q_1}{u_1}$ give $\frac{q_2 - q_1}{u_1 - u_2} = \frac{q_1}{u_1}$. After some arrangement, this gives $\frac{u_2}{u_1} = 2 - \frac{q_2}{q_1} = 2 - \beta$

⁴ Note that $z=u$ in this case.

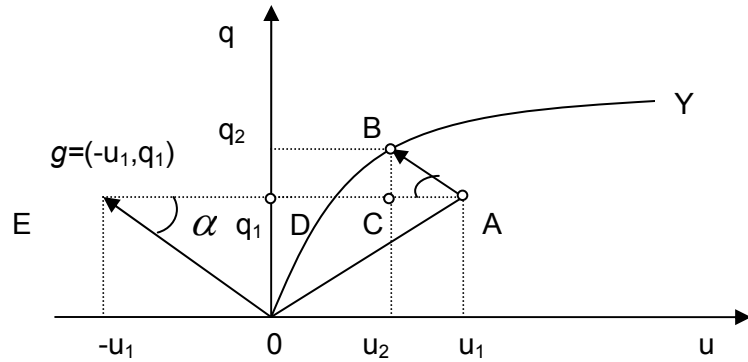


Figure 1: Directional distance function with direction vector $g=(-u,q)$

3. Nutrient-orientated efficiency and productivity measures

Coelli, et al. (2007) utilise an alternative environmental efficiency measure that involves the incorporation of the materials balance condition into the production model. In these models, the desirable output vector was fixed and undesirable outputs were viewed as the net balance of nutrient content as defined in (1).

When q is fixed, the surplus balance is minimized when the aggregate input nutrient content ($N = \mathbf{a}'\mathbf{x}$) is minimized⁵. In this method, instead of minimizing inputs, they minimized the aggregate contents contained in the input vectors. This is done on the grounds that a firm is more environmentally efficient if it produces a lower nutrient balance.

$$N(\mathbf{q}, \mathbf{a}) = \min_{\mathbf{x}} \{ \mathbf{a}'\mathbf{x} \mid \langle \mathbf{x}, \mathbf{q} \rangle \in P \} \text{ where } P \text{ is the output set} \quad (7)$$

The input vector that contains the minimum nutrient content is denoted \mathbf{x}_e and the minimum nutrient content equals to $N_e = \mathbf{a}'\mathbf{x}_e$. The nutrient content at the observed input vector is denoted $N = \mathbf{a}'\mathbf{x}$. The technically efficient input vector is denoted by \mathbf{x}_t .

These three input vectors are illustrated in Figure 2, for the simple case where there are two input variables. The slopes of the iso-nutrient lines reflect the ratios of nutrient contents of the

⁵ This excludes the case where the nutrient balance is negative. The reality is that there is the positive balance of nutrients used in agricultural production. The positive balance goes to the environment and makes the environment polluted. A positive balance is denoted as surplus.

two inputs. The intercepts of these lines represent the total amount of nutrient (N) contained in the input vectors \mathbf{x} , \mathbf{x}_e , \mathbf{x}_t . The iso-nutrient line passing through the observed point (x_1, x_2) has a larger intercept than the line passing through the technically efficient point (x_{1t}, x_{2t}) . Similarly the iso-nutrient line passing through the technical efficient point has an intercept that is larger than the line passing through the nutrient minimising point (x_{1e}, x_{2e}) .

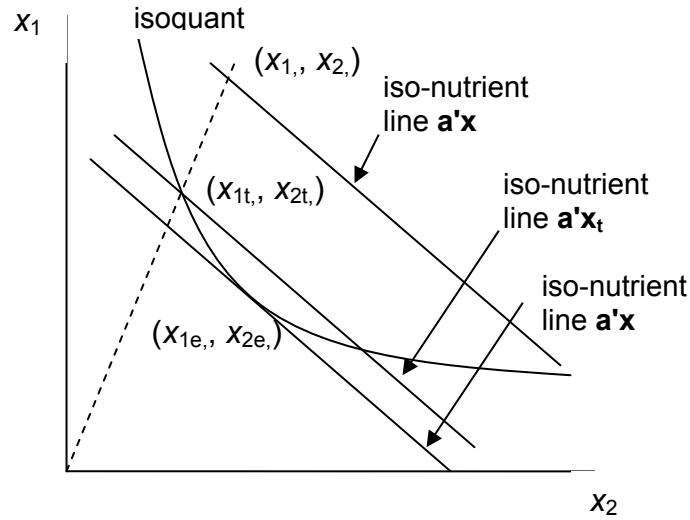


Figure 2: Nutrient minimisation

Next, we define nutrient-orientated efficiency (NE), technical efficiency (TE) and nutrient-orientated allocative efficiency (NAE).

$$TE(\mathbf{q}, \mathbf{x}) = \min_{\theta} \{ \theta \mid \langle \theta \mathbf{x}, \mathbf{q} \rangle \in Y \}, \quad (8)$$

where θ is a scalar taking a value between zero and one. The \mathbf{x}_t is the solution to this optimization problem. $N_t = \mathbf{a}'\mathbf{x}_t$ is defined as the nutrient content at the technically efficient input vector and hence

$$TE = \frac{N_t}{N} = \frac{\mathbf{a}'\mathbf{x}_t}{\mathbf{a}'\mathbf{x}} = \theta \quad (9)$$

Following Coelli, et al. (2007), the nutrient-orientated efficiency measure (NE) of a firm is defined as the ratio of the minimum nutrient content over the observed nutrient content:

$$NE = \frac{N_e}{N} = \frac{\mathbf{a}'\mathbf{x}_e}{\mathbf{a}'\mathbf{x}}. \quad (10)$$

NE then can be decomposed into technical efficiency (TE) and nutrient-orientated allocative efficiency (NAE):

$$NE = TE \times NAE, \quad (11)$$

where

$$NAE = \frac{N_e}{N_t} = \frac{\mathbf{a}'\mathbf{x}_e}{\mathbf{a}'\mathbf{x}_t}. \quad (12)$$

TE relates to the operation of the firm on the frontier of the production technology (i.e. the production possibility curve) while NAE relates to using the correct input mix given the observed nutrient contents. All three efficiency measures take values between zero and one. The value of unity indicates full efficiency while less than unity implies inefficiency.

As noted in Coelli, et al. (2007), NE can be estimated following a procedure similar to estimating cost efficiency in which the vector of nutrient contents of the inputs (\mathbf{a}) is used instead of prices.

There are some advantages of using this nutrient-orientated efficiency measure. First, in the setting of distance functions and frontier functions (i.e. revenue, cost or profit functions), this approach allows the estimation of shadow prices of nutrient reduction and the estimation of effects on nutrient reduction by policy changes (e.g. taxation). This was discussed in Coelli, et al. (2007).

The second advantage is that these nutrient-orientated efficiency and productivity measures are applicable to the analysis of both individual nutrient flow and aggregate flow of various nutrients. In agricultural production, for example, there are concerns on the balances of various things, such as nitrogen, potassium, phosphorous, sulphur and carbon. This approach can quantify environmental efficiency and productivity measures by applying the materials balance condition to the balance of different individual nutrients or to the aggregate balance of all these nutrients. The aggregate balance of different nutrients needs a choice of weightings for different nutrients.

Coelli, et al. (2007) discussed the case when there are two nutrients, which required two material balance equations. If there are two inputs and one output, the equations are:

$$z_1 = a_{11}x_1 + a_{21}x_2 - b_1q \quad (13)$$

and

$$z_2 = a_{12}x_1 + a_{22}x_2 - b_2q. \quad (14)$$

If the chosen weights are v_1 and v_2 , the aggregate balance equation becomes

$$v_1z_1 + v_2z_2 = (v_1a_{11} + v_2a_{12})x_1 + (v_1a_{21} + v_2a_{22})x_2 - (v_1b_1 + v_2b_2)q \quad (15)$$

and the method proceeds normally.

For example, a national agricultural system uses different types of energy, feed, fertilizer, pesticides and seed in its production and pollutes NO_x , PO_x , SO_x or CO_x to the environment. The materials balance equation in (15) can be used to estimate the aggregate balance of materials given a particular choice of weights for the different materials.

The third desirable feature of this approach is that it avoids the potential correlation between the undesirable outputs and conventional inputs in empirical studies. For example, one might want to compare the environmental performance of crop farms which produce nitrogen to the environment. The production model can have nitrogen as an undesirable output while fertilizer as an input. Statistical data for nitrogen is normally estimated by using the formula (fertilizer) \times (nitrogen content factor). Consequently, multicollinearity is a potential problem in this model. This problem, however, is not present in the materials balance condition approach because in (2) there is no undesirable output vector.

Since the surplus balance of nutrients causes pollution, some countries (especially OECD member countries) have started regulating the use of nutrients in agricultural production. One of the most common environmental policies involves the regulation of the limit of emission that the farmer can pollute to the environment (Dowd, et al. 2008; Nam, et al. 2007; Pretty, et al. 2001; Sterner and Kohlin 2003). Under this regulation, farmers are taxed or levied on the nutrient balance which exceeds a specified limit. One example of this regulation framework is

the Mineral Accounting System (MINAS) which monitors the nutrient balance of farms in the Netherlands (Van Der Brandt and Smit 1998).

Under such an environmental regulation system, the farmers operate under a nutrient balance constraint. Applying the nutrients balance condition equation in (1), one can separate two different types of nutrient constraints restricting the behaviour of the farmers: (a) given that the output vector is fixed, the limit on the nutrients balance means that the farmers' operation is restricted by the maximum level of nutrients in input and (b) given that the input vector is fixed, the limit on nutrients balance suggests that the farmers are required to achieve the target of minimum total quantity of nutrients in output. These two types of nutrient constraints however can be modeled in a similar manner to the modeling of firms operating under a cost budget restriction and revenue target restriction. Färe and Grosskopf (1994) provide techniques to measure efficiency and productivity performance of the farmers using cost- and revenue-indirect technologies. The application of these price-based techniques to nutrient-based problems could be an interesting area of future research.

Nutrient-oriented total factor productivity

In this section, we use the nutrient-orientated efficiency measure to construct a Nutrient-oriented Total Factor Productivity (NTFP) index. This index builds upon the concept of the input-orientated Malmquist TFP index first proposed by Caves, et al. (1982a; b). The index is constructed by measuring the radial distance of the observed output and input vectors in period t and $t+s$ relative to two reference technologies: technology in period t and technology in period $t+s$.

First, using technology in period t as a reference technology, the Malmquist nutrient-orientated TFP index for period t and $t+s$ is defined as changes in the nutrient-orientated efficiency in period $t+s$ over period t :

$$M_i^t = \frac{NE_i^{t,t+s}}{NE_i^{t,t}}, \quad (16)$$

where the first and second superscripts refer to the reference technology and time period respectively. The subscript 'i' refers to the input-orientation. For example, $NE_i^{t,t+s}$ refers to the environmental efficiency score calculated using the observed data for a firm operating in time

period $t+s$ relative to the reference technology from time period t , using an input-oriented framework.

Similarly, using the technology in period $t+s$ as a reference technology, a Malmquist nutrient-orientated TFP index may be defined as:

$$M_i^{t+s} = \frac{NE_i^{t+s,t+s}}{NE_i^{t+s,t}} \quad (17)$$

Our NTFP change index (NTFPC) is then defined as the geometric mean of the two previous indices:

$$NTFPC^{t,t+s} = \left[\frac{NE_i^{t,t+s}}{NE_i^{t,t}} \times \frac{NE_i^{t+s,t+s}}{NE_i^{t+s,t}} \right]^{1/2} \quad (18)$$

All NE s in are defined as follows:

$$NE_i^{t,t} = \frac{\mathbf{a}'\mathbf{x}_e^{t,t}}{\mathbf{a}'\mathbf{x}^{t,t}} = \frac{\mathbf{a}'\mathbf{x}_e^{t,t}}{\mathbf{a}'\mathbf{x}_t^{t,t}} \times \frac{\mathbf{a}'\mathbf{x}_t^{t,t}}{\mathbf{a}'\mathbf{x}^{t,t}} = NAE_i^{t,t} \times TE_i^{t,t}. \quad (19)$$

$NE_i^{t,t}$ can be estimated in a nutrient input-oriented framework (e.g. by a cost-minimizing DEA) and $TE_i^{t,t}$ is estimated in a standard input-orientated framework given a input vector $\mathbf{x}^{t,t}$ of time t corresponding to a specified output level of \mathbf{q}^t at time t .

$$NE_i^{t+s,t+s} = \frac{\mathbf{a}'\mathbf{x}_e^{t+s,t+s}}{\mathbf{a}'\mathbf{x}^{t+s,t+s}} = \frac{\mathbf{a}'\mathbf{x}_e^{t+s,t+s}}{\mathbf{a}'\mathbf{x}_t^{t+s,t+s}} \times \frac{\mathbf{a}'\mathbf{x}_t^{t+s,t+s}}{\mathbf{a}'\mathbf{x}^{t+s,t+s}} = NAE_i^{t+s,t+s} \times TE_i^{t+s,t+s} \quad (20)$$

$NE_i^{t+s,t+s}$ is estimated in a nutrient input-orientated framework and $TE_i^{t+s,t+s}$ is estimated in a standard input-orientated framework given a input vector $\mathbf{x}^{t+s,t+s}$ at time $t+s$ corresponding a specified output level of \mathbf{q}^{t+s} at time $t+s$.

$$NE_i^{t,t+s} = \frac{\mathbf{a}'\mathbf{x}_e^{t,t+s}}{\mathbf{a}'\mathbf{x}^{t,t+s}} = \frac{\mathbf{a}'\mathbf{x}_e^{t,t+s}}{\mathbf{a}'\mathbf{x}_t^{t,t+s}} \times \frac{\mathbf{a}'\mathbf{x}_t^{t,t+s}}{\mathbf{a}'\mathbf{x}^{t,t+s}} = NAE_i^{t,t+s} \times TE_i^{t,t+s} \quad (21)$$

$NE_i^{t,t+s}$ is estimated in a nutrient input-orientated framework and $TE_i^{t,t+s}$ is estimated in a standard input-orientated framework given a input vector $\mathbf{x}^{t,t+s}$ of time t+s corresponding a specified output level of \mathbf{q}^t at time t.

$$NE_i^{t+s,t} = \frac{\mathbf{a}'\mathbf{x}_e^{t+s,t}}{\mathbf{a}'\mathbf{x}^{t+s,t}} = \frac{\mathbf{a}'\mathbf{x}_e^{t+s,t}}{\mathbf{a}'\mathbf{x}_t^{t+s,t}} \times \frac{\mathbf{a}'\mathbf{x}_t^{t+s,t}}{\mathbf{a}'\mathbf{x}^{t+s,t}} = NAE_i^{t+s,t} \times TE_i^{t+s,t} \quad (22)$$

$NE_i^{t+s,t}$ is estimated in a nutrient input-orientated framework and $TE_i^{t+s,t}$ is estimated in a standard input-orientated framework given a input vector $\mathbf{x}^{t+s,t}$ of time t corresponding a specified output level of \mathbf{q}^{t+s} at time t+s.

Following Caves, et al. (1982a; b), the standard input oriented Malmquist TFP index is defined as

$$TFPC_i = \left[\frac{TE_i^{t,t+s}}{TE_i^{t,t}} \times \frac{TE_i^{t+s,t+s}}{TE_i^{t+s,t}} \right]^{1/2}, \quad (23)$$

which can be decomposed into

$$TFPC_i = \frac{TE_i^{t+s,t+s}}{TE_i^{t,t}} \left[\frac{TE_i^{t,t}}{TE_i^{t+s,t}} \times \frac{TE_i^{t,t+s}}{TE_i^{t+s,t+s}} \right]^{1/2} = TEC_i \times TC_i, \quad (24)$$

where TEC_i is technical efficiency change and TC_i is the geometric mean of two technical change indices, evaluated at the period t and period t+s data points, respectively.

Thus, using equations 18 to 24, we have

$$NTFPC_i = TFPC_i \times \left[\frac{NAE_i^{t,t+s} \times NAE_i^{t+s,t+s}}{NAE_i^{t,t} \times NAE_i^{t+s,t}} \right]^{1/2} \quad (25)$$

and hence

$$NTFPC_i = TEC_i \times TC_i \times \left[\frac{NAE_i^{t,t+s} \times NAE_i^{t+s,t+s}}{NAE_i^{t,t} \times NAE_i^{t+s,t}} \right]^{1/2} = TEC_i \times TC_i \times NAEC_i \quad (26)$$

Technical efficiency change (TEC) refers to changes in technical efficiency of the observed unit against the technically efficient unit; technical change (TC) refers to the shift of the technically efficient frontier; and nutrient-orientated allocative efficiency change (NAEC) measures the effect of allocative decisions on environmental performance.

4. OECD Application

The OECD has recently released a report on the environmental effects of agriculture of its member countries for the years from 1990 to 2004 (OECD 2008). This report was the latest output from the broader project of establishing environmental indicators for agriculture which began before 1997. The unique feature of this report is that it brings together the most up to date comparative data on the environmental performance of agriculture in OECD countries.

One of the main points of discussion in this report relates to the estimation of gross nitrogen and phosphorous balances of member countries over the survey period. In our study we utilize the data provided by this project to estimate the environmental performance of these member countries by constructing nutrient-orientated efficiency and productivity measures. The scope of this paper focuses on both the nitrogen and phosphorous balance. In terms of the eutrophication effects, the choice of weights is straightforward in this case: the eutrophying power of phosphorous is known to be ten times more than that of nitrogen (Coelli et al. 2007).

The boundary of national agricultural production system

Figure 3 provides a diagrammatical representation of the boundary and the flow of nitrogen in a national agricultural production system. This figure is extracted from Hoang and Alauddin (2009) which is a modified version of the farm gate method of accounting for nitrogen and phosphorous flows.

The agricultural production of a country is considered to be a “black box” in which there is an interaction of livestock and crop production activities. Inside the box, harvested fodder crops and grazed grass are consumed by the livestock and the excretion of the livestock is a source of fertilizer for crops. The input side of the box includes fertilizer (i.e. inorganic and organic but not manure), feedstuff, seeds and planting material, purchased breeding/baby livestock, plus biological nitrogen and phosphorous fixation. The output side has three main groups: marketed livestock products, marketed crop products, and all nitrogen and phosphorous-containing items

(e.g. fodder crops, grass, manure) exported to other countries or used for non-agricultural purposes.

The soil surface method which was used by OECD (2008) is an alternative method of accounting nutrients balance. This method defines the nutrient balance as the difference between the nutrient inflows entering into the soil and nutrient outflows going out of the soil. Given the objective of our research is to use the nutrient balance as indicators for the environmental performance of the whole national agricultural sector which involves both cropping and livestock activities, we decided to use the modified farm gate method. This is because this method is more accurate and delivers a more meaningful interpretation (Hoang and Alauddin 2009).

Specifically, there are three main important advantages of using the modified farm gate method over the soil surface method. First, OECD (2008), in implementing the soil surface balance method, estimated nitrogen content in manure by multiplying the number of livestock with a particular coefficient which relates to the amount of manure produced in a year and how much nitrogen is in each unit of manure. This way of estimating the nutrient content in manure potentially causes high uncertainty. The modified farm gate method does not have manure in the input or output terms because they are contained within the black box.

Secondly, as noted in OECD (2008), there is a double-counting error in their calculation regarding atmospheric deposition of nitrogen into the soil. In the modified farm gate method, this item is not present therefore it avoids this double-counting error.

Thirdly, the computed nutrient balance produced by the modified farm gate method delivers more valuable economic and environmental implications than the soil surface method (Hoang and Alauddin 2009). For example, under the soil surface method, in order to reduce the nutrient surplus, a country can reduce fertilizer supply and livestock manure. Theoretically, an easy way of reducing livestock manure is to scale down the size of livestock production⁶. However, scaling down the livestock production is not always economically feasible, especially in those countries where livestock production is a main agricultural production activity of their agricultural sector (i.e. where livestock production is more profitable than crop production). Also, under the soil surface method, the use of manure for crop production as a way of

⁶ One can also reduce the livestock manure deposition into the soil by exporting the livestock manure from agriculture to other commercial activities. However, this is not always economically feasible.

abatement is implicitly ignored. On the other hand, under the modified farm gate method, one can think of maximizing the recycling of manure from the livestock production for crop production activities to reduce the nutrient balance. This is arguably more economically attainable.

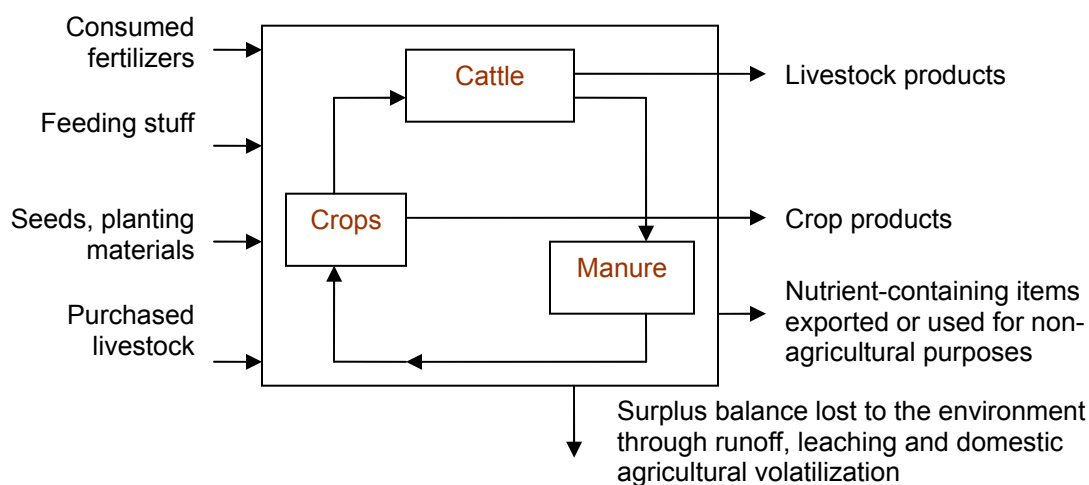


Figure 3: Modified farm gate method of accounting nutrient balance

Input and output variables

The empirical analysis in this paper involved annual data on 28 OECD countries during the period 1990-2003. The biological nutrient fixation and nutrient removed from the system for non-agricultural purposes are not included in our analysis because of a lack of data and their insignificant contribution in the balance⁷. The stock of live animals was treated as an input for livestock production. An increase in the live animal stock in any year was credited to the output in that year. Similarly, any decrease in the live animal stock was debited to the output.⁸

⁷ OECD (2008) estimated a very insignificant amount of nutrient in these three categories.

⁸ In a year, a country could have a negative change (decrease) or a positive change (increase) in the stock of live animals. A positive stock change is treated as extra output and added to the output. A negative stock change is treated as input and subtracted from the output. Yield, defined as tonnes per head, is used to convert number of head of stock into tonnes. However, there are a few of negative values (49 out of 392x155= data points) in the output quantity because of negative stock change. There are some potential explanations for this: (1) measurement error due to the use of yield to convert the number of head data into tonnes data, (2) the negative stock change of a particular livestock but this animal was not for livestock production activities (e.g. breeding or recreational purposes) and (3) in that year a country could have reduced or stopped the production of a particular livestock commodity therefore live animals were slaughtered but data on production of that commodity was not recorded. If any of these is the real reason for a negative data point in the output side, it is however reasonable to change it to zero. Setting negative values to zero is also for the sake of protecting the dataset from losing observations.

The national agricultural production system has 131 crop commodities and 24 livestock commodities on the output side and seven main categories of inputs (i.e. land, labor, energy, fertilizer, feed and seed and planting material, machinery, pesticide, and water).

This paper used DEA⁹ to estimate efficiency scores under the assumption of constant return to scale (CRS) production technology¹⁰. Due to degrees of freedom constraints, we aggregated the 155 output commodities into one aggregate output variable and the 61 commodities in feed and seed into one aggregate feed and seed (FnS) variable. On the input side, we did not include information on water and pesticide because of incomplete data. The input-output matrix in the system then becomes

- One output term: aggregate output
- Five input terms: fertilizer, land, labor, machinery and aggregate FnS.

There are three data requirements for each input and output variable: quantity, nitrogen content and phosphorous content. For aggregating output commodities into an aggregate output term, we also need price data of 155 commodities of 28 countries in 14 years (1990-2003).¹¹ For the aggregate FnS term, we need quantity and price data of 61 commodities to aggregate them into one aggregate FnS input term and nitrogen and phosphorous content of these 61 commodities to aggregate into one aggregate nutrient content for the aggregate FnS input term.

The main source for quantity and price data was FAO's website (FAOSTAT). Data for nitrogen content of the output commodities was compiled from various food composition tables of OECD member countries¹².

⁹ See Appendix 1 for brief description of the DEA method & software used in this paper.

¹⁰ There are three reasons why the CRS assumption is more appropriate than variable return to scale (VRS) assumption in the empirical work in this paper. First, the analysis involves the use of aggregate country-level data (Coelli and Rao 2005). Secondly, Grifell-Tatje and Lovell (1995) found that the Malmquist TFP index may not correctly measure TFP changes when VRS is assumed. Thirdly, the input terms do not have any items that capture the factors which causes scale inefficiency (e.g. sector governance errors, corruption, bureaucracy).

¹¹ All aggregation is done using a multilateral Fisher index.

¹² These countries reported micronutrient values (either nitrogen content or protein content or phosphor) in 100 g of a particular commodity of edible food. This is actually part of a number of international projects of constructing international food composition table such as FAO's Infoods (available at

Quantity data for land is in 1,000 hectare units of agricultural land from OECD (2008), quantity data for labor is the total population working in agriculture from FAO, quantity data for fertilizer is total tonnes of active nutrients (nitrogen, phosphorous and potash) from FAO and OECD (2008), quantity data for machinery is the total number of agricultural tractors, balers, ploughs, harvesting machines, seeders, threshing machines, and milking machines. The nutrient contents for labor and machinery are zero. The nutrient content for land is also assumed to be zero.¹³ The nitrogen and phosphorous content of fertilizer is calculated as the ratio of total (weighted) nitrogen and phosphorous fertilizer over total active nutrient quantity.

In order to estimate the quantity of the aggregate output term, we calculated transitive Fisher quantity index numbers using price data as weights. There are some zeros in the original quantity and price data in some countries due to data missing. The zero quantities were left as zeros. Missing prices data were filled using the Country Product Dummy (CPD) method developed by Summers (1973)¹⁴. The same techniques were used to calculate the quantity data for aggregate FnS input term.

Another aggregation job was required for the nutrient (i.e. nitrogen and phosphorous) contents of the aggregate FnS input term. There were three steps involved in creating this aggregate nutrient content. First, we constructed quantity indices (Q_j) of country j with prices as weights (this step is identical to the first step in aggregating the output term). Second, we calculated total nutrients (TN_j of country j) that are contained in all items in aggregated terms ($TN_j =$

http://www.fao.org/infoods/directory_en.stm), EU's EUROFIR (available at www.eurofir.net) and LANGUAL (available at <http://www.langual.org>). From these resources, we collected food composition tables of thirteen OECD countries including Australia, Belgium, Canada, Denmark, Finland, Italy, Japan, New Zealand, Norway, Spain, Sweden, Switzerland and USA.

¹³ The best indicator of nutrient content of land should be the nutrient content in the soil that the crops can access to. At the farm level, this data can be drawn from nutrient test of soil quality. However at national level, the soil test estimate is impossible. However, we identified three possible ways of setting land nutrient content: (1) the nutrient content is zero, (2) balance of nutrient estimated by the soil surface balance approach and (3) the accumulative nutrient accumulated from the balance of nutrient estimated by the soil surface balance approach. All of these three treatments face different criticism. When nutrient content of land is set to zero, this means that the nutrient content in soil is not used by the plants. This is a very strong assumption. However, given the practice that there was overuse of fertilizer in OECD countries over the survey period (OECD 2008) and the fact that the major amount of nutrient coming to the soil leaches deep under the ground and becomes inaccessible to the plant, this assumption sounds to be reasonable. The second and the third treatment, however, have measurement errors and some difficulties in interpretation. For example, OECD (2008) estimated the net balance of nutrient of Hungary in 1991 was negative, this negative balance does not have any interpretation regarding how much nutrient in the soil in 1991 was used by crops.

¹⁴ A detailed description of the CPD method is provided in Appendix 2.

$\sum_{i=1}^K (x_{ij}n_{ij} + 10x_{ij}p_{ij})$, where n_{ij} and p_{ij} are nitrogen and phosphorous content of single commodity items (x_i) among K items of country j^{15}). Third, aggregated nutrient content (ANC_j) is the ratio of total nutrient content divided by $TQ_j * QI_j$ where TQ_j is total quantity of all the items in the aggregated terms ($\sum_{i=1}^K x_{ij}$).¹⁶

Efficiency scores

Table 1 provides basic descriptive statistics for the distribution of three DEA efficiency scores: technical efficiency, allocative efficiency and nutrient-orientated efficiency. The mean technical efficiency (TE) score of 0.798 suggests that the average country should be able to produce their current output with 20.2% fewer inputs. The mean nutrient-orientated allocative inefficiency (NAE) score of 0.671, suggests that the average country could reduce nutrients by a further 32.9%, if they were to adjust the input mix. Thus, the overall mean nutrient-orientated efficiency (NE) score of 0.526 indicates that the average country should be able to produce their current output with an input vector that contains 47.4% less nitrogen and phosphorous¹⁷.

Table 1: DEA efficiency scores

Efficiency measure	Mean	Stdev	Min	Max
Technical efficiency (TE)	0.798	0.182	0.396	1.000
Nutrient-orientated allocative efficiency (NAE = NE/TE)	0.671	0.213	0.248	0.955
Nutrient-orientated efficiency (NE)	0.526	0.193	0.150	0.897

¹⁵ As discussed earlier, the relative eutrofying power of nitrogen and phosphor is 1:10

¹⁶ There were some missing data in the nutrient content of feed and seed commodities in some countries. This was essentially because we did not have access to their food composition tables. However, we believe that nutrient contents in food commodities in countries of similar biological and weather conditions do not vary much. Based on this assumption, we applied nutrient contents of Korea to Japan, Mexico to USA and Canada. Nutrient content in Austria, France, Greece, Hungary, Iceland, Ireland, Netherlands, Poland, Portugal, and Turkey are estimated using the average of Belgium, Denmark, Finland, Italy, Norway, Spain, Sweden, Switzerland, and UK.

¹⁷ It should be noted that these country-level NE scores should not be interpreted correspondingly as a particular amount of damage caused to the environment by the nutrients balance. This is because that locational characteristics (e.g. soil type, topography and rainfall) vary from country to country and the estimated scores do not capture pollution abatement activities that countries could be engaging in. However it is also of interest to incorporate abatement activities into the model if data is available.

Figure 4 graphs the movement of mean nutrient-orientated, nutrient allocative and technical efficiency scores over the 14 years period. The movement of nutrient-orientated efficiency scores in many years was in the opposite direction of the technical efficiency scores. The mean nutrient-orientated efficiency scores were around 0.52 over the survey period. It saw a big drop in 1991, 1992 and in 2002. Figure 5 shows the changes in the output levels¹⁸. Combining these two figures, we observed that the drop in nutrient-orientated efficiency levels in 2002 was primarily due to a drop in output while the fall in 1991 and 1992 was apparently due to more intensive use of fertilizer.

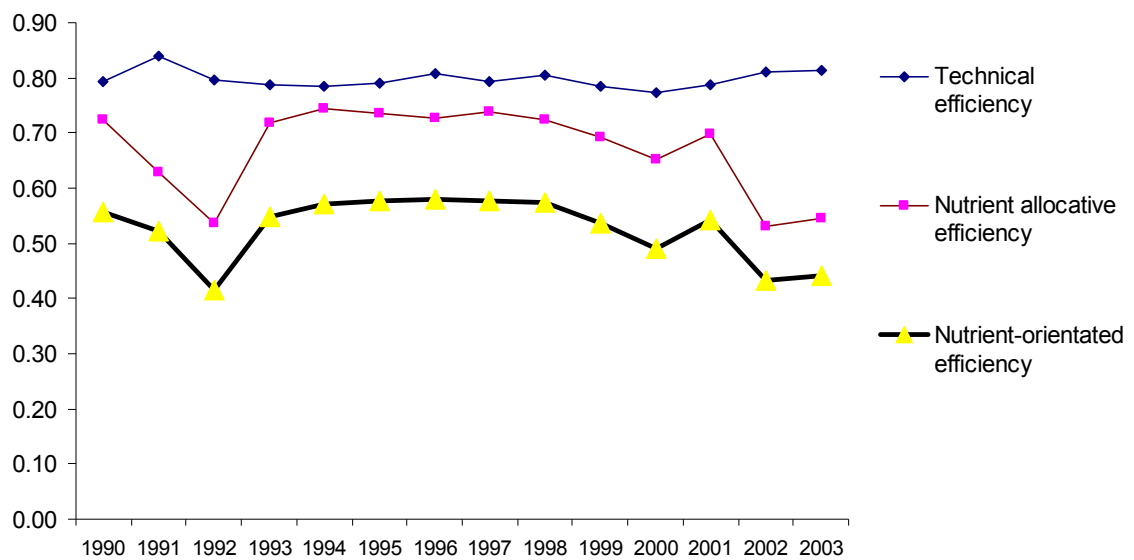


Figure 4: Mean technical, nutrient-orientated allocative and nutrient-orientated efficiency scores

¹⁸ Which are measured by changes of the average values of output quantity indexes.

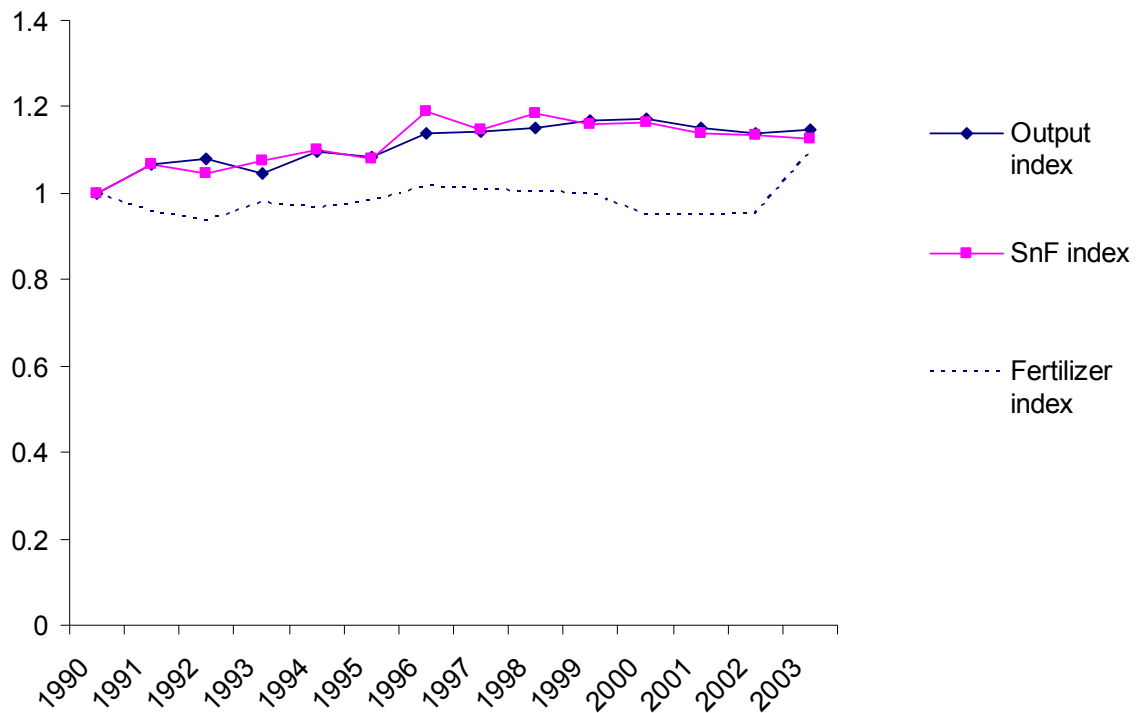


Figure 5: Output and input indices

The result also indicates that there are only three countries which were efficient in terms of the use of nitrogen and phosphorous. They were Hungary (in 1991 and 1992), Switzerland (in 2000, 2001, and 2003) and the Netherlands (in the remaining years). There are some interesting factors that may partly explain the high nutrient efficiency in these three countries during these periods.

For Hungary, this achievement happened during the early years of the transition period from central economy to market economy. During the period before 1990, the farming production used an excessive amount of fertilizer. But the shift had moved farms from an intensive production orientated system to adoption of more extensive production methods. The more extensive farming was linked particularly to a large decrease in use of commercial fertilizer and feed and seed. The quantity of fertilizer applied on farms in 1991 and 1992 were less than 48% and 28% of the amount used in 1990 respectively. The use of feed and seed also dropped by 5% in 1991 and 26% in 1992 from 1990 accordingly. The use of machinery however increased sharply in these two years while the output level in 1991 was nearly the same level in 1990. This finding is consistent with OECD (2008).

In the Netherlands, the government had focused its environmental policies in agriculture on reducing the pollution caused by nutrient surplus. Thanks to these efforts, this country gained significant improvement in terms of the nitrogen and phosphorous balance. The nutrient policy has gone through three phases (Grinsve, et al. 2005; OECD 2003). The first phase from 1984 to 1990 was to stop the increase in livestock production. The second phase from 1990 to 1998 involved a step-wise decrease of pressures resulting from surplus quantities of animal manure by using application limits and a manure quota system. The third phase from 1998 to 2005 applied compulsory Minerals Accounting System (MINAS) in which the nutrient balance of farmers is monitored. Under this initiative, nitrogen and phosphorous surpluses exceeding certain limits were subject to levies. There was also a nutrient reduction budget of around USD 700 million through livestock farm closure schemes during 1998-2003 (Grinsve, et al. 2005). The government also provided financial assistance in the form of tax reductions to the farmers (Beers, et al. 2002; Grinsve, et al. 2005). To comply with international environmental agreements, the agricultural sector has been set targets for reducing nitrogen and phosphorous emissions into the North Sea and ammonia emissions into the atmosphere (OECD 2008).

In Switzerland, there has been a growing emphasis on the environmental policies in agriculture. From 1993, Ecological Direct Payments (EDP) as a primary financial assistance framework for farmers was granted on condition that the farmers adopt a set of environmental management practices (OECD 2008). The revision of the Agricultural Policy Reform Programme which provided the basic framework governing agricultural policy for the 1999-03 period required that any general direct payment to farmers meet five environmental criteria (Badertscher 2005; OECD 2004). A balanced use of nutrients, crop rotation, soil protection and improved pesticide management are among these criteria. In addition, the Water Protection Act requires farmers to limit manure and fertiliser application per hectare; install facilities to store manure for at least three months; and adopt practices to prevent pollution of water by fertilisers and pesticides. Under the Order on Hazardous Substances soil nutrient assessment is compulsory for each crop during the growing season (OECD 2004; 2008).

Table 2 reports the average values of the three efficiency measures over the period 1990-2003 of 28 countries and their rankings. It notes that the rankings change dramatically between TE to NE. For the case of TE, Australia, Belgium-Luxembourg, the Netherlands, New Zealand, and United States have the best ranks. However in the terms of nutrient efficiency, only the Netherlands retained their position while Australia dropped to 17th rank, Belgium-Luxembourg

to 5th rank, New Zealand to 21st rank, and the United States to 20th rank. The Friedman test confirmed there was a significant disagreement between the rankings in nutrient-orientated efficiency scores and technical efficiency scores¹⁹.

Table 2: Average efficiency scores for the period 1990-2003

Country	Mean TE	Rank	Mean AE	Rank	Mean NE	Rank
Netherlands	1.000	1	0.897	5	0.897	1
Switzerland	0.913	10	0.955	1	0.875	2
Greece	0.981	8	0.797	11	0.785	3
Italy	0.896	12	0.872	8	0.778	4
Belgium-Luxembourg	1.000	1	0.740	12	0.740	5
Portugal	0.751	17	0.915	3	0.689	6
Hungary	0.909	11	0.730	13	0.674	7
Austria	0.701	21	0.904	4	0.638	8
Mexico	0.991	7	0.640	16	0.635	9
Turkey	0.728	18	0.871	9	0.632	10
Denmark	0.951	9	0.607	19	0.580	11
Czech	0.688	22	0.816	10	0.566	12
Japan	0.768	16	0.728	14	0.558	13
Spain	0.635	24	0.890	7	0.554	14
Poland	0.550	25	0.949	2	0.522	15
Korea	1.000	6	0.515	20	0.515	16
Australia	1.000	1	0.474	21	0.474	17
Germany	0.663	23	0.707	15	0.464	18
Sweden	0.479	26	0.893	6	0.426	19
United States	1.000	1	0.399	25	0.399	20
New Zealand	1.000	1	0.376	26	0.376	21
France	0.881	13	0.424	23	0.371	22
Canada	0.813	14	0.402	24	0.326	23
United Kingdom	0.707	19	0.461	22	0.325	24
Norway	0.440	27	0.625	18	0.272	25
Finland	0.396	28	0.635	17	0.252	26
Ireland	0.796	15	0.317	27	0.251	27
Iceland	0.703	20	0.248	28	0.150	28

¹⁹ The result of the test: Friedman = 37.35, Kendall = 0.69 and p-value = 0.08. We also did a test on the rankings in TE, NE and NAE which gives *p-value* = 0.02, this suggests the rankings in the efficiency considerations are significantly different (at 5% level of significance).

Nutrient-oriented total factor productivity growth

Table 3 reports the average productivity changes over the period 1990-2003 of the 28 member countries. In terms of nutrient balance, the OECD achieved a mean growth in NTFP of 1.5% per annum over the 14 year period, compared with 0.8% in the traditional TFP growth. This was due to the presence of technological progress in terms of the use of nutrients. The nutrient-orientated technological change was estimated to be around 0.7% per year over the survey period.

There were 12 countries experiencing negative growth in the nutrient-orientated productivity. Among these countries, decreased traditional TFP in eight countries caused the negative growth in NTFP. On the other hand, the negative growth in NTFP in the remaining four countries (Australia, United States of America, Canada and Portugal) was attributable to the nutrient-orientated technological regress. New Zealand and Australia were the worst two performers in terms of NTFP growth. In these countries the reason for the negative NTFP and TNC growth was because of overuse of nitrogen fertilizer. For example, the total consumption of fertilizer in Australia increased 89.9% (63.7% for New Zealand, 29.5% for Canada, 27.9% for United States) from 1990 to 2003 compared with an increase of 8.8% of all OECD countries.

Spain (10.9% growth), Denmark (9.8% growth) and Greece (5.0% growth) achieved the highest NTFP growth. This achievement was mainly due to significant growth in the traditional TFP for Spain and Denmark and was mainly due to nutrient-orientated technological progress for Greece. In the case of Korea and Iceland, their environmental performance improvement was due to reduced (relative) use of nitrogen and phosphorous content inputs, regardless that the traditional TFP decreased.

Table 4 and Figure 6 reports the average productivity growth for 28 countries in each of the years in the 1991-2003 period. There were four years (1993, 1994, 2002 and 2003) that experienced negative growth in the nutrient-oriented total factor productivity index, where the negative growth was a consequence of both decreased traditional TFP and a reduction in nutrient-orientated allocative efficiency. From 2000 onwards, the OECD has seen a slight reduction in the nutrient-orientated technological growth. This nutrient-orientated productivity trend suggests that either the “easy gains” in environmental improvements have been achieved, or that OECD countries may be starting to be less vigilant in tackling these environmental issues.

Table 3: Mean productivity growth, 1990-2003

Country	Mean TFPC	Mean NAEC	Mean NTFPC
Australia	1.021	0.956	0.978
Austria	1.040	0.975	1.013
Belgium-Luxembourg	1.030	1.004	1.032
Canada	1.033	0.963	0.992
Czech	0.992	1.004	0.994
Denmark	1.069	1.029	1.098
Finland	0.990	1.037	1.031
France	1.026	0.993	1.021
Germany	1.019	0.988	1.007
Greece	1.003	1.047	1.050
Hungary	0.957	1.042	0.997
Iceland	0.960	1.079	1.027
Ireland	0.986	1.039	1.027
Italy	1.000	1.025	1.026
Japan	0.988	0.999	0.987
Korea	0.965	1.059	1.024
Mexico	1.022	1.009	1.030
Netherlands	0.991	1.004	0.995
New Zealand	0.988	0.957	0.944
Norway	0.989	1.006	0.997
Poland	1.009	1.002	1.012
Portugal	1.004	0.995	0.999
Spain	1.107	1.004	1.109
Sweden	0.995	0.996	0.988
Switzerland	1.034	1.013	1.047
Turkey	0.990	1.001	0.989
United Kingdom	1.002	1.016	1.017
United States	1.026	0.965	0.991
Geometric Mean	1.008	1.007	1.015

Table 4: Mean productivity growth of 28 countries

Year	Mean TFP	Mean NAE	Mean NTFP
1991	1.099	1.096	1.203
1992	0.997	1.024	1.020
1993	0.980	0.978	0.956
1994	0.975	1.020	0.994
1995	1.000	1.020	1.020
1996	0.998	1.011	1.011
1997	1.006	1.006	1.013
1998	1.013	1.004	1.016
1999	1.027	1.000	1.029
2000	0.993	1.042	1.033
2001	1.020	0.995	1.013
2002	0.975	0.985	0.962
2003	1.026	0.919	0.942
Mean	1.008	1.007	1.015

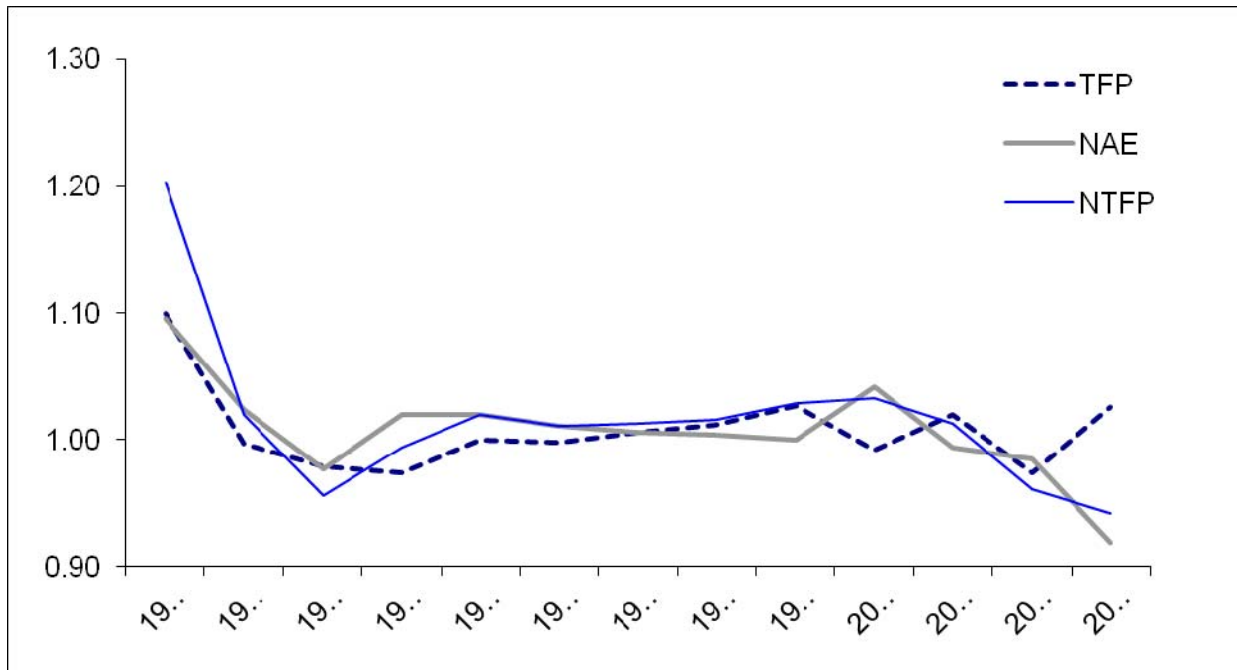


Figure 6: Trends in productivity measures

5. Conclusions

A new environmental productivity index is proposed that incorporates changes in nutrient-orientated environmental efficiency over years. The new index, a *Nutrient-oriented Total Factor Productivity* (NTFP), is constructed in a similar way to that of the Malmquist total factor productivity (TFP) index. We show that changes in this new NTFP index may be decomposed into technical efficiency change (TEC), technical change (TC) and nutrient-orientated allocative efficiency change (NAEC) components. TEC relates to countries catching up to the production frontier; TC refers to shifts in the production frontier; while NAEC reveals information about the changes in environmental efficiency due to allocative factors. The principal advantage of this new environmental productivity index is that it is constructed from nutrient-orientated environmental efficiency scores which satisfy the materials balance condition.

The NTFP index allows one to measure agricultural productivity growth which incorporates environmental effects. It can be used in farm-level, district-level and country-level analyses, given that the available data on inputs and outputs capture the differences in production technologies across production units.

An empirical analysis involving annual data on the national agricultural production of 28 OECD member countries over the period from 1990 to 2003 estimated a mean nutrient-orientated efficiency (NE) score of 0.526. This indicates that the average country should be able to produce their current output with an input vector that contains 47.4% less nitrogen and phosphorous. In terms of NTFP, the OECD achieved an average annual growth of 1.5% over the 14 years period, compared with 0.8% in traditional TFP growth. The difference is due to the allocative efficiency improvements in terms of the use of nutrients. The nutrient-orientated allocative efficiency change was estimated to be approximately 0.7% over the survey period, suggesting that the environmental policies, implemented by many countries, is having a notable effect.

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Appendix 1: DEA method

Data Envelopment Analysis (DEA) is a non-parametric mathematical programming approach to frontier estimation. A number of detailed reviews of the methodology are available in Seiford and Thrall (1990), Lovell (1993), Ali and Seiford (1993), Charnes et al. (1995) and Seiford (1996).

In this appendix, we provide a brief description of DEA in a constant returns to scale (CRS) model where there is data on K inputs (denoted by an input vector \mathbf{x}) and M outputs (denoted by an output vector \mathbf{q}) on each of N firms or decision making units (DMUs). For the i -th DMU these are represented by the vectors \mathbf{x}_i and \mathbf{q}_i , respectively. The $K \times N$ input matrix, \mathbf{X} , and the $M \times N$ output matrix, \mathbf{Y} , represent the data of all N DMUs. The purpose of DEA is to construct a non-parametric envelopment frontier over the data points such that all observed points lie on or below the production frontier.

For each DMU we would like to obtain a measure of the ratio of all outputs over all inputs, such as $\mathbf{u}'\mathbf{q}_i/\mathbf{v}'\mathbf{x}_i$, where \mathbf{u} is an $M \times 1$ vector of output weights and \mathbf{v} is a $K \times 1$ vector of input weights. To select optimal weights we can specify the mathematical programming problem:

$$\begin{aligned} & \text{Max}_{\mathbf{u},\mathbf{v}}(\mathbf{u}'\mathbf{q}_i/\mathbf{v}'\mathbf{x}_i) , \\ & \text{st} \quad \mathbf{u}'\mathbf{q}_j/\mathbf{v}'\mathbf{x}_j \leq 1, j=1, 2, \dots, N, \\ & \quad \mathbf{u}, \mathbf{v} \geq 0. \end{aligned} \tag{A1.1}$$

This involves finding values for \mathbf{u} and \mathbf{v} , such that the efficiency measure of the i -th DMU is maximized, subject to the constraint that all efficiency measures must be less than or equal to one. However (A1.1) has an infinite number of solutions because it is a ratio formulation. To avoid this, we impose the constraints $\mathbf{v}'\mathbf{x}_i = 1$, which provides the linear program:

$$\begin{aligned} & \text{Max}_{\boldsymbol{\mu},\mathbf{v}}(\boldsymbol{\mu}'\mathbf{q}_i) , \\ & \text{st} \quad \mathbf{v}'\mathbf{x}_i = 1 \\ & \quad \boldsymbol{\mu}'\mathbf{q}_j - \mathbf{v}'\mathbf{x}_j \leq 0, j = 1, 2, \dots, N \\ & \quad \boldsymbol{\mu}, \mathbf{v} \geq 0, \end{aligned} \tag{A1.2}$$

where the notation change from \mathbf{u} and \mathbf{v} to $\boldsymbol{\mu}$ and \mathbf{v} reflects the transformation.

Using the duality in linear programming, we can derive an equivalent envelopment form of this problem:

$$\begin{aligned}
 & \text{Min}_{\theta, \lambda} \theta, \\
 & \text{st} \quad -\mathbf{q}_i + \mathbf{Y}\lambda \geq 0 \\
 & \quad \theta \mathbf{x}_i - \mathbf{X}\lambda \geq 0, \\
 & \quad \lambda \geq 0,
 \end{aligned} \tag{A1.3}$$

where θ is a scalar and λ is a $N \times 1$ vector of constants. The value of θ obtained will be the efficiency score for the i -th DMU. It will satisfy $\theta \leq 1$, with a value of 1 indicating a point on the frontier and hence a technically efficient DMU. The linear programming problem in (A1.3) are solved N times, once for each DMU in the sample. A value of θ is then obtained for each DMU.

An additional DEA problem is used to identify the input vector which minimizes nutrient usage (and hence nutrient surplus for a given output vector). It is specified as:

$$\begin{aligned}
 & \text{Min}_{\mathbf{x}_i^*, \lambda} \mathbf{a}_i' \mathbf{x}_i^*, \\
 & \text{st} \quad -\mathbf{q}_i + \mathbf{Y}\lambda \geq 0 \\
 & \quad \mathbf{x}_i^* - \mathbf{X}\lambda \geq 0, \\
 & \quad \lambda \geq 0,
 \end{aligned} \tag{A1.4}$$

where \mathbf{a}_i is the vector of input nutrient contents and \mathbf{x}_i^* is the optimal input vector. One can then use these results to calculate the nutrient efficiency measures using equation (10).

In this paper we use DEAP version 2.1 to calculate the technical efficiency scores and the nutrient efficiency scores (the latter using the cost efficiency DEA option). The software is available at <http://www.uq.edu.au/economics/cepa/deap.htm>. More technical details of this software is presented in Coelli (1996).

Appendix 2: Description of the Country Product Dummy (CPD) method

Missing observations in the prices data were filled using the Country Product Dummy (CPD) method developed by Summers (1973). This CPD method is widely used in many research papers and by various international statistical organizations, including FAO, OECD and EuroStat.

The CDP method presents a simple regression method to estimate the price of a commodity of a country given that the price of this commodity is available at least in one other country. The method postulates that the observed price of the i^{th} commodity in the j^{th} country, denoted as p_{ij} , is the product of three components: the purchasing power parity or the general price level in a country relative to other countries (denoted by PPP_j); the price level of the i^{th} commodity relative to other commodities and a random disturbance term v_{ij} . That is, the model specifies that

$$p_{ij} = PPP_j \times P_i \times v_{ij}, \quad (A2.1)$$

which in logarithmic form becomes

$$\ln p_{ij} = \ln PPP_j + \ln P_i + \ln v_{ij} = \pi_j + \eta_i + u_{ij}. \quad (A2.2)$$

To estimate π_j and η_i , it is possible to apply ordinary least squares to the following model:

$$\ln p_{ij} = \sum_{j=1}^M \pi_j D_j + \sum_{i=1}^N \eta_i D_i^* + u_{ij} \quad (A2.3)$$

where D_j and D_i^* are country and commodity dummy variables, respectively, with the property that $D_j = 1$ if price observation p_{ij} belongs to j^{th} country and 0 otherwise and that $D_i^* = 1$ if price observation p_{ij} refers to i^{th} commodity and 0 otherwise. This model can be estimated easily by a standard econometric software package after imposing one restriction of the form $\pi_j = 0$ (i.e. a base country has $PPP=1$).