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MEASUREMENT OF AGRICULTURAL TOTAL FACTOR PRODUCTIVITY GROWTH INCORPORATING ENVIRONMENTAL FACTORS: A NUTRIENTS BALANCE APPROACH

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 Total Factor Nutrient-Orientated Productivity (*TFNP*) Index, and incorporates a materials balance condition. *TFNP* measures changes in nutrient-orientated efficiency and can be decomposed into efficiency change (*EC*), technological change (*TC*) and nutrient-orientated technological change (*NTC*) 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 *TFNP* 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 of public and political debate. This raises the need to adjust traditional methods of measuring efficiency and productivity in order to take into account the 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 bad output or 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) suggests the use of an alternative modeling approach that uses the materials balance condition in deriving an environmental efficiency measure[2]. This study argues that the environmental pollution was 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 meets the materials balance condition.

[2] Lauwers et al (1999) and Reinhard and Thijssen (2000) also propose efficiency measurement methods that incorporate the use of the materials balance condition. The former study involves the use of DEA while the latter study involves the econometric estimation of a shadow cost system.

In this 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. In this approach the information about materials content of inputs is modeled in a similar manner to which price information is normally incorporated. The environmental efficiency is also decomposed into technical efficiency (TE) and allocative efficiency (AE).

In this paper, we take this nutrients balance approach to measure the environmental efficiency of the national agricultural sector of 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-orientated allocative efficiency (NAE). We also construct a total factor nutrient-orientated productivity (TFNP) index. This index is an environmentally adjusted Malmquist productivity index which incorporates the traditional total factor productivity (TFP) information and environmental concerns.

This 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 total factor nutrient-orientated productivity (TFNP) index is presented in Section 3. The empirical work on national agriculture of OECD member countries for the years of 1990-2003 is discussed in Section 4. A conclusion is provided 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 materials 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, phosphor 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 to 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 changes 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. 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. This paper raises a variety of issues relating to the development of environmental performance indicators. They include 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. The author 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 are run. The first model allows 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 does the same thing, except it imposes 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) adapted 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 suggest scaling the output vectors according to a vector of directions which can be flexibly selected. The direction vector they proposed is 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 $m = 1,2,...M$ outputs, $\mathbf{q} \in \Re_{+}^{M}$ using a vector of $k = 1,2,...K$ inputs, $\mathbf{x} \in \Re_{+}^{K}$. 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

$$\mathbf{z} = \mathbf{ax} - \mathbf{bq} \tag{1}$$

where a and b are vectors of known non-negative constants. Following Coelli, et al. (2007), we allow the possibility that some of inputs could have zero amount of 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 $\mathbf{u}$:

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

The authors define the directional distance function

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

where $\mathbf{g(u,q)}$ 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 $g(-u,q)$ 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 suggests

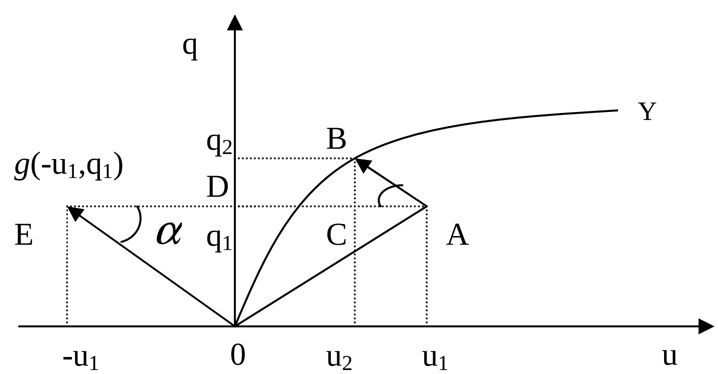
$$u = ax - b\beta q \text{ (i.e. z = u)} \tag{4}$$

$$(2-\beta)u = ax - b\beta q \tag{5}$$

and (4) and (5) give

$$(ax - 2bq)(\beta - 1) = 0. \tag{6}$$

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 (e.g. 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 $tg\alpha = \frac{BC}{CA} = \frac{q_2 - q_1}{u_1 - u_2}$ and $tg\alpha = \frac{OD}{DE} = \frac{q_1}{u_1}$ give $\frac{q_2 - q_1}{u_1 - u_2} = \frac{q_1}{u_1}$. After some arrangement, this gives $\frac{u_2}{u_1} = 2 - \frac{q_2}{q_1} = 2 - \beta$

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

3. Nutrient-orientated efficiency and productivity measures

Reinhard and Thijssen (2000) and Coelli, et al. (2007) proposed 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 is fixed and undesirable outputs are 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 ($N = \mathbf{a'x}$) is minimized[4]. In this method, instead of minimizing inputs, they minimize 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.

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

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

These three input vectors can be 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 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 larger than the line passing through the nutrient minimising point (x_{1e},x_{2e}).

[4] 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.

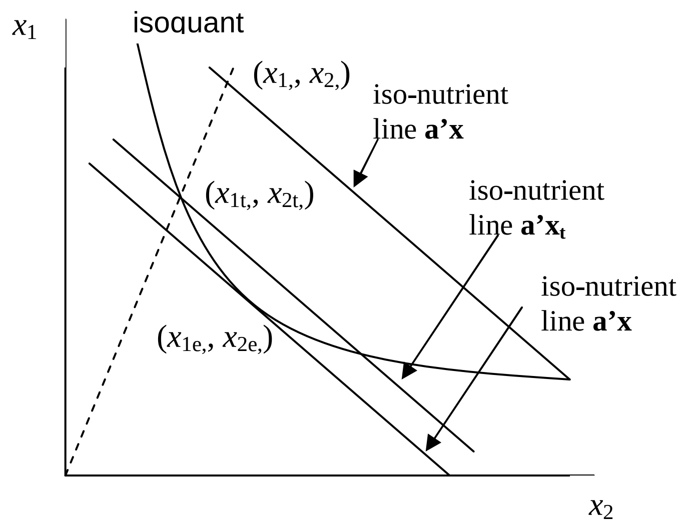


Figure 2: Nutrient minimisation

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

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

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

$$TE = \frac{N_t}{N} = \frac{\mathbf{a'x_t}}{\mathbf{a'x}}\ . \tag{9}$$

Following Reinhard and Thijssen (2000) and 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:

$$NE = \frac{N_e}{N} = \frac{\mathbf{a'x_e}}{\mathbf{a'x}}\ . \tag{10}$$

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

$$NE = TE \times NAE \tag{11}$$

where

$$NAE = \frac{N_e}{N_t} = \frac{\mathbf{a'x_e}}{\mathbf{a'x_t}}. \qquad (12)$$

TE relates to the operation of the firm on the frontier of the production technology (i.e. production possibility curve) while NAE relates to using the correct input mix given the observed nutrient contents. All the 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 the similar procedure of estimating cost efficiency in which the vector of nutrient contents of the inputs (**a**) is used as weights.

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 nitrogen, potassium, phosphor, sulphur or 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) discuss the case when there are two nutrients, which requires two material balance equations. If there are two inputs and one output, the equations are:

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

and

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

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

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

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 (14) 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.

Total factor nutrient-orientated productivity

In this section, we use the nutrient-orientated efficiency measure to construct a Total Factor Nutrient-Orientated Productivity (TFNP) 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 productivity index for period t and $t+s$ is defined as changes in the nutrient-orientated efficiency in period $t+s$ over period t:

$$M_i^t = \frac{NE_i^{t,t+s}}{NE_i^{t,t}} \tag{16}$$

where the first and second superscripts refer to the reference technology and time period respectively. The subscripts *'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, the Malmquist nutrient-orientated productivity index is defined as:

$$M_i^{t+s} = \frac{NE_i^{t+s,t+s}}{NE_i^{t+s,t}} \tag{17}$$

The *TFNP* index is defined as the geometric mean of the two previous indices:

$$TFNP^{t,t+s} = \left[\frac{NE_i^{\ t,t+s} * NE_i^{t+s,t+s}}{NE_i^{\ t,t} * NE_i^{t+s,t}} \right]^{1/2} \tag{18}$$

All NEs in are defined as follows:

$$NE_i^{\ t,t} = \frac{\mathbf{a'x_e^{t,t}}}{\mathbf{a'x^{t,t}}} = \frac{\mathbf{a'x_e^{t,t}}}{\mathbf{a'x_t^{t,t}}} \times \frac{\mathbf{a'x_t^{t,t}}}{\mathbf{a'x^{t,t}}} = NAE_i^{\ t,t} * \times TE_i^{\ t,t} \tag{19}$$

$NE_i^{\ t,t}$ 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 $x^{t,t}$ of time *t* corresponding to a specified output level of q^{t} at time *t*.

$$NE_i^{\ t+1,t+1} = \frac{\mathbf{a'x_e^{t+1,t+1}}}{\mathbf{a'x^{t+1,t+1}}} = \frac{\mathbf{a'x_e^{t+1,t+1}}}{\mathbf{a'x_t^{t+1,t+1}}} \times \frac{\mathbf{a'x_t^{t+1,t+1}}}{\mathbf{a'x^{t+1,t+1}}} = NAE_i^{\ t+1,t+1} \times TE_i^{\ t+1,t+1} \tag{20}$$

$NE_i^{\ t+1,t+1}$ is estimated in a nutrient input-orientated framework and $TE_i^{\ t+1,t+1}$ is estimated in a standard input-orientated framework given a input vector $\mathbf{x}^{\mathbf{t+1,t+1}}$ at time *t+1* corresponding a specified output level of $\mathbf{q}^{\mathbf{t+1}}$ at time *t+1*.

$$NE_i^{\ t,t+1} = \frac{\mathbf{a'x_e^{t,t+1}}}{\mathbf{a'x^{t,t+1}}} = \frac{\mathbf{a'x_e^{t,t+1}}}{\mathbf{a'x_t^{t,t+1}}} \times \frac{\mathbf{a'x_t^{t,t+1}}}{\mathbf{a'x^{t,t+1}}} = NAE_i^{\ t,t+1} \times TE_i^{\ t,t+1} \tag{21}$$

$NE_i^{\ t,t+1}$ is estimated in a nutrient input-orientated framework and $TE_i^{\ t,t+1}$ is estimated in a standard input-orientated framework given a input vector $x^{t,t+1}$ of time *t+1* corresponding a specified output level of q^{t} at time *t*.

$$NE_i^{\ t+1,t} = \frac{\mathbf{a'x_e^{t+1,t}}}{\mathbf{a'x^{t+1,t}}} = \frac{\mathbf{a'x_e^{t+1,t}}}{\mathbf{a'x_t^{t+1,t}}} \times \frac{\mathbf{a'x_t^{t+1,t}}}{\mathbf{a'x^{t+1,t}}} = NAE_i^{\ t+1,t} \times TE_i^{\ t+1,t} \tag{22}$$

$NE_i^{\ t+1,t}$ is estimated in a nutrient input-orientated framework and $TE_i^{\ t+1,t}$ is estimated in a standard input-orientated framework given a input vector $x^{t+1,t}$ of time *t* corresponding a specified output level of $\mathrm{q}^{\mathrm{t+1}}$ at time *t+1*.

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

$$TFP = \left[\frac{TE_i^{t,t+1} \times TE_i^{t+1,t+1}}{TE_i^{t,t} \times TE_i^{t+1,t}} \right]^{1/2} \tag{23}$$

and can be decomposed into

$$TFP = EC \text{ x } TC \tag{24}$$

so we have

$$TFNP_i = TFP_i \times \left[\frac{EAE_i^{t,t+1}}{EAE_i^{t,t}} \times \frac{EAE_i^{t+1,t+1}}{EAE_i^{t+1,t}} \right]^{1/2} \tag{25}$$

and

$$TFNP_i = EC_i \times TC_i \times \left[\frac{NAE_i^{t,t+1}}{NAE_i^{t,t}} \times \frac{NAE_i^{t+1,t+1}}{NAE_i^{t+1,t}} \right]^{1/2} = EC_i \times TC_i \times NTC_i \tag{26}$$

Efficiency change (*EC*) 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. Nutrient-orientated technological change (*NTC*) measures the shift in the environmentally efficient frontier.

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 discussions 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 using 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 graphical presentation of the boundary and the flow of nitrogen in a national agricultural production system. This 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 phosphor fixation. The output side has three main groups: marketed livestock products, marketed crop products, and all nitrogen and phosphor-containing items (e.g. fodder crops, grass, manure) exported to other countries or used for non-agricultural purposes.

The soil surface balance 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. We used the modified farm gate approach in this paper because of following reasons.

First, the modified farm gate method does not estimate the manure excretion of livestock which potentially causes measurement errors. 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. The modified farm gate method does not have manure in the input or output terms since 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, the non-agricultural domestic nitrogen deposition consists of all nitrogen in the air or in the water that enters into the black box through different ways of deposition (e.g. rainfall). These sources of nitrogen exclude nitrogen produced by domestic agricultural activities (e.g. ammonia volatilization from manure and fertilizer), therefore it avoids the double-counting error.

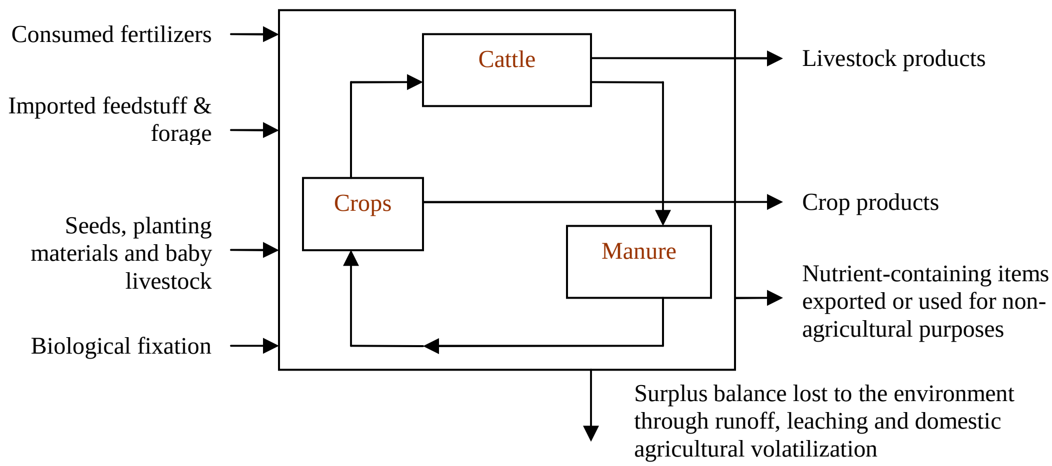


Figure 3: Modified farm gate method of accounting nutrient balance

Thirdly, the computed nutrient balance produced by the modified farm gate method delivers more valuable economic implications than the soil surface method, at least at the national level. 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 production[5]. 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 crops production as a way of 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.

Input and output variables

[5] 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.

The empirical analysis in this paper involves 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 balance[6]. 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.[7]

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 DEA to estimate efficiency scores. 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 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).[8] For

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

[7] 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 heads of stock change to 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 heads into tones 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 were 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 the size.

[8] All aggregation is done using a multilateral Fisher index.

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 phosphor 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 countries[9].

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.[10] 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

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

[10] 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, there are 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.

quantity and price data in some countries because some countries did not produce all items. The zero quantities were left as zeros. Missing prices data were filled using the Country Product Dummy (CPD) method developed by Summers (1973)[11]. 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 (QI_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 ($TN_j = \sum_{i=1}^{K}(x_{ij}n_{ij} + 10x_{ij}p_{ij})$, where n_{ij} and p_{ij} are nitrogen and phosphorous content of single commodity items (x_i) among K items of country j[12]). 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 ($\sum_{i=1}^{K} x_{ij}$).[13]

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

[11] A detailed description of the CPD method is provided in Appendix 1.

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

[13] There were some missing data in the nutrient content of feed and seed commodities. 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 apply 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.

be able to produce their current output with an input vector that contains 47.4% less nitrogen and phosphor.

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

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 levels[14]. Combining these two figures, we observed that the drop in nutrient-orientated efficiency levels in 2002 was due to the drop in the output while the drop in 1991 and 1992 was due to more intensive use of fertilizer.

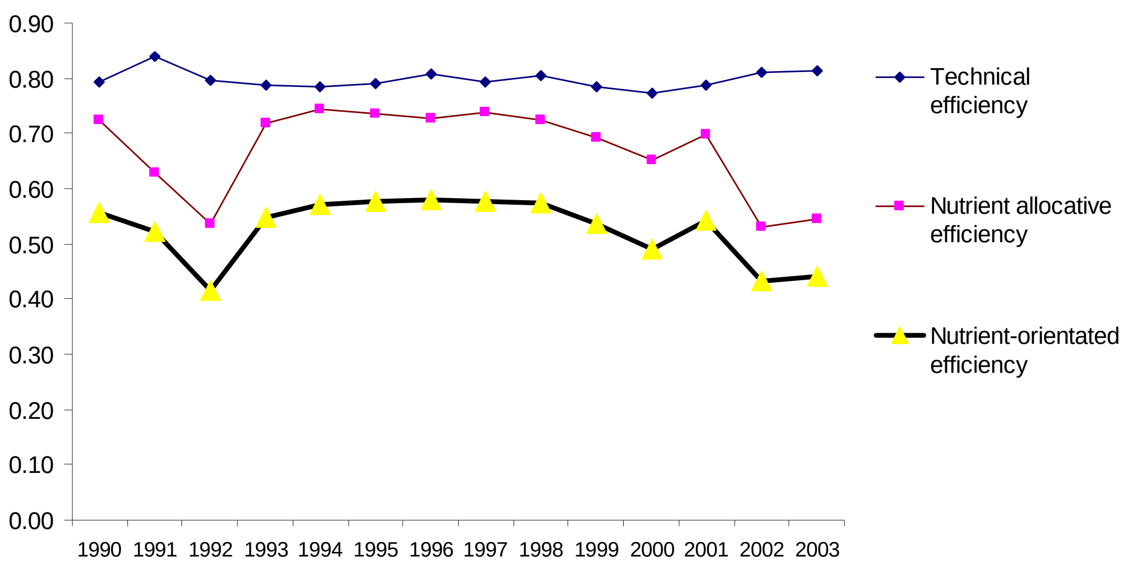


Figure 4: Mean technical, nutrient-orientated allocative and nutrient-orientated efficiency scores

[14] Which are measured by changes of the average values of output quantity indexes.

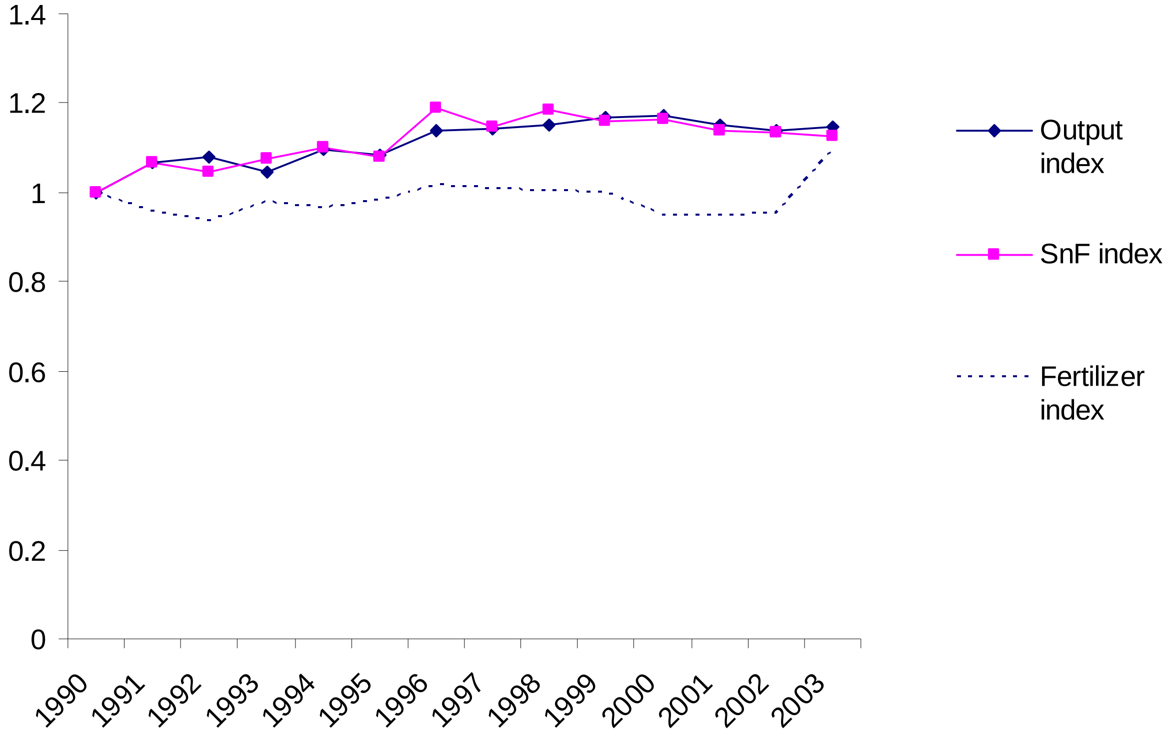


Figure 5: Output and input indices

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 nutrient. 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 phosphorus 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 phosphorus 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 scores[15].

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

[15] 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).

Total factor nutrient-orientated 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 on average gained a mean growth 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 the negative growth in the nutrient-orientated productivity. Among these countries, decreased traditional TFP in eight countries caused the negative growth in TFNP. On the other hand, the negative growth in TFNP 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 TFNP growth. In these countries the reason for the negative TFNP 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 TFNP 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.

It is interesting to note that Netherlands, as the most environmentally efficient country, also experienced negative growth (-0.5%) due to its decrease in the traditional TFP even though the TNC had progressed.

Table 3: Mean productivity index over 1990-2003

Country	Mean TFP	Mean TNC	Mean TFNP
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 and Figure 6 reports the average productivity growth for these 28 countries in each of the years in the 1991-2003 period. There were four years (1993, 1994, 2002 and 2003) that experienced the negative growth in the total factor nutrient-orientated productivity index and the negative growth was caused by both decreased traditional TFP and nutrient-orientated technological regress. From 2000 onwards we see 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 4: mean productivity growth of 28 countries

Year	Mean TFP	Mean TNC	Mean TFNP
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

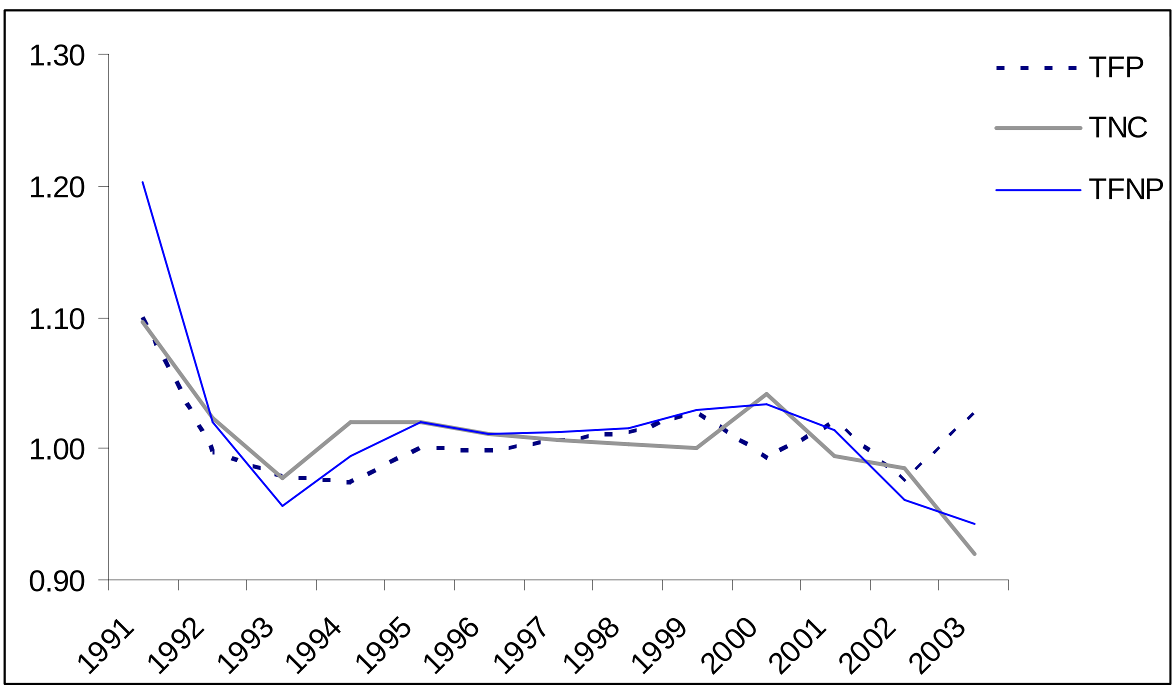


Figure 6: Trends in productivity measures

5. Conclusions

A new environmental productivity index is proposed that measures the changes of nutrient-orientated environmental efficiency over years. The new index, a *total factor nutrient-orientated productivity* (TFNP), is constructed in a similar way to that of the Malmquist total factor productivity (TFP) index. This new environmental productivity index is decomposed into efficiency changes (EC), technical change (TC) and technological nutrient-orientated change (TNC). EC refers to changes in technical efficiency, TC refers to the shift of the traditional production technology while TNC reveals information about the changes in environmental efficiency. 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.

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 phosphor. In terms of TFNP, the OECD gained an average annual growth of 1.5% over the 14 years period, compared with 0.8% of traditional TFP growth. The difference is due to the presence of technological progress in terms of the use of nutrients. The nutrient-orientated technological change was estimated to be approximately 0.7% over the survey period.

Appendix 1: detailed 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 works and by 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 at least in one country is available. The method postulates that the observed price of a commodity (i.e. i^{th} commodity) in a country (i.e. 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 *PPPj*); the price level of the i^{th} commodity relative to other commodities and a random disturbance term v_{ij}. The model says that

$$p_{ij} = PPP_j \times P_i \times v_{ij} \tag{27}$$

In logarithmic form, it becomes

$$\ln p_{ij} = \ln PPP_j + \ln P_i + \ln v_{ij} = \pi_j + \eta_i + u_{ij} \tag{28}$$

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

$$\ln p_{ij} = \sum_{j=1}^{M} \pi_j D_j + \sum_{i=1}^{N} \eta_i D_i^* + u_{ij} \tag{29}$$

where D_j and D_i^* are respectively country and commodity dummy variables 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 value π_j=0 (i.e. a base country has PPP=1).

Appendix 2: Annual mean nutrient-orientated efficiency (NE), technical efficiency (TE) and nutrient-orientated allocative efficiency (NAE) scores from 1990 to 2003

Year	Mean scores			Minimum score			1st quartile (Q1)			3rd quartile (Q3)		
	NE	TE	NAE	NE	TE	NAE	NE	TE	NAE	NE	TE	NAE
1990	0.556	0.792	0.724	0.161	0.218	0.161	0.395	0.702	0.544	0.710	0.846	0.979
1991	0.521	0.840	0.629	0.125	0.355	0.125	0.368	0.771	0.415	0.678	0.869	0.805
1992	0.415	0.795	0.537	0.109	0.330	0.109	0.292	0.718	0.373	0.519	0.788	0.689
1993	0.547	0.788	0.719	0.125	0.375	0.125	0.372	0.659	0.508	0.703	0.769	0.987
1994	0.570	0.785	0.743	0.158	0.366	0.177	0.398	0.677	0.504	0.764	0.807	1.000
1995	0.577	0.790	0.736	0.153	0.393	0.254	0.381	0.667	0.489	0.774	0.797	0.975
1996	0.581	0.808	0.727	0.163	0.432	0.305	0.401	0.699	0.497	0.719	0.858	0.957
1997	0.578	0.792	0.739	0.161	0.375	0.356	0.419	0.693	0.466	0.750	0.801	0.994
1998	0.573	0.806	0.723	0.170	0.392	0.275	0.401	0.693	0.477	0.706	0.899	0.943
1999	0.537	0.786	0.692	0.130	0.394	0.313	0.370	0.659	0.465	0.672	0.835	0.917
2000	0.491	0.772	0.651	0.125	0.402	0.270	0.362	0.612	0.454	0.616	0.764	0.864
2001	0.542	0.787	0.697	0.162	0.390	0.286	0.368	0.629	0.475	0.716	0.787	0.951
2002	0.432	0.812	0.530	0.159	0.431	0.230	0.297	0.692	0.398	0.536	0.808	0.648
2003	0.440	0.814	0.545	0.172	0.448	0.172	0.296	0.685	0.394	0.563	0.841	0.648

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