Analysis of Agricultural Sustainability: A Review of Exergy Methodologies and Their Application in OECD

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ANALYSIS OF AGRICULTURAL SUSTAINABILITY: A REVIEW OF EXERGY METHODOLOGIES AND THEIR APPLICATION IN OECD COUNTRIES

Abstract:

The present paper proposed the combination of Cumulative Exergy Extraction from the Natural Environment (CEENE) and Extended Exergy Analysis (EEA) to analyse international environmental performance in agricultural production. The unified approach allowed the cumulative analysis of comprehensive extraction of all types of resources and services from the ecosystem in agriculture. The analysis, therefore, enabled a more accurate comparison of the environmental performance of different countries or systems based on different indicators of sustainability. The application was conducted for 29 OECD countries for the years from 1990 to 2003 with some important findings. Firstly, the organic contents in top soil, feed and total water withdrawal were the three types of resources that agricultural production extracted most from the environment. Secondly, during the fourteen years surveyed, the efficiency of using exergy in the livestock sector was much lower than the efficiency in the crop sector. Thirdly, the environmental loading of economic investment had increased slightly, implying a minor increase in the pressure on the environment overtime. In addition, the empirical study on OECD countries confirmed that rankings varied widely based on different indicators. The empirical results gave some evidence to support the use of Non-Renewability- Yield Ratio firstly defined in the present paper because the rankings based on this indicator was more consistent with many other indicators.

Keywords: agricultural production, agricultural sustainability, exergy analysis, eco-environmental performance, OECD agriculture, sustainability indicators.

Nomenclature

$\mathbf{x}$	vector of inputs
$\mathbf{q}$	vector of outputs
$\mathbf{c}$	vectors of the (cumulative) exergy contents of $\mathbf{x}$
$\mathbf{d}$	vectors of the (cumulative) exergy contents of $\mathbf{q}$
z	(cumulative) exergy balance

1. Introduction

Literature on sustainable agriculture confirms that agriculture depends critically on the resources and services of the ecosystem. Furthermore, in order to be sustainable, agriculture should enhance the quantity and quality of these resources and services (Abroi and Katyal, 1990, Costanza *et al.*, 1997, Ikerd, 1993, Raman, 2006). Therefore, analysis on the cumulative extraction of the total environmental resources is the core of the investigation of agricultural sustainability. However, few studies take a holistic view in analysing the extraction of total resources of the agricultural production.

Recently exergy analysis has been extensively used in resource accounting, sustainable and environmental economics (Bastianoni *et al.*, 2008, Dewulf *et al.*, 2007, Hau and Bakshi, 2004, Jørgensen *et al.*, 1995, Rosen, 2002). The methodologies of the exergy analysis have been refined to include life cycle assessment and merged with the emergy analysis in some extents (Bastianoni *et al.*, 2008, Bastianoni *et al.*, 2007, De Meester *et al.*, 2006, Jørgensen *et al.*, 1995, Sciubba and Ulgiati, 2005). The core advantage of the exergy analysis is that all inputs including human capital, man-made capital and the resources and services of the ecosystem as well as polluting factors can be compared adequately and scientifically using both exergy content and cumulative exergy content. The uses of exergy content and cumulative exergy content are implicitly imposed by the two thermodynamic laws: the law of energy and mass conservation and the principle of non-conservation of entropy.

There are a number of exergy-based studies in the agricultural industry and these studies were conducted at many scales: farm, sectoral, regional, national and international. Bastianoni *et al.* (2005) constructed four indicies based on exergy and emergy contents to compare the sustainability of wine producing farms in Tuscany and Piemonte in Italy. Among the four indices, the authors argued that ratio of exergy stored in the system to the emergy content in the inputs has high potentiality to become the most ecologically oriented indicator of sustanability in the long run.

Dincer *et al.* (2005) investigated the energy and exergy utilization in the agricultural sector of Saudi Arabia for the years from 1990 to 2001. This study considered the variations of energy and exergy efficiencies for the agricultural sector for its two essential input components: tractors using diesel and pumps using electricity. The study found out that the overall exergy efficiencies was slightly less than the corresponding energy efficiencies. The authors argued that the technique presented in their study is beneficial for analysing sectoral energy and exergy use for providing the real picture of the agricultural industry.

Utlu and Hepbasli (2006) took a similar method to analyse the energy and exergy efficiencies in Turkish agricultural industry for the years from 1990 to 2001. Their estimates for Turkey were lower than the efficiencies in Saudi Arabia reported in Dincer *et al.* (2005). Recently Al-Ghandoor and Jaber (2009) also conducted the similar investigation in Jordan's agricultural industry and found out that the exergy efficiency was much lower than the energy efficiency due to high loss of exergy in space and heating and outdated equipment. Jordan's energy and exergy efficiencies were lower than Turkish and Saudi Arabian efficiencies because of differences in sub-sector structure and the types of energy used.

A number of studies in which the structures of exergy utilization of agricultural industry were discussed relative to the whole the society were done in many countries such as China, Swede, Japan, Norway, Canada, Brazil, Turkey and Italy (see for example Chen *et al.*, 2006, Ertesvåg, 2005, Rosen, 1992, Schaeffer and Wirtshafter, 1992, Sciubba, 2001, Wall, 1977, Wall, 1990). The exergy analysis methodologies used in these studies varied but the results of these studies provided useful evidence for sustainable analysis.

Recently Chen *et al.* (2009) analysed the exergetic efficiency of Chinese agriculture for the years from 1980 to 2000. Extensive exergy accounts were constructed for all the exergy inflows and outflows of the agricultural industry. The exergy inflows include the exergy from free renewable natural resources (such as sunlight, geothermal heat, rain and wind), purchased economic investments (seeds, labour, organic manure, irrigation water, fossil fuels, electricity, chemical fertilizers, pesticides, plastic mulches and mechanical equipments), and environmental emission (due to animal waste, fertilizer, pesticides and plastic mulch). The outflows take into account the exergy in the yield of cropping, forestry, stockbreeding and fishery industries. In this study, topsoil loss was found to be of the same importance as the economic investment as a whole. Animal wastes accounted for most of the environmental emission while fertilizers, pesticides and plastic mulches were the minor pollution sources. The estimated system transformity of exergy was around ten per cent. The study also found that the contribution of the agricultural industry into the main economy was much more than that the investment made by the main economy into the agriculture.

In contrast to the existing literature, the present study investigates the sustainability of agricultural production in an international context using the combination of most advanced exergy analysis methodologies. The objective of national agricultural production systems is limited to two aspects of sustainability: the cumulative extraction of total resources and services of the ecosystem and the cumulative pollution. In this approach, the sustainability of different national agricultural systems are compared by using various exergy-based indicators. The present paper provides an empirical application for 29 OECD countries for the years from 1990 to 2003. The paper is structured as follows. Section 2 describes the main methodologies of exergy analysis. Section 3 provides an overview of the resources and services of the ecosystem and their interaction with the agriculture system. Section 4 establishes the objective function of the sustainable analysis in agricultural production and details all exergy inflows and outflows of national agricultural production systems. Section 4 reviews main indicators of sustainability. Section 5 illustrates the empirical application in OECD countries. Section 6 concludes the paper.

2. The Methodologies of Exergy Analysis

Exergy refers to the usefulness or value or quality of any energy forms Rosen *et al.* (2008). Technically, it is measured using thermodynamics principles as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment (Rosen *et al.*, 2008, Szargut *et al.*, 1988, Wall, 1977). Unlike energy, exergy is not subject to the law of conservation (except for ideal processes). Rather exergy is consumed or destroyed, due to irreversibilities in real processes (Dincer and Rosen, 2007, Wall, 1977).

Originally, exergy analysis uses the conservation of energy principle together with non-conservation of entropy principle for the analysis, designing and improvement of chemical and thermal processes. This method is particularly useful for quantifying types, magnitudes of wastes and losses of energy in the systems. Therefore, it helps identify the margin available to design more efficient energy systems by reducing inefficiencies (Rosen *et al.*, 2008).

Exergy is a measure of the quantity and quality of any matters, materials, and energy forms contained in the stock and the flows of natural resources. By using the exergy, we can describe various types of resources in terms of a common physical unit which is an expression for both the quantity and quality (Ayres and Ayres, 1998, Wall, 1977). Because of this, exergy analysis has been widely used for global, regional and national accounting of natural resources (Ayres and Ayres, 1998, Chen *et al.*, 2006, Dewulf *et al.*, 2007, Hermann, 2006, Wall, 1977) and the measurement of the quality of natural resources (Amini *et al.*, 2007, Chen and Ji, 2007, Silow and In-Hye, 2004).

Exergy analysis has also been extended for cumulative exergy consumption and life cycle assessment as well as the evaluation of the sustainability of industrial products and processes. Industrial Cumulative Exergy Consumption (ICEC) analysis is defined as the measure of the maximum amount of useful energy that can be extracted when matter is brought to equilibrium with its surrounding environments (Hau and Bakshi, 2004). This method analyses the efficiency by considering exergy requirements in the process as well as its supply chain. Exergetic Life Cycle Analysis (ELCA) and Extended Exergy Accounting (EEA) incorporate further the exergy consumption in the demand chain and the exergy consumption in the labour in the ICEC (Cornelissen *et al.*, 2001, Sciubba, 2001). Ecological Cumulative Exergy Consumption (ECEC) analysis includes the exergy content of ecosystem services in the ICEC analysis by taking advantages of information and innovations of emergy analysis[1] (Hau and Bakshi, 2004). The ECEC analysis can be additionally refined to combine the life cycle analysis in the resource accounting (Dewulf *et al.*, 2007). This accounting method was named Cumulative Exergy Extraction from the Natural Environment (CEENE) which quantifies the eight categories of exergy "taken away" from natural ecosystem: renewable resources, fossil fuels, nuclear energy, metal ores, minerals, water, land and atmospheric resources.

Dincer and Rosen (2007) provide an interesting discussion on the interdisciplinary triangle by the field of exergy analysis with energy, environment and sustainable development. Undoubtedly, energy resources are needed for the societal development but the consumption of energy has caused adverse effects on the environment. Sustainable development requires the sustainable supply of energy resources that is available not only to the current generation but also to future generations. Exergy analysis first and foremost helps improve the energy efficiency, which in turns reduce environmental pollution and increases the availability of energy resources for future uses. More importantly, exergy analysis has also been an extremely useful tool in designing and measuring the efficiency of processes of sustainable energy production (i.e. Joshi *et al.*, 2009, Midilli and Dincer, 2007, 2009, Midilli *et al.*, 2006).

These methods have been extensively used in many applications including the following main areas: society exergy accounting for the use and conversion of natural resources in many countries (e.g. Chen and Chen, 2007a, b, c, Chen and Chen, 2007d, e, Ertesvåg, 2001, 2005, Ertesvåg and Mielnik, 2000, Gasparatos *et al.*, 2009a, b, Schaeffer and Wirtshafter, 1992, Wall, 1987, 1990), the analysis of environmental health and sustainable development (e.g. Jørgensen *et al.*, 2008, Meyer *et*

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[1] The emergy analysis is another thermodynamic approach which was developed and has been used for the analysis of ecological and economic systems. Literature review on emergy analysis is available at www.emergysystem.org. Detailed discussions on differences between emergy analysis, energy analysis and exergy analysis are discussed widely in the relevant literature (see for example Bastianoni *et al.*, 2007, Brown and Herendeen, 1996, Herendeen, 2004, Sciubba and Ulgiati, 2005).

al., 2009, Rosen, 2002, Rosen *et al.*, 2008, Sciubba *et al.*, 2008) and the efficiency analysis of many economic industries such as transportation, electricity, and fuel production (e.g. Coskun *et al.*, 2009, Dewulf and Van Langenhove, 2003, Dewulf *et al.*, 2005, Ji *et al.*, 2009, Saidur *et al.*, 2007, Utlu and Hepbasli, 2007). The exergy required to convert the waste back to useful matters was also conducted for the life cycle of plastic (Dewulf and Langenhove, 2004).

3. Agriculture, Ecosystem and Sustainable Agriculture

Agriculture depends critically on ecosystem resources and services. Ecosystem resources and services consist of flows of materials, energy, or information from the natural capital stock combined with manufactured and human capital stocks to produce human welfare (Costanza *et al.*, 1997, Raman, 2006). They serve as critical inputs into agricultural production such as air, sunlight, water, and organic matters, biological communities and micro-organisms attached with land. The ecosystem resources and services also serve as sink for wastes from the agricultural production and consumption of food.

Insert Figure 1

Following Sollner (1997), Figure 1 illustrates the interaction between the agriculture and non-agriculture with the ecosystem. The dotted boxes refer to the boundary of activities which involve the loops of money exchanges. The whole economy consists of agriculture and non-agriculture. The agricultural system covers activities related to agricultural production, consumption and recycling. The ecosystem resources and services such as sunlight, air, water, organic matters and biological communities attached with land lie outside the dotted boxes since they are currently not related to any money-exchange activities. The dotted box can be expanded to include these resources and services if there are some schemes to internalize these into the circular exchange loops.

The most basic function of agriculture is to produce food for the human. The human population keeps increasing while the scale of agriculture is constrained by ecosystem resources and services. As a result, the output expansion has become the primary objective of sustainable agriculture. The present study, therefore, focuses on the production side.

Sustainable agriculture means different things to different groups of people (Douglass, 1984). However, there are some features attached to a "sustainable agriculture" system when it is considered as a component of an economy in a larger ecosystem. The following criteria adopted by 350 agricultural scientists are widely known (Abroi and Katyal, 1990). A sustainable agriculture is one that, over the long term: (1) enhances environmental quality and resource based on which the agriculture depends; (2) provides for human fibre and food needs; (3) is economically viable; and (4) enhances the quality of life for farmers and society as a whole.

The first feature is a necessary foundation for an agricultural system to meet the other three criteria of sustainability. Ikerd (1993) argued that an agriculture which fails to conserve resources, protect the environment, and produce efficiently, will not be economically viable and fail to enhance the quality of life for farmers and society as a whole. By failing to conserve and protect environmental resource base, the system will face decreasing productivity and eventually lose productive ability. Failing to protect the environment, the system eventually produces more harm than good. Inefficient use of resources will not generate enough profits to enhance or even maintain the quality of life for producers and the society as a whole.

Agricultural production activities have bad influences on the quality of the environment via two main pathways. Firstly, the production extracts the natural resources and this reduces the availability of the resources for next generations. For example, crops extract water or fishery extracts various species from biological communities in river and sea systems. Secondly, the environmental effects (for example pollution) caused by agricultural production activities themselves as well as the production of inputs used in agricultural production degrades the quality of the environment. For example the nitrogen surplus sent to the environment has been blamed for eutrophication problems or the production of electricity, fertilizer, pesticides, and the operation of irrigation water have contributed to the total gas emission. On these grounds, the sustainability of agricultural production first and foremost deals with two core aspects: cumulative and total resource extraction and cumulative and total pollution.

4. Unified Approach in measuring cumulative and total resource extraction and pollution in agricultural production

Unified approach

To investigate the efficiency of using cumulative extraction of total resources and services of the ecosystem in the analysis of sustainable agriculture, the present study combines the approaches of Cumulative Exergy Extraction from the Natural Environment (CEENE) and Extended Exergy Analysis (EEA). Following Ayres and Ayres (1998) and Rosen (1999), a simple mathematical expression of the combined approach is:

$$z = \mathbf{c'x} - \mathbf{dq} = loss + waste \tag{1}$$

where **x** and **q** are vectors of inputs and outputs of a system and **c** and **d** are strictly positive vectors of exergy contents in inputs and outputs.

There are some important implications in Equation 1. Firstly, exergy content is a natural measure of the physical values of the quantity and quality of all types of the resources and services of the environment. Exergy content is also a measure of all types of inputs and outputs of agricultural production. This suggests that by using exergy contents, all inputs and outputs are now comparable using the physical common unit of exergy.

Secondly, vectors **c** and **d** in Equation 1 represent the exergy contents of industrial inputs (i.e. fertilizers, pesticide, fuels, electricity) as used in original exergy analyses. Industrial Cumulative Exergy Consumption (ICEC) method accounts for cumulative consumption of exergy in these industrial inputs by expressing **c** and **d** as vectors of the cumulative exergy contents of industrial inputs. The CEENE further extends the cumulative exergy vectors to include the cumulative extraction of exergy from all relevant services and resources of the ecosystem. CEENE also takes into account the use of ecosystem services and resources as the sink for the waste from agricultural production as well as the production of industrial inputs. EEA further allows the expansion of vectors **c** and **d** to account for labour and other monetary inputs of agricultural production (i.e. expenses on research and development, marketing, and education). By combining CEENE and EEA, Equation 1 becomes:

$$cumulative\ z = \mathbf{c'x} - \mathbf{dq} = cumulative\ loss + cumulative\ waste \tag{2}$$

where **c** is the vector of cumulative exergy contents of all industrial, economic, and ecosystem inputs.

We note that both Equations (1) and (2) strictly regulated by the second laws of thermodynamics which implies that the exergy is not conserved but destroyed during the production process. The total exergy in the inputs (equal to **cx**) is partly destroyed and partly converted to good outputs (**bq**) and *waste*. The *loss* in Equation (1) refers to the amount of exergy which is destroyed while the *waste* refers to the amount of exergy contained in matters which actually or potentially causes pollution. Similarly after the deduction of cumulative loss of exergy, the cumulative exergy in the inputs (**c'x**) is converted partly to good output (**bq**) and partly sent to the environment as *cumulative* *waste*. In other words, Equation (2) is also a simple representation of the life cycle assessment of the effects on the environment.

Inputs and outputs

The inputs and outputs are defined by the boundary of agricultural production system in relation to a larger economic system which is a sub-set of the ecosystem. The standard statistical classification of national agricultural production activities includes four sectors: crop, livestock, fishery and forestry. Some empirical studies analysed all of these four sectors (Chen and Chen, 2007a, b, Chen *et al.*, 2009). Our empirical study on OECD countries, however, limits the boundary to crops and livestock sectors only. This is because these two sectors are the primary sources of economic incomes for farmers and the primary sources of environmental pollution in OECD countries (OECD, 2008). Table 1 lists the relevant input and output items which are related to the crops and livestock production.

There are four groups of inputs and outputs in Table 1. The three items in Free Renewable Resources (FR) actually are basic resources and services that the ecosystem serves the production of livestock and crop. These resources and services are for free use and renewable. Two items in Free Non-Renewable (FN) resources include the loss of organic matter in the top soil due to cropping and the use of ground and surface water. Labour is considered as Purchased Renewable resources (PR) because farmers have to purchase these resources. The five items in Purchased Non-renewable resources (PN) cover all purchased resources which are not renewable. The cumulative exergy consumption is used to capture the total extraction of resources and services of the ecosystem using the life cycle assessment approach. All purchased resources also represent economic investment by the whole system in the production process. In the output side, all the desirable outputs of the production are classified into crop products and livestock products. As in Figure 1, these outputs flow directly from production box to consumption box.

Insert table 1 here

Different from the previous studies, the present study investigates the exergy efficiency in an international context. The international analysis facilitates the relative efficiency comparison of different countries. There are two potential important contributions of the international comparison analysis into policy consideration. First, the relative comparison provides individual countries with benchmarks as well as the peers so that they can learn lessons from to improve the efficiency. Secondly, the relative efficiency scores can be used further in other econometric analysis to identify the factors which determine the difference in efficiency scores among countries. While the present study addresses the first issue, the second issue will be examined in a future study.

5. Indicators of sustainable agriculture

Following Brown and Herendeen (1996), Brown and Ulgiati (1997) and Odum (1996), the indicators are defined in the following sections to illustrate different aspects of the sustainability of the defined agricultural production.

$$\text{Renewability Index: } RI = (FR + PR)/(FR + FN + PR + PN) \quad (3)$$

RI is the ratio of renewable resources (free and purchased) to total resources extracted. Higher value of RI suggests a higher level of agricultural production sustainability. In the long run, only systems with higher renewability index are sustainable.

$$\text{Environmental Loading of Investment: } ELI = (PR + PN)/(FR + FN) \quad (4)$$

This indicator is defined as the ratio of total exergy of economic investment to total exergy of free ecosystem resources and services. This indicator measures the loading of economic investment on the local natural resource associated with agricultural production. During the production process, exergy is destroyed (i.e. loss of exergy) or lost to the ecosystem (i.e. waste of exergy). The majority of exergy lost to the environment are contained in many forms of polluting matters (for example CO and NO) which suggests the loading to the environment. Higher ELI suggests higher environmental loading or higher free environmental resource costs associated with the economic investment. This indicator reveals the intensity of economic investment in agricultural production and is a measure of the ecosystem stress due to production activity. Lower ELI suggests less intensive investment or less pressure on the environment.

$$\text{Investment-Yield ratio: } IYR = (PR + PN)/Y \quad (5)$$

This is the ratio of total exergy in the purchased (renewable and non-renewable) resources to total exergy in the outputs. This ratio indicates the exergy efficiency of the system to make use of economic investment. Lower IYR implies higher exergy efficiency of using the economic investment in producing desirable outputs (i.e. food).

$$\text{Ecosystem Resource-Yield ratio: } ERYR = (FR + FN)/Y \quad (6)$$

This indicator is defined as the ratio of total exergy in the resources and services of the ecosystem extracted by the production process. This index indicates the intensity of the environmental resource contribution to the production system. The system with higher ratio depends more on the ecosystem resources and services.

System transformity: $STr = (FR + FN + PR + PN)/Y$ (7)

As the total exergy extracted from the ecosystem divided by the total exergy in outputs, this indicator measures the input expended in the yield of one unit of output and stands for the overall system transformity for the whole production system. This indicator is the sum of *IYR* and *ERYR*. Larger the values of STr, lower efficiency levels of the system.

Non-Renewability Yield Ratio: $NRYR= (FN+PN)/Y$ (8)

This ratio is related to RI and exergy loss and waste of agricultural production. The exergy balance condition regulates any exergy-consuming processes. Obviously, this condition also is applicable to agricultural production.

Using Equations (2), (7) and (9), we have: *NRYR = (1 – RI) / (1 –Cumulative Loss – Cumulative Waste)*, where *Cumulative Loss* and *Cumulative Waste* are the ratios of cumulative exergy which have been lost and emitted to the environment to total exergy in inputs. This equation implies that NRYR can be a good aggregate index of the sustainability of agricultural production because it embodies renewability, cumulative loss and cumulative waste. A larger NRYR implies that the system is less sustainable.

Following Hoang and Alauddin (2010), we also propose a new indictor named Total Exergy Extraction – Value Yield Ratio (*TEEYR*) which establishes the connection between total and cumulative resource extraction and economic value of production.

$TEEYR = (FR + FN + PR + PN)/YV$ (9)

TEEYR is calculated as the ratio of total exergy extraction to the purchasing power parity (PPP) USD value of production outputs, therefore has a unit of total exergy extraction per one PPP dollar of production output. PPP value of production is used to make the indicator internationally comparable using the concept of the law of one price. A higher value of *TEEYR* suggests that the system extracted more exergy to produce one internationally comparable dollar of output. A lower value of *TEEYR* is desirable.

6. OECD empirical study

Recently there are a number of studies investigating the environmental performance of agricultural production in OECD countries for the last two decades (see for example Hoang and Coelli, 2009, Hoang and Alauddin, 2010, OECD, 2008). Among these studies, OECD (2008) provides the most comprehensive investigation since it looks into many aspects of environmental performance including the use of chemical inputs (fertilizers and pesticides), the use of water and energy, and the changes in land use. However, indicators used by OECD are only partial. Therefore, the assessment faces a problem of comparing among different types of pollution as well as integrating the use of different types of environmental resources. Other studies paid their focus only on the efficiency of nutrients such as nitrogen and phosphorus. To further facilitate these research efforts, the present study used OECD dataset to illustrate the application of the proposed unified approach in analysing the total and cumulative resource extraction and pollution caused by the crop and livestock production in OECD countries.

Data source

Data are required for quantities and cumulative exergy contents for all inputs and outputs specified in Table 1. The sources for quantity data are from Food and Agriculture Organisation (FAO), OECD, and EuroStat. The data on cumulative exergy contents are from a variety of sources. Detailed description of sources, calculation equations, assumptions and treatment made to missing values are in Appendix 1.

The exergy from the solar radiation, wind and geothermal heat are computable using the suggestion by emergy analysis (see for example, Brandt-Williams, 2001, Odum, 2003). The fact was that the exergy amount supplied by these services of the ecosystem was largely dominant with respect to other inputs, making the analysis less sensible to the variation of the other inputs. Because of this, this input term (FR1 in Table 1) was dropped in our reported results and this requires special care with the interpretation of some of the generated indicators such as Renewability Index, Environmental Loading of Investment, Ecosystem Resource-Yield Ratio and System Transformity. However, we believe that in the future when the utilisation of these exergy resources becomes more significant (for example by using more wind-based and solar-based energy generators by the farmers), these exergy inputs should be considered carefully.

Ideally the cumulative exergy content of purchased renewable and non-renewable resources listed in Table 1 should be used. But data on the cumulative exergy contents were not fully available and the following treatments were made. Firstly, following Fukuda (2003), the exergy content of labour (GJ/1000 working hours) is the metabolizable energy of food consumption. Secondly, cumulative energy consumption in the production of machinery, fertilizers, and pesticides were used. Thirdly, direct energy consumption of concentrated pig feed reported in van der Werf *et al.* (2005) plus metabolizable energy of feed were used. Fourthly, only metabolizable energy of seed was included and this underestimated the exergy consumption for this item. Fifthly, total on-farm energy consumption was used. This data was reported by OECD and covered the energy consumption for irrigation, drying, horticulture, machinery, livestock housing, forestry, fishing, and hunting. We were not able to separate the energy for the crop and livestock sectors from this total on-farm energy consumption and hence we acknowledged the actual exergy consumption in the crop and livestock sectors in the empirical study was overestimated. Lastly, buildings, other man-made capital and other services such as research, development, and training were ignored because of data unavailability.

For free renewable and non-renewable resources listed in Table 1, exergy content was used and this treatment was in line with other empirical studies (Brandt-Williams, 2001, Chen *et al.*, 2009, Dewulf *et al.*, 2007, Odum, 1996). We highlighted following calculation notes: (1) Exergy content for non-agricultural nutrient atmospheric deposition was assumed to be the total exergy content of Mg(NO3)2 which deposited to the land from non-agricultural sources; (2) The estimation of exergy in total evapotranspiration and run-off and top soil loss was based on the average evapotranspiration and run-off rates and total loss from top soil (which were reported on EmergySystems.org) multiplied with total area of permanent crops, meadows and pasture land measured; (3) Gibbs free energy was used for water withdrawal; and (4) metabolizable energy was used for crop and livestock outputs.

The estimation of the PPP value of production requires data on prices of the outputs. Data on prices of outputs are the producers' prices from FAO and are not complete. Missing prices data were filled using the Country Product Dummy method developed by Summers (1973). Detailed discussion of this estimation is provided in Hoang and Coelli (2009).

The exergy content of the crop and livestock outputs are metabolizable energy which equals the total amount of joules in fat, protein and carbohydrate compositions in 100 g of edible crop and livestock products. Both food composition databases of FAO and U.S. Department of Agriculture (USDA) were used to estimate the average values of joules in each food items.

Exergy Balance Sheet

Table 2 reports the exergy balance of the mean OECD country which was averaged for the 14-year period from 1990 to 2003. The annual total extraction is estimated to be around $7.263*10^8$ GJ of which 56.13 per cent came from the free resources (note that solar radiation, wind and geothermal heat were not included) and 43.87 per cent was from the investment. This finding suggests that the more than 50 per cent of resources consumed cumulatively by agricultural productions were not priced. In order words, these resources stayed outside the dotted box of Figure 1. If there is no mechanism to involve the commercial exchange of these resources in the market, the prices of inputs and outputs are unlikely to capture the actual extraction of resources by agricultural production activities in OECD. The renewable resources accounted for a negligible 0.48 per cent of the total extraction, leaving 99.52 per cent of the total extraction from the non-renewable resources. This is another alarming finding for OECD agriculture since their farming practice was too dependent on non-renewable resources.

The three important sources of exergy for agricultural production were the organic content in top soil, feed and total water withdrawal, totally accounting for more than 91 per cent of total exergy extraction. The organic matter in the top soil was identified the largest source of exergy in agriculture, contributing 45.29 per cent of the total extraction. This finding further strengthens alarming states of soil erosion and land quality degradation in OECD (see for example Boardman and Poesen, 2006, Francaviglia, 2003). The extraction of resources in the forms of feed accounted for 35.21 per cent while the total exergy extraction from water accounted for 10.61 per cent.

The total economic value of the crop and livestock products was estimated to be around $8.947*10^8$ USD millions which has been adjusted for purchasing power parity among OECD countries. If this economic value reflected the exergy in the outputs, we would be able to estimate the unit price of every useful GJ equal to US$1.619 million (i.e. = (YV1+YV2)/ (Y1+Y2) in Table 2). When this unit economic value of GJ was priced for free non-renewable and purchased resources, the shadow economic value of the exergy balance was the loss of US$ $2.815*10^8$ millions.

Using Equation (1), the annual cumulative exergy balance of the mean OECD country was estimated to be around $1.738*10^8$ GJ, accounting for nearly 24 per cent of total exergy input. This balance was consisted of two components: *loss* and *waste*. The exergy loss referred to the amount of exergy destroyed in the production process. The exergy waste referred to the amount of exergy left in matters with high entropy level. These matters actually or potentially cause environmental pollution which degrades the quality of the total environment. As noted earlier this balance however did not take into account exergy from the sun, winds and geothermal heat therefore it underestimated the loss of exergy[2]. The input side did not account for cumulative exergy in buildings and other services hence the balance underestimated the pollution. Equation (1), however, is not able to separate loss and waste from the balance, making it impossible to analyse the magnitude of pollution caused by agricultural production.

Insert table 1 here

Relative performance of crop and livestock sectors

Further classifying exergy flows in Table 2 also facilitate the relative comparison of crop and livestock sectors. Following Hoang and Alauddin (2010), the entire production system can be viewed as the farm which is mixed between crop and livestock farming activities. The inputs and outputs in Table 1 describe the external flows of exergy coming into and coming out from the gate of this mixed farm. However there are two important internal flows of exergy inside the farm: (1) the crop sector also supplies forage which is used internally by the livestock and (2) the livestock sector produces excreta (i.e. manure) which are consumed by the crops. These two internal flows reflect the recycling of the nutrients, which has influence on the nutrient balance of the whole system. High internal use of manure implies that less nutrient sent to the environment (as *waste*), suggesting that less pollution. Similarly high use of forage means that less loss and waste of exergy.

A simple indicator used to compare the relative performance of the two sectors is transformities defined as the ratios of the exergy in inputs used in each sector to the exergy in corresponding output. Tables 3 and 5 report the relative performance of the two sectors for the mean OECD using the annual data for the years from 1990 to 2003 under two scenarios: full recycling of manure for crop production and no recycling of manure. We highlighted some important notes on the data used in these tables. Firstly, data mainly came from data on Table 2 and footnotes in Tables 3 and 5 described the details. Secondly, some inputs in Table 2 such as water, labour and energy were shared by the two sectors but data for each sector were not available. The exergy proportions in the outputs of each sector (i.e. Y1/(Y1+Y2) and Y2/(Y1+Y2)) were used to derive the exergy proportion in these inputs. Thirdly, exergy in the milking machinery was for the livestock sector

[2] When exergy from solar radiation, winds and geothermal heat were considered, the exergy balance was around 99 per cent of the total and cumulative exergy, suggesting that 99 per cent of the total exergy from the ecosystem was destroyed and lost.

while exergy in tractors, threshers and harvesters was for the crop sector. Fourthly, the exergy in manure equalled to (the ratio of nitrogen in manure to nitrogen in livestock output- Y2)*(exergy in Y2) and the exergy in forage equalled to (the ratio of nitrogen in forage to nitrogen in crop output- Y1)*(exergy in Y1)[3].

Insert tables 2 and 3 here

Due to data unavailability on how much manure was utilized by the crop sector in OECD countries, we used two extreme scenarios: one when all the manure was recycled and one when zero manure was recycled and the respective results were detailed in Tables 3 and 5. When all manure of the livestock sector was used by the crop sectors and all the forage were consumed by the livestock, the transformity of the crop sector was much higher than the transformity of the livestock sector, suggesting that the efficiency of converting exergy in the former sector was much smaller than the latter sector. At the other extreme, when there was no recycling of the manure, the exergy efficiency of the crop sector became much higher than the efficiency of the livestock sectors.

Even these two extreme scenarios might not have happened in OECD countries over the years surveyed but the implication suggests that the recycling of manure plays an important role in analysing the relative performance of the two sectors in national or international contexts. National statistics on how the consumption of manure is important and these statistics further facilitate the sector-wise analysis on the agricultural sector. This, in turn, supports the environmental analysis for policy implications. For example, Oenema (2004) provides a good discussion on the issues related to manure policies, manure markets and environmental performance of farms in European agriculture.

Indicators of agricultural production sustainability

Table 5 presents the values of the seven indicators of the sustainability of agricultural production. Within our literature review, there was not any national and international study which is similar to our investigation. Because of this, we were not able to make the comparison of OECD countries with non-OECD countries. We however hope that these results can be used as benchmarks for

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[3] This calculation rests on the assumption that the exergy is proportional to the ratios of nitrogen content in manure (forage) to nitrogen content in the livestock output (crop output). This treatment was chosen since the exergy content data on forage and manure were not available.

future studies. Our following discussions are for descriptive purposes. Another important note on these indicators is that the exergy from solar radiation, winds and geothermal heat were not included.

The Renewability Index implies that only 0.5 per cent of the total cumulative extraction was the renewable resources including evapotranspiration, water run-off, nutrient atmospheric deposition, and labour, leaving 99.5 per cent of the total cumulative extraction of non-renewable resources. This result reported an alarming status of resource extraction in OECD agriculture. Environmental loading of the investment was estimated around 0.781, suggesting that total exergy of the purchased inputs was 78.1 per cent of the free resources from the ecosystem. It should be noted that this result might underestimate the loading of the investment on the environment because main resources such as top soil nutrients and water were included in free non-renewable resources, making the value less than 1. If water and top soil nutrient were included in the purchased investment, the value for environmental loading index would be more than 444, meaning the amount of investment (mostly purchased non-renewable resources) put high pressure on the environment.

There was little difference between the Investment-Yield and Ecosystem Resource-Yield indexes. We note that the values of these indexes were less than unity because exergy from solar radiation, winds and geothermal heat was dropped. This confirms that the exergy from these resources and from top soil nutrients and water had a significant contribution of the exergy in the outputs.

The system transformity of 1.315 interprets that in order to produce one GJ of the agricultural outputs the mean OECD country used 1.315 GJ of different resources. When solar radiation, winds and geothermal heat were accounted for, the system transformity was about 2138, which means that only 0.05 per cent of the total system exergy was cumulatively converted into desirable food in OECD agriculture.

The Non-Renewability - Yield Ratio of 1.308 entails that for every GJ of outputs, the OECD used 1.308 GJ of non-renewable resources. The Total Exergy Extraction – Value Yield Ratio of 0.812 means that in order to produce one billion of USD dollar of crop and livestock outputs, OECD extracted cumulatively a total exergy amount of 0.812 GJ.

Environmental performance over time

Figure 2 illustrates the values of the seven indicators of the agricultural sustainability for the 14 years surveyed. There were some key findings. Firstly, renewability index had decreased marginally in its values, suggesting that the proportion of renewable resources in total resources had declined marginally and the proportion of non-renewable resources had increased marginally. Secondly, the environmental loading of economic investment had increased slightly, implying a slightly increased stress on the environment. The reason for these trends was due to increased consumption of purchased non-renewable resources which was caused mainly by increased consumption of feed. Thirdly, there were some fluctuations in the system transformity and Investment-Yield indexes during the early 1990s and this was caused by the fluctuations in the outputs as depicted in Figure 3. It should be noted that it appears low correlation of increased consumption of purchased resources (including feed) and outputs, implying that increased consumption of purchased outputs does not secure an increase in outputs. The reason might be because the output also depends on weather conditions which in turn are determined by long term effects of the consumption of non-renewable resources and pollutions. Another trend diagnosed in Figure 2 is that the Total Resource Extraction – Yield Ratio (in Equation 8) had dropped in its value significantly from 2.057 to 0.313 (GJ/PPP million USD). As shown in Figure 3, this drop was mainly caused by the increase in the economic value of crops and output outputs which was driven by increases in the prices of the outputs.

Insert figures 2 and 3

OECD rankings

Table 6 lists the rankings of 29 OECD countries in terms of seven indicators discussed in Section 5. The rankings varied among the indicators and interpretations should be taken with high caution. For example, Denmark was ranked in the first position in terms of Ecosystem Resource-Yield Ratio but was ranked the last positions in terms of Renewability Index and Environmental Loading of Economic Investment. Another example is Mexico which performed very well in term of Environmental Loading of Economic Investment but very badly in terms of Ecosystem Resource-Yield Ratio, System Transformity and Non-Renewability Yield Ratio.

Table 7 details the p-values of pair-wise Kendall ranking tests for these indicators. We observed that the ranking based on Non-Renewability Yield Ratio is not significantly different from the rankings based on Investment-Yield Ratio, Ecosystem Resource-Yield Ratio and System Transformity. Within this empirical study on OECD, Non-Renewability Yield Ratio appears to provide the most consistent rankings. Based on this indicator France, Greece and Turkey were the top performers while Iceland, Mexico and Japan were the worst performers.

The success of France was due to the high exergy in the crop and livestock outputs. The total exergy in the outputs of France was the same that of Canada but the French cumulative resource extraction was less than half of Canadian cumulative extraction. Similarly for the case of Greece, its total output exergy was around 4 per cent higher Denmark's output but the cumulative extraction was less than 70 per cent of the cumulative extraction of Demark. Turkey posed an interesting case with the first rank in terms of Total Exergy Extraction - Yield Value Ratio. This performance of Turkey was also reported in Hoang and Alauddin (2010) in terms of eco-environmental performance defined as the ratio of economic value to the farm gate nitrogen balance.

Iceland presented a very interesting story in OECD. Its agriculture has been characterised by small land and intensive livestock sector. During 1990 – 2003, more than 99.5 per cent of its agricultural land was devoted for permanent meadows and pastures which supplied the forage for the livestock. The livestock output was around 95 per cent of total exergy output (i.e. in GJ) and 94 per cent of total economic value (in PPP USD). Diary, beef and sheep farming accounted for the largest proportion of the livestock production (i.e. more than 70 per cent). Due to intensive grazing practice, the exergy in the organic carbon contained in the top soil became one of the main exergy input source. The fact was than during the years surveyed, more than 80 per cent of Icelandic cumulative resource extraction was from the top soil nutrients. This fact was further supported by alarming evidence of soil erosion and land degradation reported in many other studies (see for example Arnalds and Barkarson, 2003, OECD, 2001).

Mexican agriculture was also characterized by nearly 75 per cent of agricultural land for permanent meadows and pastures. As reported in other studies, due to overgrazing, many parts of Mexico had experienced serious soil erosion and land degradation (i.e. Borejsza *et al.*, 2008, Cotler and Ortega-Larrocea, 2006, Institut de Recherche Pour le Développement, 2009). The finding of the present paper provided further evidence of large extraction of resources by gazing in Mexico: top soil loss was estimated to be around 85 per cent of total cumulative resource extraction. Additionally the efficiency of exergy conversion in the livestock sector was much lower than the crop sector (i.e. livestock sector accounted for 11 per cent of the total exergy output while used 70 per cent of cumulative resource extraction). In terms of economic value, the livestock sector created nearly 47 per cent, confirming that livestock is an important economic sector in Mexican agriculture. This implies that domestic policies should pay more attention to improve the efficiency in the livestock sector to make the total agricultural sector more sustainable.

Insert tables 6 and 7

In terms of Exergy Output - Yield Value Ratio, Turkey, Italy and Korea scored the best ranks while Canada, United States and Ireland were in the bottom of the list. Since this indicator is determined partly by the economic value of the output which is influenced by many factors. Those factors include but are not limited to competition in the national and international markets, the changes in the prices due to the demand and supply effects, and the support from the government and domestic markets. While in-depth analysis on these interrelationships goes beyond the scope of the present paper, we also wanted to shed some lights on the relationship between the environmental performance and the support from domestic policies.

Table 8 reports the share of the Market Price Support (MPS) of the total economic production value for non-European Union countries. Market Price Support (MPS) refers to the annual monetary value of gross transfers from consumers and taxpayers to agricultural producers, arising from various policies that create a gap between domestic market prices and border prices. PSE (2009) estimates annual MPS for all individual agricultural commodities at the farm gate level. The share is calculated as the ratio of MPS of all commodities to the total economic value (using the producer prices). PSE (2009), however, only publishes the data for European Union (EU) and non-EU countries only.

Table 8 provides some preliminary evidence that those countries with high domestic policy support would score worse in terms of Exergy Output - Yield Value Ratio. For example, Canada had high market price support which equalled to more than 77 per cent of the production value stayed in the bottom of the ranking. There could be two reasons for this. First, with a high level of support the farmers would focus less on increasing the efficiency of the use of such inputs as feed and chemical fertilizers. This would cause high nitrogen balance. Secondly, with heavy domestic policies support, the domestic prices which the farmers face might have been distorted. Further investigation on the impacts of the domestic policy support on the environmental performance is warranted.

Insert table 8

7. Conclusion

The present study proposed the combination of Cumulative Exergy Extraction from the Natural Environment and Extended Exergy Analysis to analyse international environmental performance in agricultural production. The unified approach allows the cumulative analysis of comprehensive extraction of all types of resources and services from the ecosystem in agriculture. The analysis therefore enables the more accurate comparison of the environmental performance of different countries or systems based on different indicators of sustainability.

The application was conducted for 29 OECD countries for the years from 1990 to 2003 with some important findings. First, the organic contents in top soil, feed and total water withdrawal were the three types of resources that agricultural production extracted most from the environment. Secondly, during the 14 years surveyed, the efficiency of using exergy in the livestock sector was much lower than the efficiency in the crop sector. Thirdly, the environmental loading of economic investment had increased slightly, implying a minor increase in the pressure on the environment overtime. In addition, the Total Resource Extraction – Yield Ratio had dropped sharply from 2.057 to 0.313 (GJ/PPP million USD), caused by increases in the prices of the outputs.

The existing literature has proposed different indicators to rank the relative sustainability of different countries in international comparison contexts. The present paper also proposed two new measures: (1) Non-Renewability- Yield Ratio as the ratio of total non-renewable resources to total yield and (2) Total Exergy Extraction – Value Yield Ratio as the ratio of total exergy extraction to the purchasing power parity (PPP) USD value of production outputs. The former can be a good aggregate index of the sustainability of agricultural production because it embodies renewability, cumulative loss and cumulative waste. The latter establishes the connection between total and cumulative resource extraction and economic value of production.

The availability of many indicators raises the question of consistency in the rankings based on various indicators. The empirical study on OECD countries confirmed that rankings varied widely based on different indicators. The empirical results, however, delivered supporting evidence for the use of Non-Renewability- Yield Ratio because the rankings based on this indicator was more consistent with many other indicators.

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