Ecological-economic assessment of farms using multi-input multi-output models: life cycle assessment and extensions

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Abstract: *A multi-input multi-output model is developed by extending the life cycle assessment (LCA) framework for analyzing the relationship between agricultural production and environmental impacts. The inputs include farm land and materials such as fertilizers, pesticides, and animals. The outputs are of two types: one is agro-economic production such as crop and milk yields and the other is environmental impacts including GHG emissions, which are calculated using LCA. Ratio and additive models are defined for analyzing the relationship between management intensity, land productivity, and environmental impacts based on the farm model and are applied to dairy and rice farming in Japan. The results indicate that intensive agricultural practices do not lead to higher levels of environmental degradation per product and that trade-offs between land productivity and environmental impacts per area are dependent on the output measures. These models can be extended for analyzing the land-use competition between food and energy production.*

Keywords: *farm model, management intensity, environmental impacts, ratio model, additive model*

Introduction

Environmental degradation due to agricultural expansion and intensification is a primary concern for the society (Tilman et al., 2001; Tilman et al., 2002). One of the important environmental issues is global warming and its seriousness necessitates considering how to establish sustainable agricultural systems to reduce green house gas (GHG) emissions from agricultural production. Since the emissions originate not only from agricultural production as foreground processes but also from fertilizers, pesticides, and machinery production as background processes, the life cycle approach plays an important role. Indeed, the number of applications of life cycle assessment (LCA) in agriculture has increased recently (Hayashi et al., 2006).

LCA measures environmental impacts per functional unit. Environmental impacts per unit product have commonly been used because LCA was originally developed for assessing products. However, assessing environmental impacts per unit area is also important in agricultural systems because one of the main objectives of practicing agriculture can be related to land preservation other than food production. Previous surveys on environmental assessment methods in agriculture recommend using both area-based and product-based indicators (van der Welf and Petit, 2002; Halberg et al., 2005; Payraudeau and van der Werf, 2005; van der Welf et al., 2007).

Although using both the types of indicators makes our judgment on environmental impacts prudent, understanding the relationship between the two is necessary in obtaining a clear interpretation of the research results, because each indicator shows a different result. A method for establishing the relationship is to use the fact that environmental impacts per product (yield) can be divided into environmental impacts per area and yield per area. This research direction is equivalent to developing a multi-input multi-output model, which can be recognized as an extension of LCA.

Therefore, in this paper, we developed a multi-input multi-output model by extending LCA. Furthermore, based on this model, we defined two models (ratio and additive) for analyzing the relationship between agricultural production and environmental impacts such as GHG emissions and human toxicity. Although studies have been conducted on multiple inputs and outputs in LCA (See, e.g., Heijungs and Suh, 2002), they are restricted to inventory analysis. In agricultural LCA, allocation procedures have been discussed for multiple outputs such as main products (wheat), co-products (straw and leaves), and crop residues (Nemecek and Kægi, 2007). In contrast, the outputs of our model are related to impact categories and thus they can be recognized as multiple objective models applied to ecological-economic assessment.

The structure of this paper is as follows. In Section 2, a multi-input multi-output farm model is developed and efficiency measures including the ratio and additive models are presented. In Section 3, the models are applied to milk and rice production in Japan and the relationship between management intensity and environmental impacts is discussed. The possibility of extending the model for analyzing the land-use competition between food and energy production is discussed in Section 4, because of the importance of bio-energy production in the mitigation of global warming impacts.

Models

Multi-input multi-output models have been developed in economic production theory and data envelopment analysis (DEA) (See, e.g., Färe and Grosskopf, 2003). In this paper, we explicitly account for the relationship between the following two research areas: (1) agricultural production theory, in which many production functions have been discussed and (2) agro-ecology based on the relationship between management intensity and environmental impacts (Tilman et al., 2002), more specifically, the relationship among management intensity, land productivity (yields), and environmental impacts (Hayashi et al., submitted).

We define two types of production functions

$$y_i = f_i(x_1, x_2, \ldots) \tag{1}$$

and

$$z_i = g_i(x_1, x_2, \ldots) \tag{2}$$

where x_i is the i-th input, y_i is the i-th economic output such as the crop yield, and z_i is the i-th environmental output such as global warming potential. We adopted the terms “the production functions of economic and environmental outputs (goods),” instead of using “the production functions of good and bad outputs (goods and bads).” The reason is that environmental impacts of agricultural production include environmental burdens and benefits. In other words, multifunctionality in agriculture has to be considered.

The inputs and outputs are summarized in Table 1. The inputs include land and materials such as fertilizers and pesticides. Labor is also considered as an input. There are two types of outputs. One is economic indicators such as rice and milk yields and the other is environmental indicators (impacts) such as global warming potential, which are calculated using LCA. Ecosystem services such as the provision of biodiversity are also included in the outputs.

Table 1. Examples of inputs and outputs in the models

Inputs	Outputs (economic indicators)	Outputs (environmental indicators)
Fixed input	Yields (products)	Climate change (CO_2 eq.)
Land	Rice	Stratospheric ozone depletion (CFC-11 eq.)
Buildings	Wheat	Human toxicity (1,4-DCB eq.)
Machinery	Milk	Ecotoxicity (1,4-DCB eq.)
Variable input	Meat	Photo-oxidant formation (ethylene eq.)
Labor	Eggs	Acidification (SO_2 eq.)
Seed	Sugar cane	Eutrophication (PO_4^{3-} eq.)
Fertilizers	Rape seed	Loss of life support function
Pesticides	…	Loss of biodiversity
Energy carriers	Gross margin	…
Water	…	
Feedstuffs		
Straw		
Animals		
…		

For simplicity, we changed the economic and environmental production functions (1) and (2) to the following two-input models

$$y = f(x_L, x_V) \tag{3}$$

and

$$z = g(x_L, x_V) \tag{4}$$

where x_L is the land area, x_V is a variable input, y is an economic output (yield), and z is an environmental output. These two functions are illustrated in Figure 1. They provide a theoretical framework for establishing the relationship between inputs and outputs.

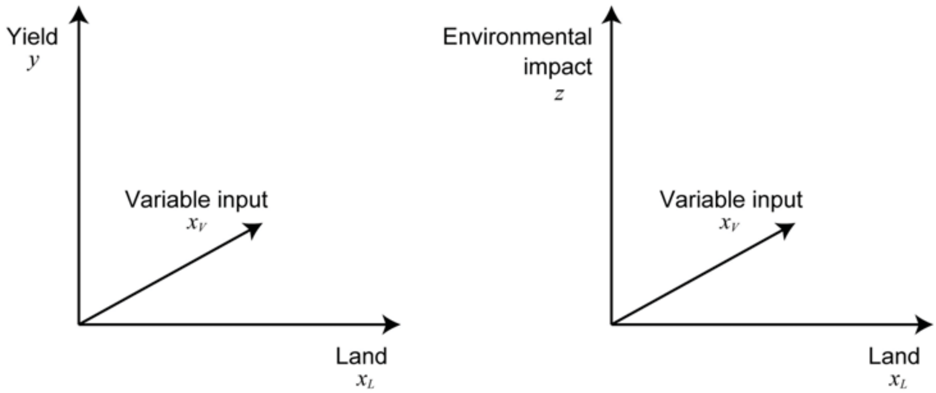

Figure 1. Graphical illustrations of the economic production function (left) and the environmental production function (right).

These farm-based variables (indicators) can be converted into area-based indicators (Figure 2). For example, management intensity is defined as the ratio of the level of a variable input (*b*) and the land area (*a*) for Farm A. The function of management intensity on yield per area can be defined as a yield function and environmental impact per area can be defined as an impact function (Hayashi et al., submitted). Using yield and impact functions, we can define the two models that explain the relationships between the two outputs. The first model is the ratio model defined as the ratio of the two outputs (*z*/*y*), and it illustrates the relationship between management intensity and environmental impact per unit product. The second model is the additive model that illustrates the trade-offs between yield per area and environmental impact per area (Hayashi et al., submitted).

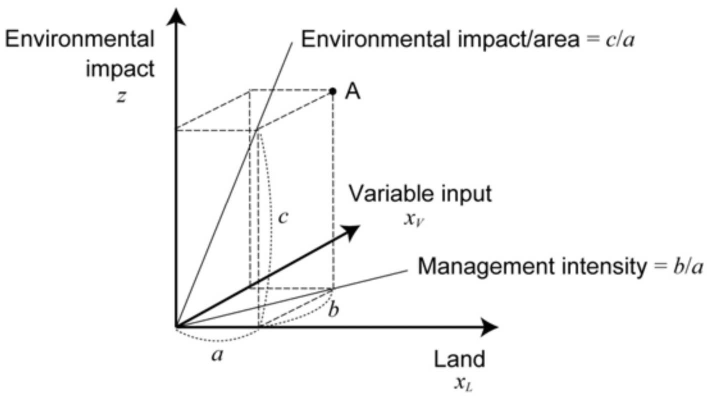

Figure 2. From farm-based to area-based indicators. For example, for Farm A (the coordinate a, b, c) the land area (a) and the level of a variable input (b) can be converted into management intensity (b/a).

Applications

In this section, the models discussed in the previous section are applied to milk and rice production in Japan.

Milk production

Reducing GHG emissions from dairy farms is one of the important policy tasks in establishing sustainable agricultural systems and thus this section focuses on CO_2 emissions from the farms. Data from 133 dairy farms in 1997 at a town in the northern part of Japan were collected and used for analysis; since the data collected from seven farms were recognized as outliers, 126 samples were used for the analysis. CO_2 emissions from each farm were estimated using the farm records related to, e.g., feeding, fertilizer and pesticide application, and energy and electricity use.

The results of applying economic and environmental production functions are shown in Figure 3. Both milk production and CO_2 emissions increase with increase in land area and the number of cows. In other words, the farm sizes measured by both land and animals affect the positive impacts on the level of production of economic goods (milk) and environmental goods (CO_2).

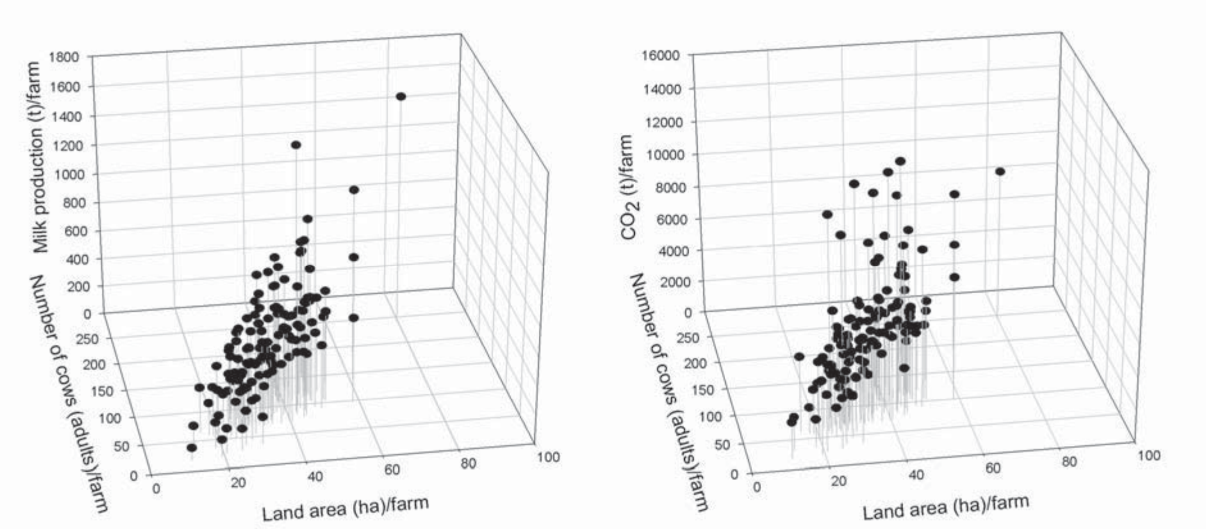

Figure 3. The production functions of economic goods (left) and environmental goods (right) for dairy farms.

The relationships between management intensity, which is defined as the number of cows per farm (*y*-axis in Figure 3) divided by the land area per farm (*x*-axis), and the production levels of economic and environmental goods per each dairy farm are illustrated in Figure 4. Although the original definitions of the yield and impact functions are based on area-based indicators, we use farm-based indicators in the figures since attention was paid to the responses of the farmers in this section. The smoothing lines in the graphs depict locally weighted regression smoothing calculated by S-PLUS Ver. 7. The default values were used for the parameters in the local regression model. The results show that management intensity has positive correlations with both milk production per farm and CO_2 emissions per farm.

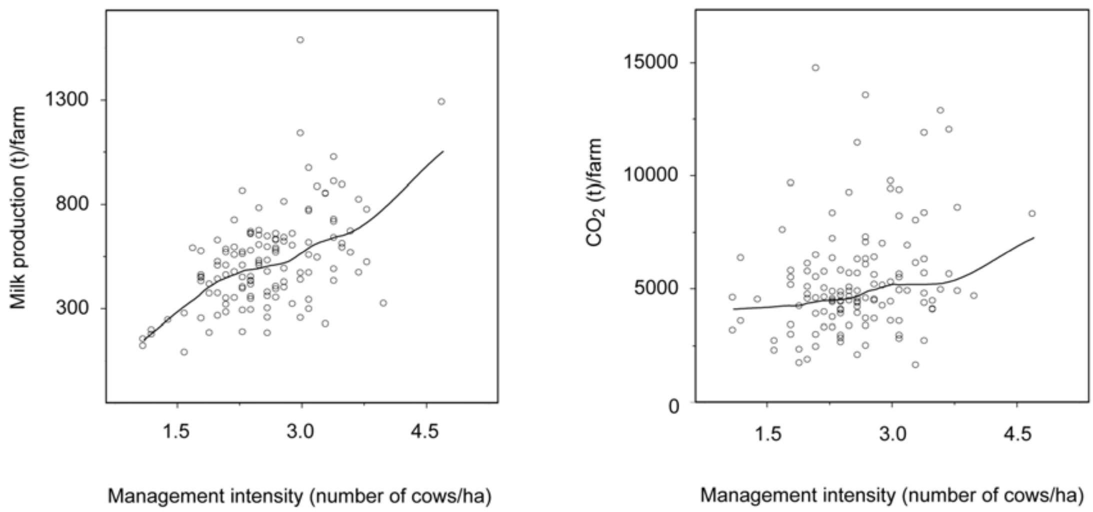

Figure 4. The yield function (left) and the impact function (right) for dairy farms.

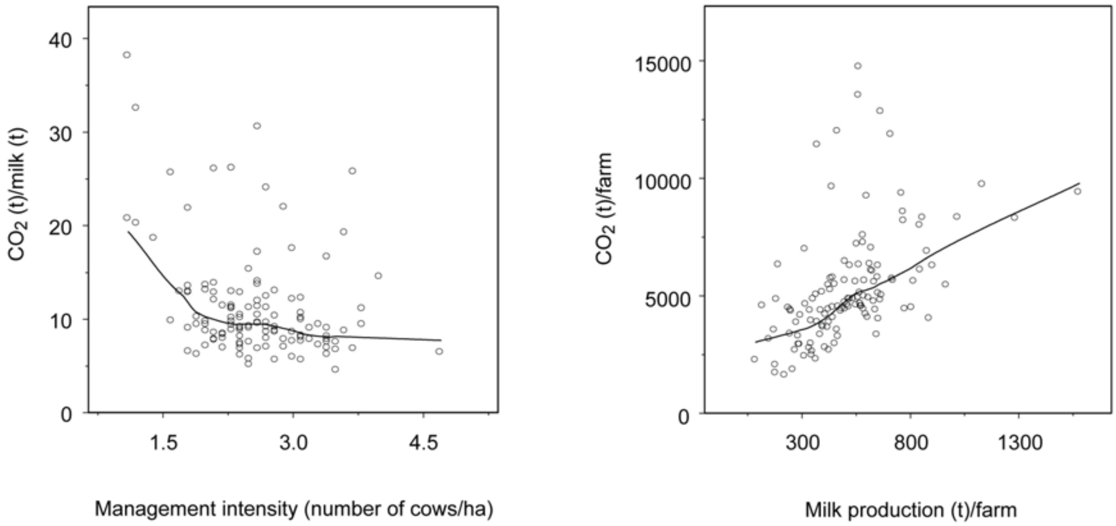

Figure 5.The ratio model (left) and the additive model (right) for dairy farms.

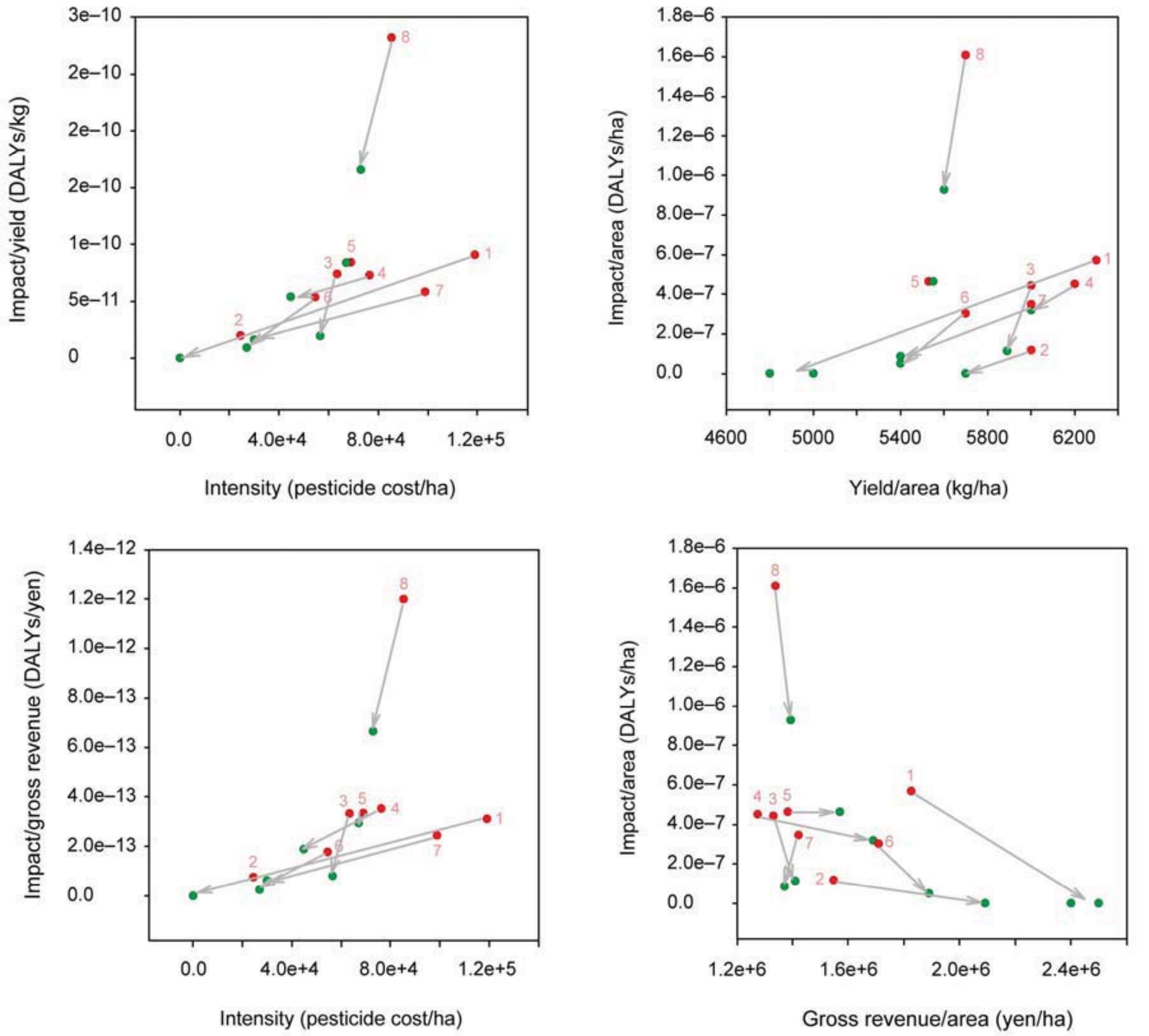

Figure 6. The ratio model (left) and the additive model (right) for rice production. Each arrow means the transition from conventional production (source) to "environmentally friendly" production (destination) at the farm.

An interesting result was observed in the relationship between management intensity and environmental impacts per product. As shown in Figure 5, the ratio model illustrates negative correlation between management intensity and CO2 emissions per ton of milk. In contrast, the trade-offs between the production and environmental impacts per farm are illustrated by the additive model. Although these discussions are based on farm-based indicators, area-based indicators (the original version of the models) can also be used.

Rice production

In this example, we focus on the transition phase from conventional rice cultivation to “environmentally friendly” practices in addition to investigating the relationship between agricultural production and environmental impacts. Furthermore, we illustrate that the result (e.g., the relative superiority between farming systems) is dependent on the definition of the performance measures of the yields. The data of eight rice farms, which cooperated with the prefectural government in 2004, were collected to assess the impacts of the prefectural policy to reduce the use of artificial fertilizer and pesticide application. A life cycle impact assessment framework (a multimedia fate, exposure, and effect model) was used for estimating the environmental impacts of pesticide applications (see, e.g., Pennington et al., 2002). The environmental impacts were measured by disability adjusted life years (DALYs).

Figure 6 depicts the results of the ratio and additive models for the physical (the upper two graphs) and monetary (the lower two graphs) yields. The ratio model indicates that “environmentally friendly” practices are more efficient for both cases, while the additive model shows sustainable directions on the impact-revenue plane, although there are trade-offs on the impact-yield (physical) plane. The reason is related to the decrease in yield per area and the increase in environmental impacts and in revenue per area as a result of the reductions of pesticide application in “environmentally friendly” practices.

Discussions

Applications of the multi-input multi-output model have clarified the relationships between the scales of indicators and indicator definitions as ratios. There are three scales in indicators. First, the starting point of the definitions is farms as decision making units and the examples for this scale include yields per farm (farm productivity) and environmental impacts per farm. Second, area-based indicators can be derived from farm-based indicators. Yields per area (land productivity) and environmental impacts per area are examples of the definitions of “output/input” and a variable input per area (management intensity) is an example of “input/input.” Third, product-based indicators, e.g., environmental impacts per products (a type of eco-efficiency), can be defined as “output/output.” Although we did not discuss the issues concerning labor such as labor productivity above, it is possible to include them in the models.

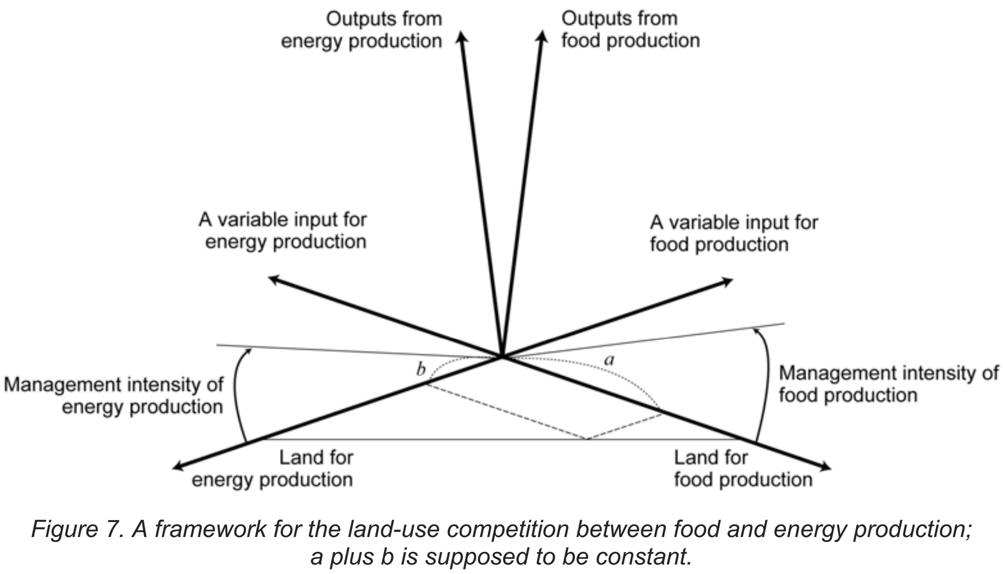

Figure 7. A framework for the land-use competition between food and energy production; a plus b is supposed to be constant.

Since the starting point of the derivation of the above-mentioned multi-scale indicators is farms, a promising research direction will be the modeling of land-use competition between food and energy production. A diagram has been shown by Haight (2007), in which a country's production and ecosystem possibilities are illustrated. In contrast, as shown in Figure 7, the purpose of our discussion is to develop a model for farm-level analysis. We assume that farms are the decision making units.

Concluding remarks

The results can be summarized as follows. (1) The ratio model illustrated that management intensity and environmental impact (CO_2 emissions) per product negatively correlated in the case of milk production. This implies that intensive agricultural practices do not necessarily cause higher levels of environmental degradation per product. (2) The additive model shows that there are, in general, trade-offs (win-lose relationships) between economic and environmental performance. However, it is possible to establish a sustainable direction (the win-win relationship) as in the case of rice production. Since our discussion is restricted to CO_2 emissions and human toxicity measured by DALYs, it is necessary to examine the other environmental categories in the future.

The multi-input multi-output farm model discussed in this study enables us to understand the ecological-economic relationship in a general framework. The ratio (eco-efficiency) and additive (trade-off) models, which are derived from the model, are complementary for analyzing the relationships among management intensity, land productivity, and environmental impacts. In particular, the trade-off information will be useful for finding directions for improvement in ecological-economic performances. It is expected that the integrated ecological-economic assessment of food and bio-energy production can be conducted using these models.

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