Introduction of uncertainty into trade-offs between productivity and life cycle environmental impacts in rice production systems: Assessing the effectiveness of nitrogen-concentrated organic fertilizers

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ABSTRACT

We compared three rice production systems, the system using a pelletized nitrogen concentrated organic fertilizer, the system using a conventional organic fertilizer, and the system using a chemical fertilizer, by calculating life cycle greenhouse gas (GHG) emissions. Two-dimensional uncertainty regions were introduced into the land-oriented expression, which was established to assess efficiency of agricultural production systems on the basis of constant returns to scale (CRS) and variable returns to scale (VRS), to analyze stability of the comparison. The results indicated that the rice production system using a high nitrogen organic fertilizer was recognized as a promising alternative and that this approach was useful in understanding the stability of the results through detecting overlaps among uncertainty regions.

Keywords: uncertainty, trade-offs, organic fertilizers, yield fluctuations, methane emissions

1. Introduction

Life cycle assessment (LCA) has been applied to measure potential environmental improvements achieved by the introduction of new agricultural practices (Notarnicola et al. 2012; van der Werf et al. 2014). A typical approach is to make comparisons among several alternative agricultural production systems. For example, many comparisons have been made between organic and conventional crop production systems using LCA (Hayashi 2013; Hokazono and Hayashi 2012; Nemecek et al. 2011; Williams et al. 2010). A remarkable result in the earlier comparisons among agricultural production systems is the presence of trade-offs between environmental and economic indicators. Since improvements in area-based environmental indicators tend to entail decrease in crop yield, it is necessary to conduct an analysis of trade-offs on the two-dimensional space. In order to illustrate the implication of the space, we coined the term “land-oriented expression”, which is contrasted to “product-oriented expression” that is equivalent to a system model using the functional unit of product weight (Hayashi 2013).

The existence of hot spots in life cycle environmental impacts, however, can make the technological improvements negligible. For example, the degree of decrease in greenhouse gas (GHG) emissions from paddy rice cultivation embodied by substituting improved agricultural inputs for conventional ones can be smaller than the range of methane emission fluctuations from paddy fields.

Therefore, we extend the trade-off analysis by explicitly introducing uncertainty modeling in order to more properly assess improvement potential of agricultural technology development. In other words, uncertainty representation is introduced into the two-dimensional land-oriented expression to focus our attention to the trade-offs and to detect stability of the results.

2. Methods

2.1. An outline of the case study

The decision problem we analyzed in this study was whether to select organic fertilizers for paddy rice cultivation in Niigata Prefecture, one of the main rice production areas in Japan. Because of increased public needs to establish environmentally sustainable rice production systems, we made a research project to establish rice production systems using organic fertilizers, which are expected to resolve the problems cause by the excess of manure from livestock production. However, the application of conventional organic fertilizers makes the prediction of the response of rice plants to the application of fertilizer nitrogen difficult. Moreover, it can be a cause of lodging and yield instability.

We expected that the development of nitrogen concentrated organic fertilizers using closed composting facilities would be a promising method to resolve the problem. Therefore, we assessed the potential improvements by applying the nitrogen concentrated organic fertilizers to paddy rice production systems using life cycle assessment.

2.2. System description

We compared three rice production systems; the system using a pelletized nitrogen concentrated (high nitrogen) organic fertilizer made from poultry manure through the use of closed-air composting techniques, the system using a conventional (low nitrogen) organic fertilizer made from poultry manure using open-air composting techniques, and the systems using a chemical compound fertilizer.

This study is an ex-ante assessment because there are no facilities for making the high nitrogen organic fertilizer in Niigata Prefecture and thus we have constructed rice production scenarios to use the organic fertilizer. High and low nitrogen fertilizers prepared at two commercial companies in Mie Prefecture were used for field experiments at Niigata Agricultural Research Institute.

Furthermore, we analyzed the effects of system expansion because the use of manure necessitates considering the application of inventory models with substitution (avoided burden) (De Vries et al. 2012; Hamelin et al. 2011; Lopez-Ridaura et al. 2009; Martinez-Blanco et al. 2011a; Martinez-Blanco et al. 2010; Martinez-Blanco et al. 2009; Martinez-Blanco et al. 2011b; Prapaspongsa et al. 2010).

2.3. Analytical framework

There are two important factors in calculating life cycle GHG emissions from paddy rice production. One is direct emissions of methane from paddy fields and the other is crop yields. Earlier applications of LCA to rice illustrates that more than half of life cycle GHG emissions from rice production can be attributed to methane emissions (Blengini and Busto 2009; Hokazono and Hayashi 2012). In comparing organic and conventional rice production systems, for example, life cycle GHG emissions per product unit for each production system are highly dependent on crop yields (Hayashi 2013). In other words, even if life cycle GHG emissions per area unit from organic production are smaller than those from conventional production, life cycle GHG emissions per product unit from organic production tend to become larger than those from conventional production. The importance of these two factors implies that uncertainties due to the two factors are also high.

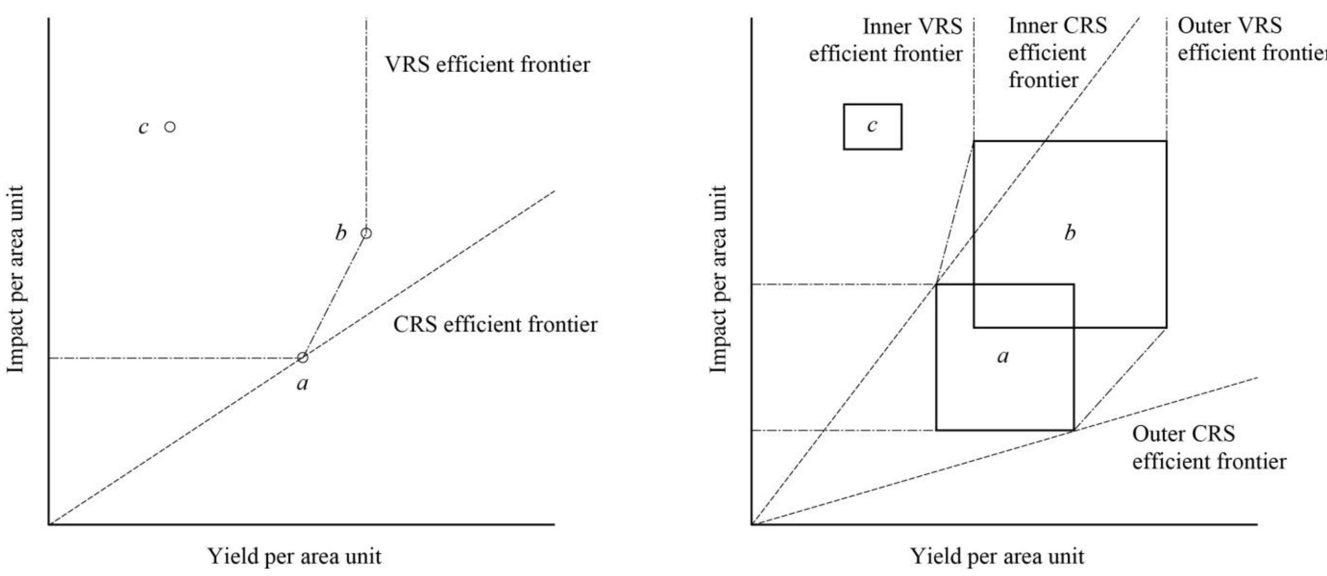

Figure 1. Two efficiency concepts defined on land-oriented expressions with and without uncertainty regions. (*a*, *b*, and *c* indicate the respective production systems.)

We apply the land-oriented expression (Hayashi 2013) to analyze the two factors. That is, using the two-dimensional space, in which the horizontal axis measures yield levels and the vertical axis measures the levels of life cycle GHG emissions, we explicitly depict uncertainties in the two factors. The land-oriented expression has an additional advantage to illustrate two efficient concepts, although the purpose of this study is the comparison and not the final selection (Figure 1). One is a concept based on constant returns to scale (CRS) and forms a straight efficient frontier, which is equivalent to the case of the product-oriented expression. The other is based on variable returns to scale (VRS) and forms a piece-wise linear efficient frontier.

In this study, we extend the expression by introducing two-dimensional uncertainty, which is depicted as an uncertainty region. As a result, outer and inner efficient frontiers are defined. In this case, the difference in efficiency between the production system a and b is somewhat inconclusive, although both a and b are more efficient than c under CRS and VRS technologies. More precisely, the efficiency orders are summarized as follows:

- the efficiency order under the CRS technology without considering uncertainty: $a \succ b \succ c$,
- the efficiency order under the VRS technology without considering uncertainty: $a \sim b \succ c$,
- the efficiency order under the CRS technology with considering uncertainty: $a \sim b \succ c$, and
- the efficiency order under the VRS technology with considering uncertainty: $a \sim b \succ c$.

2.4. Inventory data

The foreground process data were prepared on the basis of multi-year field experiments. The Japan Agricultural Life Cycle Assessment (JACLA) database (Hayashi et al. 2012) was used for background processes such as agricultural inputs including fertilizers, pesticides, and farm machines.

Data for rice cultivation are based on conventional rice production systems defined by Niigata Prefecture (Maruyama et al. 2009; Niigata Prefecture 2011). Crop yield data are gathered from field experiments at Niigata Agricultural Research Institute from 2009 to 2013 (from 2010 to 2013 for cultivation using the low nitrogen organic fertilizer). The yields are estimated using unit acreage sampling with three repetitions (Niigata Prefecture 2011).

Inventory data for organic fertilizers were prepared using experimental results conducted at Mie Prefecture Agricultural Research Institute. GHG emissions from composting processes were estimated on the basis of material balances. Emission factors for methane and dinitrogen monoxide in Greenhouse Gas Inventory Office of Japan (GIO) (2009) were used. Construction data for composting and pelletizing machines were gathered through surveys at companies.

Energy use in burning poultry manure, which was used for system expansion, was based on data available from a company in Miyazaki Prefecture. Transportation was not considered because system expansion was applied to get approximate effects of burning instead of composting.

Data on direct methane emissions from paddy fields were prepared using the results of field experiments at Niigata Agricultural Research Institute from 2009 to 2013 (from 2010 to 2013 for cultivation using the low nitrogen organic fertilizer). Measurement of methane flux was based on Minami and Yagi (1988).

2.5. Impact assessment

The impact category of global warming (IPCC 2006, 100 years) was used in impact assessment. Although we think that the other environmental impact categories such as eutrophication and acidification are important in assessing agricultural production systems with special attention to organic fertilizers, we used the category as an initial step.

3. Results

The results are illustrated in Figure 2. Horizontal ranges of the uncertainty regions show uncertainty intervals derived from annual fluctuations of crop yields. Vertical ranges are uncertainty intervals of GHG emissions derived from annual fluctuations of methane emissions. We present the results on overlaps among uncertainty regions, CRS and VRS efficiency, and the system expansion in sequence.

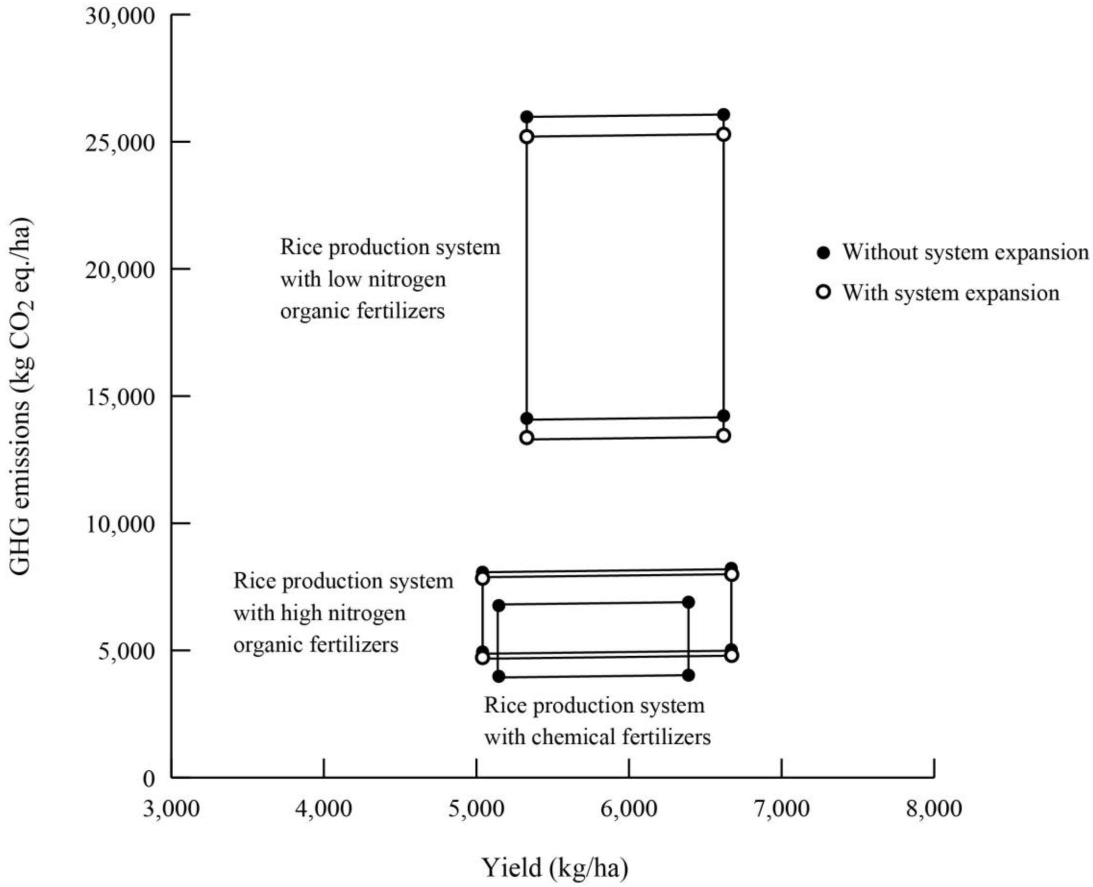

Figure 2. Uncertainty regions for each rice production system

3.1. Overlap among uncertainty regions

The configuration of two-dimensional uncertainty regions revealed that there is an overlap between the production system using the high nitrogen organic fertilizer and the system using the chemical fertilizer and that no overlap between the two systems and the system using the low nitrogen organic fertilizer.

3.2. CRS efficiency

Lines through the origin separated the following two groups: (1) the production system using the chemical fertilizer and one using the high nitrogen organic fertilizer and (2) the production system using the low nitrogen organic fertilizer. It implies that the former was CRS efficient. In other words, life cycle GHG emissions per kg of rice (as a functional unit) from the former were smaller than those from the latter.

3.3. VRS efficiency

The uncertainty region for the rice production system with the low nitrogen organic fertilizer was contained in the region between outer and inner VRS efficient frontiers. Therefore, if we use the concept of strict efficiency, we can exclude it from the systems to be selected without using preferences (weighting).

3.4. System expansion

The graphical expression also showed that the effects of systems expansion were negligible as compared with the size of the uncertainty regions. The results presented already were applicable to the both cases with and without system expansion.

4. Discussion

In summarizing these results, it is pointed out that the use of the high nitrogen organic fertilizer is promising and that the two-dimensional expressions improve our understanding about stability of results.

However, there are some limitations. The first limitation is the method to determine upper and lower bounds in intervals. Because of arbitrariness in the determination, there may be some ambiguities in judgments based on intervals. Further studies are necessary for this direction, because the problem of arbitrariness will be found in uncertainty analysis using the pedigree matrix, which is implemented in LCA software such as SimaPro and commonly used in LCA.

The second limitation is related to field measurement techniques, which are a source of arbitrariness mentioned already. Although we limited our attention to uncertainty due to annual fluctuations, uncertainty due to measurement techniques is important in agronomy and should be included into uncertainty analysis in the next step of the study.

5. Conclusion

This paper demonstrated that a method to introduce interval-based uncertainty into the two-dimensional space to detect trade-offs between productivity and GHG emissions was useful in comparing several agricultural production systems and in understanding stability of the results. The approach used in this study can be modified into the framework of land use transformation. In this case, the topic is transition from a system with chemical fertilizers to a system with organic fertilizers. An important implication of this study is that the conclusion is not straightforward in the sense that the latter is efficient as compared with the former only if organic fertilizers are made efficiently. That is, transition to a bio-based system will be established only if efficient bio-material transformation techniques are fully developed.

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7. References

Blengini GA, Busto M (2009) The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). J Environ Manage 90:1512-1522

De Vries JW, Groenestein CM, De Boer IJM (2012) Environmental consequences of processing manure to produce mineral fertilizer and bio-energy. J Environ Manage 102:173-183

Greenhouse Gas Inventory Office of Japan (GIO), Center for Global Environmental Research, National Institute for Environmental Studies, Japan (2009) National Greenhouse Gas Inventory Report of JAPAN.

Hamelin L, Wesnaes M, Wenzel H, Petersen BM (2011) Environmental Consequences of Future Biogas Technologies Based on Separated Slurry. Environ Sci Technol 45:5869-5877

Hayashi K (2013) Practical recommendations for supporting agricultural decisions through life cycle assessment based on two alternative views of crop production: the example of organic conversion. Int J Life Cycle Assess 18:331-339

Hayashi K, Shobatake K, Makino N, Hokazono S (2012) Development of a life cycle inventory database for agricultural production systems in Japan: the JALCA Database. In: Proceedings of the 10th International Conference on EcoBalance. pp 1-2

Hokazono S, Hayashi K (2012) Variability in environmental impacts during conversion from conventional to organic farming: a comparison among three rice production systems in Japan. J Clean Prod 28:101-112

Lopez-Ridaura S, van der Werf H, Paillat JM, Le Bris B (2009) Environmental evaluation of transfer and treatment of excess pig slurry by life cycle assessment. J Environ Manage 90:1296-1304

Martinez-Blanco J, Anton A, Rieradevall J, Castellari M, Munoz P (2011a) Comparing nutritional value and yield as functional units in the environmental assessment of horticultural production with organic or mineral fertilization. Int J Life Cycle Assess 16:12-26

Martinez-Blanco J, Colon J, Gabarrell X, Font X, Sanchez A, Artola A, Rieradevall J (2010) The use of life cycle assessment for the comparison of biowaste composting at home and full scale. Waste Manage 30:983-994

Martinez-Blanco J, Munoz P, Anton A, Rieradevall J (2009) Life cycle assessment of the use of compost from municipal organic waste for fertilization of tomato crops. Resour Conserv Recycl 53:340-351

Martinez-Blanco J, Munoz P, Anton A, Rieradevall J (2011b) Assessment of tomato Mediterranean production in open-field and standard multi-tunnel greenhouse, with compost or mineral fertilizers, from an agricultural and environmental standpoint. J Clean Prod 19:985-997

Maruyama K, Gocho N, Moriya T, Hayashi K (2009) Life cycle assessment of super high-yield and conventional rice production systems: a comparison based on global warming potential and energy consumption. Journal of Life Cycle Assessment, Japan 5:432-438 (in Japanese)

Minami K, Yagi K (1988) Method for measuring methane flux from rice paddies. Journal of Japanese Society of Soil Science and Plant Nutrition 59:458-463 (in Japanese)

Nemecek T, Dubois D, Huguenin-Elie O, Gaillard G (2011) Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agric Syst 104:217-232

Niigata Prefecture, Department of Agriculture, Forestry and Fisheries (2011) Guidelines for rice cultivation. (in Japanese)

Notarnicola B, Hayashi K, Curran MA, Huisingh D (2012) Progress in working towards a more sustainable agri-food industry. J Clean Prod 28:1-8

Prapaspongsa T, Christensen P, Schmidt JH, Thrane M (2010) LCA of comprehensive pig manure management incorporating integrated technology systems. J Clean Prod 18:1413-1422

van der Werf HMG, Garnett T, Corson MS, Hayashi K, Huisingh D, Cederberg C (2014) Towards eco-efficient agriculture and food systems: theory, praxis and future challenges. J Clean Prod

Williams AG, Audsley E, Sandars DL (2010) Environmental burdens of producing bread wheat, oilseed rape and potatoes in England and Wales using simulation and system modelling. Int J Life Cycle Assess 15:855-868

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