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Linking environment-productivity trade-offs and correlated uncertainties: Greenhouse gas emissions and crop productivity in paddy rice production systems

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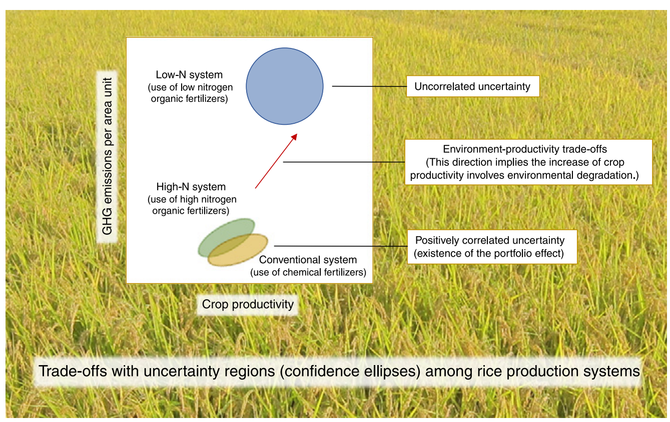
HIGHLIGHTS

- Correlated uncertainties were integrated into environment-productivity trade-offs.
- Life cycle GHG emissions and crop yields were analyzed using field and survey data.
- Three rice production systems using chemical or organic fertilizers were compared.
- There were portfolio (insurance) effects in matured technologies.
- Analysis of trade-offs and correlated uncertainties will be useful for decisions.

GRAPHICAL ABSTRACT



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ABSTRACT

In comparative life cycle assessments of agricultural production systems, analyses of both the trade-offs between environmental impacts and crop productivity and of the uncertainties specific to agriculture such as fluctuations in greenhouse gas (GHG) emissions and crop yields are crucial. However, these two issues are usually analyzed separately. In this paper, we present a framework to link trade-off and uncertainty analyses; correlated uncertainties are integrated into environment-productivity trade-off analyses. We compared three rice production systems in Japan: a system using a pelletized, nitrogen-concentrated organic fertilizer made from poultry manure using closed-air composting techniques (high-N system), a system using a conventional organic fertilizer made from poultry manure using open-air composting techniques (low-N system), and a system using a chemical compound fertilizer (conventional system). We focused on two important sources of uncertainties in paddy rice cultivation—methane emissions from paddy fields and crop yields. We found trade-offs between the conventional and high-N systems and the low-N system and the existence of positively correlated uncertainties in the conventional and high-N systems. We concluded that our framework is effective in recommending the high-N system compared with the low-N system, although the performance of the former is almost the same as the conventional system.

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1. Introduction

Life cycle assessment (LCA) is a comprehensive method to measure potential environmental impacts of whole value chains from production to disposal, and many LCA studies have already been conducted in the research fields of agriculture and food (Hellweg and Mila i Canals, 2014; Nemecek et al., 2016; Notarnicola et al., 2012; Tilman and Clark, 2014; Van Der Werf et al., 2014). A typical application is to make comparisons among several alternative agricultural production systems (comparative LCA) in order to ascertain the main differences in environmental impacts among alternative systems or to evaluate improvements achieved by invention and introduction of new agricultural practices. For example, many comparisons have been made between organic and conventional crop production systems using LCA (Blengini and Busto, 2009; Fedele et al., 2014; Hayashi, 2013; Hokazono and Hayashi, 2012, 2015; Knudsen et al., 2014; Nemecek et al., 2011; Pelletier et al., 2008; Williams et al., 2010).

There are two important topics in comparative LCA of agricultural production systems. One is the presence of trade-offs, which is the cause of the difficulty in making comparisons and selection decisions. A typical example is the trade-off between productivity and environmental impacts. Since improvements in area-based environmental indicators tend to involve decreases in crop yield, it is necessary to conduct an analysis of trade-offs on the two-dimensional space. In order to analyze the space, we coined the term "land-oriented expression." This is in contrast to "product-oriented expression," which is equivalent to a system model using the functional unit of product weight (Hayashi, 2013). The other important topic in comparative LCA is uncertainties, because in judging relative superiority of one system over another, uncertainties make the decision complicated. Uncertainties in agricultural production are traditional research topics, and parameter uncertainties in crop yields and direct field emissions, for example, have been integrated into LCA (Basset-Mens et al., 2006, 2009; Payraudeau, 2007; Zehetmeier et al., 2014). Recently, many studies have been conducted related to uncertainties (Hayashi et al., 2014a).

However, the two issues have been analyzed separately until now. In the comparison of paddy rice production systems, which is the topic of this study, trade-offs among several systems while paying attention to uncertainties related especially to crop yields and methane emissions have not yet been analyzed despite the importance of the issue. Therefore, we integrate the two central issues by introducing both the concept of trade-offs and of correlated uncertainties based on the land-oriented expression. The two concepts can be contrasted as described below.

Decision making under trade-offs implies the selection of continuous or discrete alternatives. A typical trade-off in agricultural production is between environmental impacts per area unit and crop yields, as mentioned above. By adopting one production system instead of another (i.e., by switching the production technologies), we can change the location in trade-off curves or surfaces, although the trade-offs do not disappear.

Decision making under uncertainties means the consequence of the selection decision is uncertain, and the relative superiority among alternative production systems might change. A typical example in agricultural production is the correlation of uncertainties between environmental impacts per area unit and crop yields. This is because plant growth is difficult to control solely through field practices and is affected by weather conditions. Under positively correlated uncertainty between productivity and environmental impacts, higher productivity performance tends to involve higher environmental impacts, and lower environmental impacts tend to involve lower productivity performance. In essence, a positive consequence comes with a negative consequence by nature. This can be considered as a type of portfolio effect or insurance effect (Perrings, 2014), in which the risks are spread between productivity and environmental impacts.

In this paper, we analyzed the trade-offs between greenhouse gas (GHG) emissions, especially methane emissions from paddy fields, and crop yields of three paddy rice production systems while introducing an uncertainty representation into the two-dimensional land-oriented expression. The rice production systems we analyzed include a system using a nitrogen-concentrated (high nitrogen) organic fertilizer, a system using a conventional (low nitrogen) organic fertilizer, and a system using a chemical compound fertilizer. We compared the three systems to support decisions on whether to introduce high nitrogen organic fertilizer into rice cultivation.

2. Material and methods

2.1. Analytical framework

To illustrate trade-offs and correlated uncertainty at the same time, we applied the land-oriented expression. It is a two-dimensional space, in which the horizontal axis measures yield levels and the vertical axis measures the levels of life cycle GHG emissions (Fig. 1, left-hand side). The land-oriented expression can depict the two frontier concepts. One concept is constant returns to scale (CRS) and forms a straight efficient frontier (dotted lines in Fig. 1), which is equivalent to the case of the product-oriented expression. In the figure, points *a*, *b*, and *c* show agricultural production systems. In the case of CRS, GHG emissions per product unit are defined by the tangent between the horizontal line and each dotted line ($tan\ \theta_a$, $tan\ \theta_b$, and $tan\ \theta_c$). In this case, *b* is the most efficient. The conventional product life cycle assessment uses the expression and shows environmental impacts per product unit, which is defined as $tan\ \theta_*$. The other concept is variable returns to scale (VRS) and forms a piece-wise linear efficient frontier (dashed lines). The production systems *a* and *b* are located on the frontier and the both are indifferent; there is a trade-off between *a* and *b*.

This framework suited our study because there are two important factors in calculating life cycle GHG emissions from paddy rice production. One is direct methane emissions from paddy fields and the other is crop yields. Earlier applications of LCA to rice illustrate that more than half of the 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 lower than that from conventional production, life cycle GHG emissions per product unit from organic production can be higher than those from conventional production.

Although the land-oriented expression was originally designed to illustrate trade-offs between productivity and environmental impacts, it

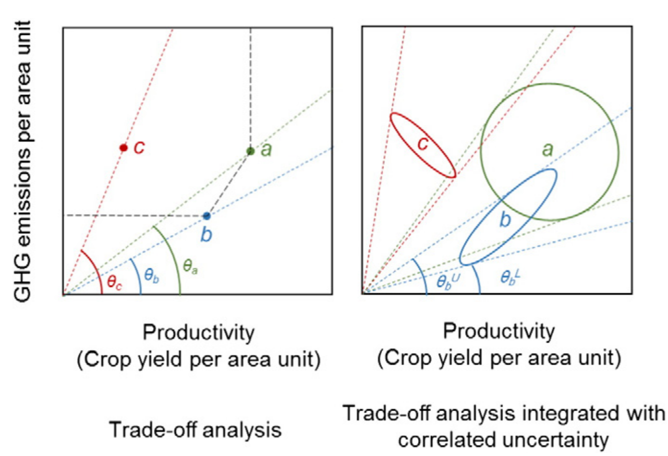

Fig. 1. Comparison between positively and negatively correlated uncertainties. The left-hand side illustrates the trade-off analysis on the land-oriented expression. In the right-hand side, which only depicts the case for CRS, trade-off analysis is integrated with correlated uncertainty.