Life-cycle assessment of ecologically cultivated rice applying DNDC-Rice model

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Abstract

Life cycle assessment (LCA) of rice should be implemented including non-CO_2 greenhouse gases (GHGs) adequately to compare mitigating options. This study evaluated environmnetal load and production cost of rice produced in Shiga, Japan, for two types of cultivation: One reduces chemical fartilizer (RF) and other utilizes green manure (UG). Non-CO_2 GHGs emissions were simulated by DNDC-Rice model. Results show utilization of green manure reduces cost of production and impact of energy consumption and eutrophication, though increses farmer's labor time and GHGs emision. Field methane emission from UG rice cultivation is 2.8 times more than RF, and it takes 80% of total LC-GHGs emission. To reduce total impact of rice production, improving water manegement would be significant for UG. Simulating material circulation in paddy field which reflects practice of fertilizer and organic matter application and water management is necessary to choice consider effective option(s) reducing environmental load and production cost through product life cycle.

Keywords: Rice, DNDC model, Greenhouse gases, Green Manure

1. Introduction

In the area of climate change, non-CO_2 greenhouse gas (GHG) emission has a greater impact of the life cycle of paddy rice than LC-CO_2 emission does. Therefore, non-CO_2 GHGs should be evaluated adequately in the life cycle assessment (LCA) of paddy rice production. When analyzing the mitigating options for the cultivation of rice, it is desirable to simulate the effects of these options in advance. Most of the current LCA studies for rice production assess non-CO_2 GHGs by using emission factors based on soil type and choice of organic matter application. However, those methods cannot be used to perform a detailed evaluation of the differences among cultivation practices. Some research has been done based on detailed measurements, but those studies cannot be used to select reduction options without field experiments.

This study applied the DNDC-Rice model to implement a comparative LCA of ecologically cultivated rice produced in Japan. This model can simulate non-CO_2 GHG emissions from a paddy field. Two cultivation practices are compared in various impact categories.

2. Methodology

2.1 Goal and Scope Definition

Two types of rice produced in Otsu, Shiga, Japan are evaluated in this study. In one cultivation method, chemical nitrogen fertilizer and the number of agrochemical components used were reduced to less than half that of conventional use (RF). Reduced nitrogen was supplied by organic fertilizer. The other method utilized hairy vetch (*Vicia villosa*) as green manure (UG). Chemical fertilizer was not applied after transplanting. Table 1 indicates an overview of both products.

We evaluated environmental impact with regard to global warming and eutrophication, as well as production cost. The functional unit was 1 kg of white rice. The target year was 2008.

The system boundary is shown in Figure 1. All input materials are taken into account except for durable goods.

2.2 Life cycle model

Yield and input data (energy use in farm and post harvesting facilities, fertilizer, agrochemicals, packaging, labor time) are collected from farmers and facilities. All impacts are allocated for the main product (brown rice) and not the byproducts (rice bran, rice husk, and rice straw). The inventory database in MILCA is used as background data. Eutrophication impact (T-P) of leaching in the field is estimated by material balance in the field and run off ratio of surplus P (5%), while the T-N load is calculated by DNDC-Rice model [1]. Labor cost is assumed to be 999¥/h [2]. Characterization and integration are based on the factors of LIME2 [3].

2.3 DNDC-Rice model

DNDC model [4] is a biogeochemical model that describes carbon and nitrogen cycle and crop growth. DNDC-Rice is a revised version of DNDC to improve its ability to estimate methane (CH_4) emission from rice paddy fields [5]. We apply this model to estimate difference of CH_4 emission between two cultivation practices.

Input parameters consist of (1) climatic information, (2) soil properties, and (3) farming management. Some

Table 1. Overview of rice produced

	RF rice	UG rice
Production site	Otsu city, Shiga, Japan	
Variety	Koshihikari (*Oryza sativa* subsp. *Japonica*)	
Area cultivated(ha)	7.3	5.9
Unit yield (kg-brown rice/ha)	4,797	4,598

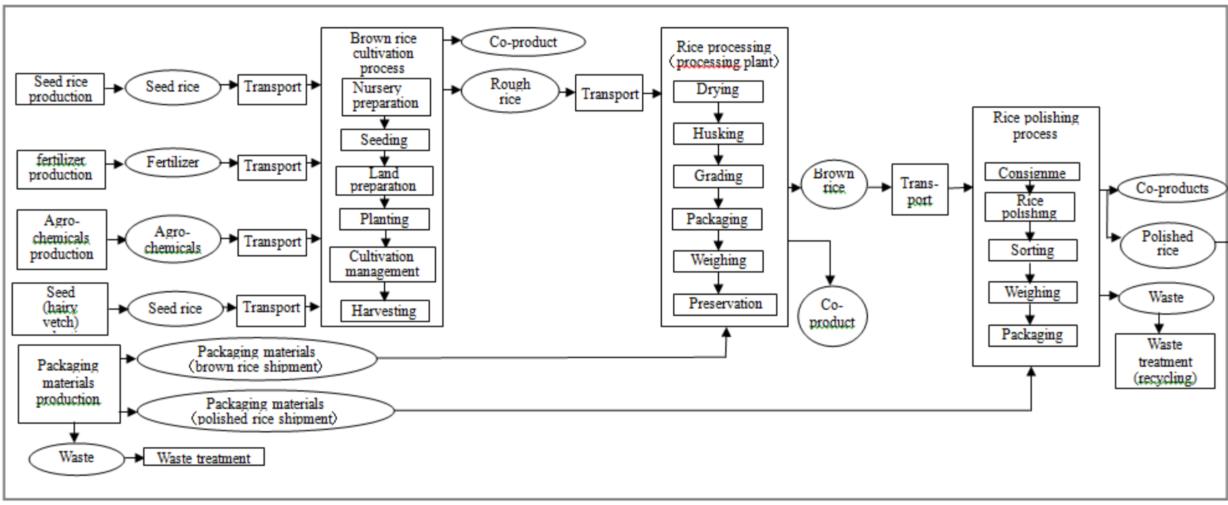

Figure 1. System boundary

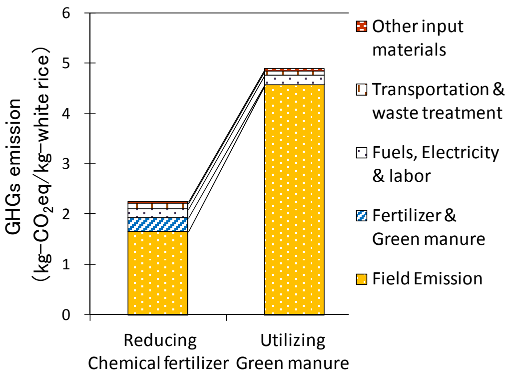

Figure 2. GHG emission from rice production

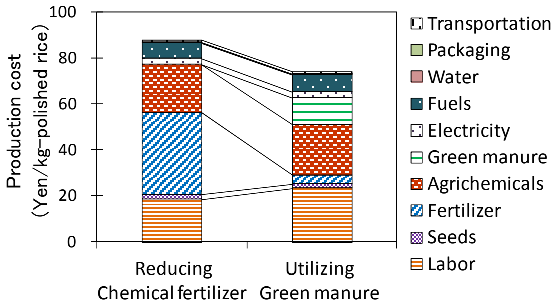

Figure 4. Production cost of rice

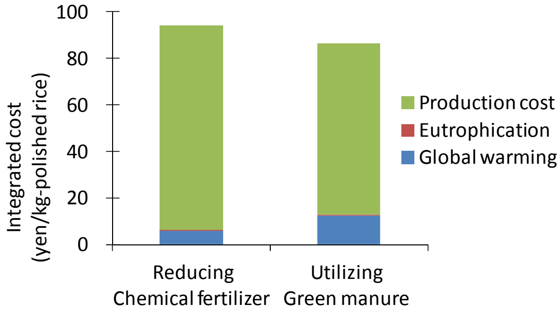

Figure 5. Estimated integrated cost

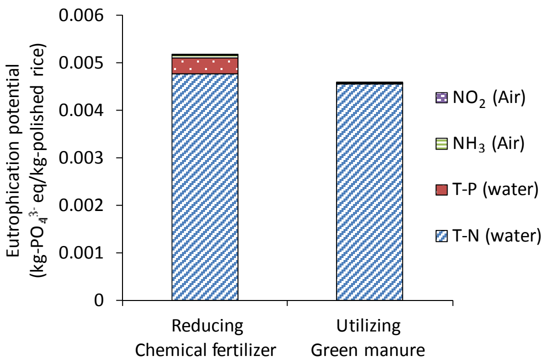

Figure 3. Eutrophication potential of rice production

important soil properties (bulk density, (initial) organic C content, pH, clay fraction) are measured.

Simulation period is 20 years to achieve nearly steady state of soil organic carbon pool by the target year. See Fumoto et al. [4] for more detail of the model.

3. Results and Discussion

Figures 2–4 present the impact based on the different categories. Life cycle GHG emission of RF rice is 2.25 kg-CO_2eq/kg-polished rice, while that of UG rice is 4.89 kg-CO_2eq/kg-polished rice. As for RF rice, 73%, 12%, and 8% of life cycle GHG emissions are field emission (CH_4, N_2O), fertilizer production, and fuel and electricity, respectively. CH_4 emission from UG rice accounts 2.8 times greater than that from RF rice owing to anaerobic decomposition of organic matter in green manure, and it accounts for 80% of the life cycle GHG emission. Lee *et al.* [6] reported approximation formula of field CH_4 emission from rice field applied Chinese milk vetch (*Astragalus sinicus* L.) based on field measurement in South Korea. Using this formula, CH_4 emission applying 31 Mg/ha (Rate in this study) of green manure is 3.2 times the case of no application, which is similar to this study.

UG rice has a 11% lower eutrophication potential than RF rice, while nitrogen load increases by incorporating green manure (Figure 3). With regard to the economic aspect, the production cost of UG rice, including the farmers' labor cost, is lower than that of RF rice owing to the low fertilizer cost, although the labor time is longer for cultivation work of hairy vetch (Figure 4).

The result of full cost assessment is shown in Figure 5. The percentages of environmental cost in the integrated

Table 2. Sensitivity analysis (GHG emission)

Case	Processes considerd	RF rice			UG rice		
		Supply chain	Field Emission	Total	Supply chain	Field Emission	Total
Flooding	Change beginning day of flooding (±1 day)	0.0% 0.0%	-1.9% 0.7%	-1.4% 0.5%	0.0% 0.0%	-3.3% 2.9%	-3.0% 2.7%
Fertilizer	Cahnge amount of fertilizer (±10%)	1.9% -0.9%	1.4% -0.6%	1.5% -0.7%			
Green manure	Amount of green manure incorporated (±10%)				0.0% 0.0%	6.0% -5.8%	5.6% -5.3%
Transportaition distance	Transportation distance of product & input materials (±10%)	1.6% -1.6%	0.0% 0.0%	0.4% -0.4%	2.0% -2.0%	0.0% 0.0%	0.1% 0.1%
Unit yield	Difference in unit yield (±10%)	-6.6% 8.1%	-9.1% 11.1%	-8.4% 10.3%	-4.9% 6.0%	-9.1% 11.1%	-8.8% 10.7%

Above: +10%/1 day, Below: -10%/1 day

cost of RF rice and UG rice are 9.1% and 15.8%, respectively. The total cost of UG rice is 91% that of RF rice, while the unit yield is 5% lower than for RF rice. To reduce the environmental cost of UG rice, reducing methane emission through the improved management of water and fertilizer should be considered.

Sensitivity is analyzed to investigate the effect of uncertainty due to the level of precision of the collected input data, the variations in climate, and farm practice schedules. Table 2 presents the cases analyzed and the results. “Field emission” denotes the change of field CH_4 and N_2O emission. “Supply chain” refers to the change of life cycle emissions through supply chain without field emission.

Postponing flooding decreases CH_4 emission, especially in UG rice cultivation, because more decomposable organic matter in green manure was decomposed under aerobic conditions. The effects of changes in fertilizer application include that of field emission change (both N_2O and CH_4), unit yield change, and content and amount of fertilizer input. When reducing fertilizer input by 10%, unit yield decreases 1.2% despite the fact that emission from the supply chain and field emission per cultivated area decrease 1.9% and 1.8%, respectively. Decreased application of green manure can reduce the field emission per cultivation area. This option is related to the timing of green manure incorporation. The options of flooding and fertilizer management (timing, content, amount) to reduce GHGs emission should be considered comprehensively, including yield change, decomposition of organic matter (CH_4 emission and carbon storage), and fertilizer manufacturing processes. These options also need to be tradeoffs between GHGs and other environmental loads and economic costs.

4. Conclusion

In this study, the DNDC-Rice model was applied to implement a comparative LCA of ecologically cultivated rice. This model can simulate CH_4 and N_2O emission by cultivation practices.

The life cycle GHG emission of rice cultivated with reduced chemical fertilizer is 2.25kg-CO_2eq/kg-polished rice, while rice that utilizes green manure (UG rice) is 4.89 kg CO_2eq/kg-polished rice, while rice that utilizes green manure (UG rice) is 4.89 kg-CO_2eq/kg-polished rice. The differences in emission are mainly due to field methane emission. The integrated cost of UG rice is lower, including environmental costs due to global warming, eutrophication, and economic cost, because of the lower fertilizer cost and the impact of eutrophication.

With regard to changes in fertilizer application, the output of both the DNDC-Rice and the LCA model affects the total impact significantly. It is important to consider life-cycle impact, the effect of yield change, the decomposition of organic matter, and the content/ manufacturing process energy of fertilizer when analyzing the mitigating options for GHG emissions in the field.

Future research needs to consider carbon storage in the field, which is not included in this study. It is also important to quantify the site-specific local impact, particularly in a closed water area, because impact factors in this study represent average values in Japan. Developing tools to describe both field emission and emission through the supply chain will be a necessary step in applying this model in other cases.

5. Acknowledgement

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6. References

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