

Improvement Potential of Life Cycle Greenhouse Gas Emissions from Paddy Fields: Assessing Influence of Sparse Transplanting and Non-puddling

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Abstract

This study conducted a life cycle assessment of new techniques and approaches in rice paddy cultivation. We evaluated reclaimed land in Hachirogata, located in Japan's Akita Prefecture. Non-puddling cultivation is a technique of planting rice without the puddling. A rotary plow is used to plant the rice in finely crushed soil. Non-puddling allows a delay in irrigation. Thus, the soil is less likely to become deoxidized and a smaller amount of methane gas is released from the disturbed soil. Sparse planting is a technique whereby the planting stalk density is reduced by 30% (21 stalks/m² to 15 stalks/m²), thereby reducing the material costs of producing seedlings. We found that use of the non-puddling technique reduced overall GHG emissions to 69% of those produced by rice cultivation using puddling. With sparse planting, GHG emissions were only reduced by a small amount to 93% of that of full planting. The current work shows that the appropriate mixture of sparse planting and non-puddling cultivation is necessary to obtain the greatest reduction in GHG emissions.

Discipline: Agricultural environment

Additional key words: Life Cycle Assessment, rice production

Introduction

Global warming is an environmental problem resulting in catastrophic climate change, creating climate disasters, such as a global rise in sea level, all of which have been attributed to the anthropogenic contributions of greenhouse gas (GHG) emissions. Agriculture and associated production activities have been identified as one of the causes of these greenhouse gases (FAO 2016). In rice fields that account for about half of the cultivated area in Japan, methane released from the decomposition of organic matter and other processes contributes to 78% of GHGs from those rice fields (Tsuruta & Ozaki 1999). The contribution of agriculture is not limited to direct emissions from rice fields. The upstream environmental impacts including those of fertilizer and pesticide production must be taken

into account in planning effective mitigation measures. Therefore, Life Cycle Assessment (LCA) or the accounting of life cycle GHG emissions (carbon footprint) has already been applied to agriculture (EDF 2016).

One of the important characteristics of LCA in agriculture is that direct GHG emissions from the fields, including those of carbon dioxide, methane, and nitrous oxide, have considerable effects on the results. For instance, since the volume of methane released accounts for 68% of the total greenhouse gases released during the life cycle (Hayashi et al. 2010), the assessment of direct GHG emissions is important in LCA of organic rice production systems (Blengini & Busto 2009, Hokazono et al. 2009, Hayashi et al. 2011, Hokazono & Hayashi 2012, Eduardo A. et al. 2015). Moreover, direct GHG emissions are dependent on agricultural practices, such as the type of manure and

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fertilization method employed. For example, a correlation exists between the fertilizer application rate and nitrous oxide emissions (Kimura et al. 1991). In addition, plowing the soil with rice straw increases the volume of methane released (Kimura et al. 1991). In Akita Prefecture where the study site is located, it became apparent that increases in greenhouse gas emissions and water deterioration were the result of applying livestock-derived organic resources (Harada et al. 2011, Hayashi et al. 2010, NARO 2010). Furthermore, it is known that methane emissions can be reduced by performing *Naka-boshi*—a method that involves the temporary draining of water from a rice field (Kimura et al. 1991)—and that lengthening the period of *Naka-boshi* can reduce the volume of emissions even more (NIAES 2012).

These characteristics imply that assessment by paying attention to site-specific conditions is crucial for LCA in agriculture; moreover, assessment combined with field measurement is a promising approach toward differentiating the environmental impacts of alternative cultivation techniques. Therefore, we calculated the life cycle GHG emissions from rice production systems in Akita Prefecture on the basis of field monitoring at the study site. The alternative cultivation techniques analyzed in this study were sparse planting cultivation and non-puddling cultivation. We conducted comparative LCA between the rice production systems by comparing the alternative techniques with those systems using conventional planting and puddling. Special attention was paid to GHG emissions per area, in addition to GHG emissions per crop yield. We scrutinized the influence of the alternative cultivation practices selected in order to estimate the improvement potential of alternative rice production systems.

Methodology and analysis

1. Study area

Ogata village in Akita lies at 140 degrees longitude east and 40 degrees latitude north. The area was created by the reclamation of Hachirogata, located at the base of the Oga Peninsula where large-scale rice cultivation is carried out. Because rice cultivation is a large-scale farming industry, labor-saving cultivation methods have been emphasized.

This soil corresponds to gray lowland soil (Gleyic Fluvisol) according to the WRB (1998). Originally, sludge covered the bottom of a lake, which has since been turned into arable land through reclamation. A predominantly strong clay with poor drainage, this soil hardened by shrinkage when it dries.

2. Cultivation techniques

In this study, we evaluated three different cultiva-

tion techniques: conventional cultivation, sparse planting cultivation, and non-puddling cultivation (sparse planting without puddling). Figure 2 shows the cultivation calendar for each technology.

(1) Sparse planting cultivation

Sparse planting cultivation is a generic term used to describe planting at reduced density as compared to that of conventional cultivation methods.

The density of sparse planting does not have a set definition. For instance, this study chronicled a 30% reduction in planting density, from 21 stalks/m² planted to 15 stalks/m². Given the reduced number of seedlings compared to conventional planting, functions such as labor, nursery processes, and seedling transportation are

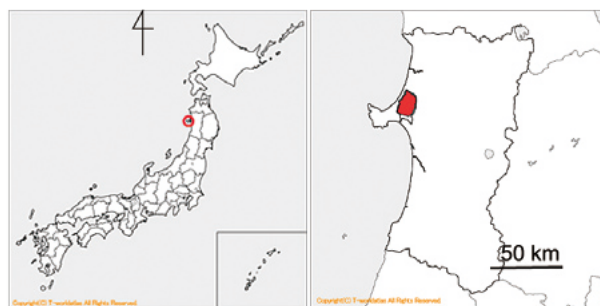
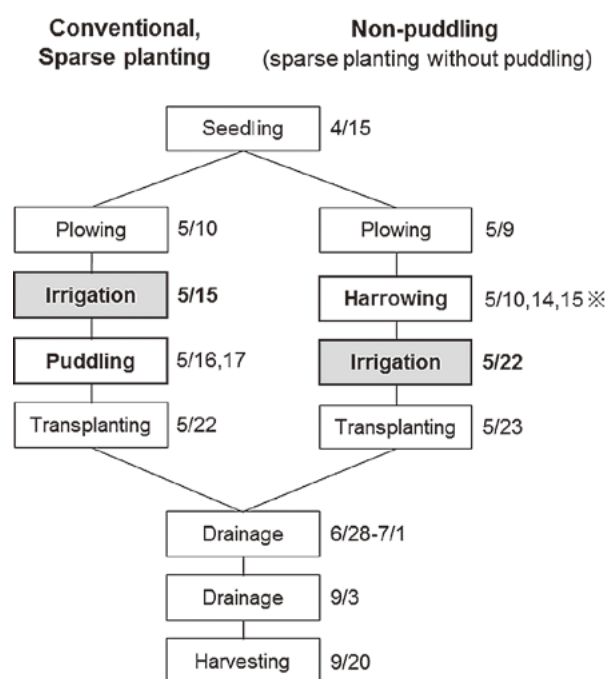


Fig. 1. Study area (Ogata-mura, Akita, Japan)



* Harrowing is usually carried out twice, but this time it was performed three times due to rain after one of those times.

Fig. 2. Cultivation Calendar (2013)

reduced. Material costs, such as for the bed soil, agricultural chemicals, and seedling boxes, are also reduced.

(2) Non-puddling cultivation (sparse planting without puddling)

Non-puddling cultivation entails the use of a drive-harrow two times after plowing, which means that rotary tilling is done without the puddling. This method has a high water quality conservation effect because there is no discharge of turbid water after puddling. Currently, non-puddling cultivation has been introduced to an area of about 300 ha in Ogata.

LCA was applied to the rice production systems in Ogata; specifically, the system using puddling cultivation was compared with the system using non-puddling cultivation. The study found that methane emissions from puddling cultivation and non-puddling cultivation were approximately equal. As a result, both emissions also have an equal impact on global warming. The reason for the shared results is that the flooding period before transplantation for both techniques was the same length (Harada et al. 2007). For

non-puddling cultivation, however, one report indicates that soil deoxidization can be reduced during the rice planting period (Nakayama & Sato 2001). Moreover, as it is possible to delay irrigation until immediately before transplantation, methane emissions could possibly be reduced by shortening the flooding period.

3. Test plots

Cultivation tests were conducted from 2011 through 2013 in rice fields of the Akita Prefecture agricultural experiment station (Ogata-mura, Akita). The test plot used a combination of both cultivation technologies, using three fields (a ~ c) located in three different places, each using measurement points (as per a growth survey and GHG survey). Each test plot is 0.1 ha in size. Table 1 lists the combination of each test group's technology. The rice variety called *Akitakomachi* was used.

Regarding water management, irrigation resulted in continuously flooded conditions from late May for transplantation until early July when drainage occurred for

Table 1. Inventory data

		Unit	a	b	c	Reference
			Conventional planting	Sparse planting	Sparse planting	
			Puddling	Puddling	Non-puddling	
Planting density	Number of seedlings	stalk /m ²	21	15	15	–
Fuel	Light oil		90	90	81	Akita Pref. (2009)
	Gasoline		65	59	59	
	Mixed oil: Gasoline	L/ha	32	32	32	
	Mixed oil: Lubricant		1	1	1	
	Kerosene		50	50	50	
Agricultural machinery	General	kg/ha	20	20	20	Akita Pref. (2009)
	Tillage		38	38	36	JAMA (2012) Interviews with farmers
Electricity		kWh/ha	10	9	9	Akita Pref. (2009)
Greenhouse	Steel	kg/ha	11	7	7	Akita Pref. (2009)
Fertilizer	Chemical fertilizer	kgN/ha	40.4	40.2	40.2	Interviews with farmers
	Organic fertilizer	kg/ha	563	563	563	
Pesticide	Insecticides		0.24	0.22	0.22	Interviews with farmers
	Fungicides	kg/ha	2.91	2.85	2.85	
	Herbicides		4.51	4.51	4.51	
Seeding	Rice seeds	kg/ha	25	18	18	Interviews with farmers
Other material	Nursery box		126	89	89	Akita Pref. (2009)
	Bed soil	kg/ha	750	525	525	
	Grain sack		47	47	47	

Naka-boshi. After *Naka-boshi*, intermittent irrigation was practiced.

The manure was based on a special cultivation farm products certification standard of Akita (less than the quantity of applying 40 kgN/ha on the farm), with the same application on each farm.

Fertilizer included sigmoid (a type that dissolves after a certain period of time, but not for some time after application) coated urea 100 type 40 kgN/ha (with the total amount of fertilization applied to one nursery box), and chicken manure pellets (analysis level T-C 30.7%, T-N 3.2%, CN ratio 9.7) 20 kgN/ha (with all-layer fertilization), for 60 kgN/ha in total.

The amount of additional fertilizer applied was adjusted depending on seedling growth. The amount of ammonia sulfate added at the nursery for a conventional planting plot was 1.5 gN/box (0.375 kgN/ha), and that for a sparse planting plot was 1.0 gN/box (0.180 kgN/ha).

In these test plots, we measured methane emissions and the yield. Measurements were conducted using bottomless square chambers made of colorless acrylic; each chamber measured 30 cm (D) × 60 cm (W) × 60 cm (H) in size. The lid was removable. From the height of rice beyond 60 cm, measurements were conducted in two stacked chambers measuring 30 cm (D) × 60 cm (W) × 120 cm (H) in size. A chamber was placed on each of the gas samplings. In order to not disturb the paddy during installation, embedded pedestals were positioned at the four corners of the chamber rides immediately after transplantation.

Gas sampling was carried out in a state where a plant is inside the chamber. There were four stalks in the chamber in conventional planting plots, and three in the sparse planting plots.

4. Fieldwork method

The items being surveyed included methane gas emissions, nitrous oxide gas emissions, rice growth and yield, and grain quality.

Methane gas was measured over the course of three years from 2011 to 2013, with nitrous oxide only being measured in 2013. Gas was gathered using the closed chamber method. The period for collecting the data lasted about three months from transplanting until full drainage. Sampling was done at approximately one-week intervals, between 9:00 a.m. and 12:00 p.m. Surveying was carried out on the same day for all test groups. Samples were collected a total of 12 times in 2011, 11 times in 2012, and 17 times in 2013. The sampling frequency in 2013 is larger as samplings had been added three times prior to transplantation and once after complete drainage. Methane was not found at any of these four times.

Emissions were calculated as follows: First, the value measured after 20 minutes is corrected to a value per

24 hours, and was regarded as the emissions per day. It was assumed to be a representative value of the period for about one week before and after the day of collection.

Methane and nitrous oxide gas concentrations were analyzed using a gas chromatograph.

5. Evaluation method of greenhouse gas emissions by LCA

(1) System boundary, impact area, and functional unit

Figure 3 shows this study's area of interest for LCA. For the purpose of investigating how much GHG emissions rice paddies contribute to our global atmosphere, we examined the production of rice, materials, fertilizers and pesticides, and the agricultural cultivation, harvest, drying and storage of rice. Buildings other than the nursery (e.g., warehouses, workshops), field maintenance, waterway maintenance, and the distribution and disposal of products were excluded from LCA. We also did not consider the absorption of carbon dioxide by the rice.

The functional unit of area was 1,000 m² (= 0.1 ha). The reasons for using a functional unit of area and not a yield are as follows: 1) the purpose of cultivation technology was not to increase yield and instead is an item to be evaluated (basin area per planted area) using other areas such as labor-saving costs, price reductions, and improvements in water quality; 2) another purpose was to evaluate GHG emissions from a rice field in line with cultivation technologies and methods; and 3) the distribution of crops post-harvest (considered the final stage of the life cycle) is not included.

(2) Using data

Data was analyzed using SimaPro8, the Dutch LCA modeling software produced by PRé Consultants Inc. Table 1 lists the main inventory data used in the analysis. Inventory data can be used as the measured field values, using the values in literature if the actual ones are not obtained.

The yield and volume of emissions used the values measured in the test plots. Machinery, fertilizer and pesticide data were obtained from interviews with farmers. Other items referred to a large system (on an assumed scale of 15 ha) of management index data for the rice paddies (Akita Prefecture 2009).

We sorted the life cycle of cultivation technology into seven processes (i.e., discharge from the surface of the field, fuel, machine production, artificial manure production, organic fertilizer production, pesticide production, materials) and evaluated the GHG emissions per area.

Emissions from a paddy are used as the value of GHG emissions generated from that paddy. As nitrous oxide rarely occurs, we only used methane emissions measured in the test plots.

We included light oil, gasoline, mixture oil, kerosene, and electricity in the fuel combustion process. The value

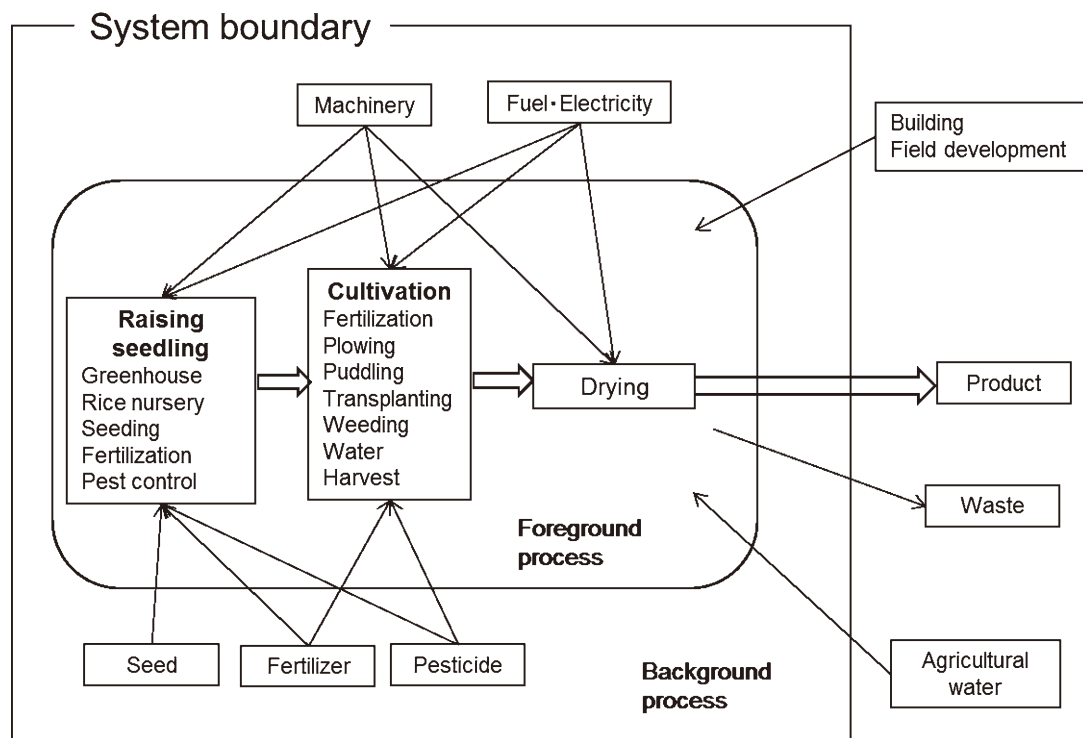


Fig. 3. System boundary of rice cultivation

obtained by summing up the fuel used in machine work was used such for the rice-transplanting machine, the combine, transportation via truck, and post-harvest drying. Electricity used for thermal insulation of the rice seed germination beds was also included.

Emissions from the manufacturing processes carried out by machinery and facilities (e.g., greenhouses) were measured using the total emissions divided by the actual useful life, and then used in the value per year. The number of years of machine use (depreciation) was required for an evaluation (in years) as close as possible to the machine's actual useful life, and was uniformly calculated at double the standard service life. A burden rate by the area to the machine was also set and made common between the items. The machine weight referred to agricultural machines according to a 2012/2013 facilities manual (Japan Agricultural Mechanization Association 2012). Repairs and the purchase of machine parts were not included in this analysis.

The production process of fertilizer was divided into chemical fertilizers and organic manure, which were calculated using component amounts of nitrogen, phosphorus, and potassium per unit area.

Pesticides were classified into five categories (i.e., insecticide, fungicide, insecticide/fungicide, herbicide, other) and measured by calculating the amount of active ingredients per unit area.

In the material manufacturing process, rice seed

materials to be used during seedling development, such as nursery soil, seedling boxes, greenhouses, and bags used for the harvest, were included in the inventory. Seed data was calculated using the weight of seeds that were sown per unit area. Materials were obtained by integrating the amount of a specific material per area by type (e.g., thermoplastic resin, stone or clay product). For the greenhouse, the weight of the steel pipe from the structure was determined by calculating the weight per area divided by the actual useful life and acreage.

Different GHGs have different types of impact on the atmosphere. The volume of emissions of each gas was multiplied by a coefficient to make it easy to compare gas emissions, and indicated the volume of carbon dioxide equivalent emissions. We used the IPCC method for GWP 100a in the evaluation. This multiplies methane by 21 and nitrous oxide by 310 in carbon dioxide equivalence, showing a 100-year impact with a numerical value using GWP (global warming potential), a formula established by the Intergovernmental Panel on Climate Change (IPCC). This same method of quantifying GHG emissions is also used under international treaties and agreements, including the Kyoto Protocol.

In sparse planting cultivation where the number of seedlings to be used is at a 30% decrease, the nursery area (greenhouse) is also reduced by 30%. As a result, the weight of the steel pipe included in the structural material

Table 2. List of the data used

Discharge process	Item	Data
–	Yield	<i>Brown rice yield</i>
Emissions from paddy	Gas emissions	<i>Methane</i>
Fuel	Fuel and power	Consumption
Machinery manufacturing	Machine	Type, machine name, actual useful life, burden ratio, extending acreage, weight
Chemical fertilizer manufacturing	Fertilizer	Trade names, <i>usage</i> , component content
Organic fertilizer production	Fertilizer	Trade names, <i>usage</i> , component content
Pesticide manufacturing	Pesticide	Trade names, <i>usage</i> , specific gravity, component amount, type
Materials manufacturing	Material	Trade names, <i>usage</i> , type, <i>weight</i>
	Seedling	<i>Amount to use</i>
	Greenhouse	<i>Area</i> , actual useful life, burden ratio, <i>acreage</i> , type, weight

Italics indicate the measured value.

of the greenhouse is reduced by 30%. Emissions according to the seedling box are then also reduced by 30%. Lastly, the seeding rate is reduced from 25 kg/ha to 17.5 kg/ha.

Sparse planting also reduces the number of times that seedlings are transported from the nursery to the rice paddies at planting time. Therefore, fuel consumption of the transportation truck is reduced by 30% (gasoline 20 L/ha → 14 L/ha). Energy consumption related to the nursery, such as electricity for heating or pesticide application to the nursery boxes, is also reduced by 30% (Table 1).

Also in this study, machinery and agricultural chemicals were the same in both trial cultivation methods, with some differences found during puddling and harrowing.

Emission reductions were also found in soil work methods. For example, when puddling is reduced, overall fuel consumption is reduced; however, where puddling does not occur, harrowing (which requires additional fuel) is required. Harrowing reportedly reduces greenhouse gases by 40% as compared to puddling (Harada et al. 2007). Therefore, the fuel consumption used for harrowing was assumed to be 40% less than that used for puddling. As a result, the total amount of light oil consumption per year is 90 L/ha for the puddling plot and 81 L/ha for the non-puddling plot.

Results

1. Methane emissions from paddies

(1) Comparison of conventional planting and sparse planting

The quantity of methane emissions from the surface of a sparse planting plot (test plot b) was compared with that of a conventional planting plot (test plot a) (Fig. 4).

The value of the conventional planting plot in 2012 was excluded as soil disturbance affected the results.

The amount of emissions in 2011 exceeded that in 2013. In 2011, the paddies did not dry out due to insufficient drainage, coupled with frequent rainfall after drainage. In 2013, there were less methane emissions due to the paddy surfaces being dry after drainage.

Methane emissions were calculated using the means of 2011 and 2013, at 248 kg/ha in the conventional planting plot, and 239 kg/ha in the sparse planting plot. The volume of emissions from the sparse planting plot was 96% of the total from the conventional planting plot. There were large variations in the sampling. There were no significant differences subject to ANOVA.

(2) Comparison of puddling and non-puddling in sparse planting

The amount of methane gas generated from the surface of the sparse planting plot was compared to those from the puddling plot (test plot b) and non-puddling plot (test plot c) (Fig. 4).

Emission amounts in 2011 were higher than those in other years due to insufficient drainage and frequent rainfall after drainage, resulting in the paddies not drying out. In 2012 and 2013, there were less methane emissions as a result of the surface being dry after drainage. Test sections showed different trends every year. In 2012, there was not much difference between the two types of planting. In 2011 and 2013, however, there was a large difference in methane production, with the non-puddling plot producing only about half of that from the puddling plot. The reasons for the small difference in 2012 were an earlier plowing date than in the other two years so as to accommodate weather

conditions, and a high plant growth rate in the non-puddling section.

The average value over the three years for the puddling plot is 227 kg/ha and that for the non-puddling plot is 146 kg/ha. The amount of methane emissions over the three years in the non-puddling plot was 64% less than that of the puddling plot. According to variance analysis of the results, there was a significant difference between the puddling plot and non-puddling plot.

2. Nitrous oxide emissions from paddies

It was confirmed that nitrous oxide gas rarely occurs in the paddy fields on reclaimed land in Hachirogata (Harada et al. 2007).

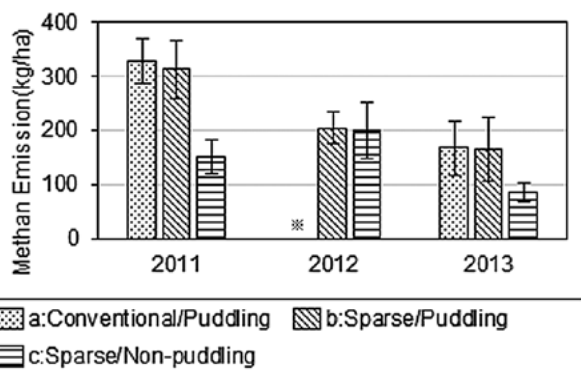
Nitrous oxide was measured 12 times from April to October 2015. Total emissions during this period were 0.7 gCH₄/m² from the conventional plot, -0.5 gCH₄/m² from the sparse planting plot, and -0.7 gCH₄/m² from the non-puddling plot. There was no significant difference due to puddling or planting density. There was no significant gas evolution reaction observed before irrigation and after drainage.

3. Global warming effect of rice

(1) Greenhouse gas emissions of paddy fields with different planting density

Figure 5 shows the GHG emissions for both the conventional planting plot (test plot a) and the sparse planting plot (test plot b). The average value over the three years from 2011 to 2013 is used.

The discharge process of emissions from the paddies accounted for most ratios in both plots and accounted for 87% of the total discharge. Emissions from other processes are in descending order as follows: chemical fertilizer



* missing
 error bars = the standard deviation
 The plowing dates: May 18-26, 2011, Apr. 19-20, 2012, and May 9-10, 2013

Fig. 4. Methane emissions

production, machinery manufacturing processes, and material manufacturing processes. Each of these processes contributed around 3% of the total emissions. These results suggest that the most efficient way to reduce greenhouse gas emissions from rice cultivation is to mitigate methane production from the actual paddies.

We compared the conventional planting plot and the sparse planting plot by process. Where foreground processes are concerned, methane production was nearly identical with sparse planting, producing 96% of the GHGs produced by conventional planting. Similarly, regarding material manufacturing processes, sparse planting yields 94% of the GHGs produced in conventional planting. It is the impact of fewer seedling boxes that reduces the overall GHGs. Little difference in emissions was noted regarding background processes (fuel, machinery, chemical fertilizers, and organic fertilizer production).

After looking at all the factors in our test plots, GHG emissions produced in sparse planting totals 97% of those in conventional planting. In other words, sparse planting only mitigates GHG emissions by 3%.

(2) Greenhouse gas emissions from each process according to the presence or absence of puddling

Figure 6 shows the GHG emissions for the sparse planting puddling plot (test plot b) and the sparse planting non-puddling plot (test plot c). The average value over the three years from 2011 to 2013 is used.

The puddling plot and non-puddling plot for each discharge process were compared. Where foreground processes are concerned, actual emissions from the paddies are responsible for the most significant difference between the plots. The volume of emissions from the non-puddling plot account for only 64% of those discharged from the puddling plot.

Regarding background processes of the machinery manufacturing and fuel processes, the non-puddling plot produced 97% of emissions produced by the puddling plot.

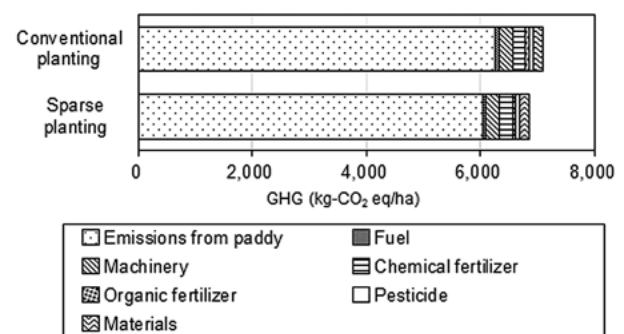


Fig. 5. Emissions for each greenhouse gas source in conventional planting plot (a) and sparse planting plot (b) (Average value of 2011 & 2013)

There was a difference in machinery, such as a harrow for non-puddling, which is used to break up and aerate the soil. The differences between emissions for the other processes (chemical fertilizer, organic fertilizer, and pesticide production) were negligible.

The total GHG emissions for the non-puddling plot were 69% of those for the puddling plot. Non-puddling can therefore mitigate GHG emissions by 31% in rice cultivation.

4. Yield

It has been pointed out that when irrigation is implemented after harrowing, just prior to transplantation, the yield and quality of rice can be adversely affected due to transplant inaccuracy and the lack of seedling growth in non-puddling cultivation (Kumano et al. 1985).

The yield was measured in each test group. The yields in the present study show that the conventional planting area yielded 590 g/m², sparse planting with puddling yielded 561 g/m², and sparse planting with non-puddling yielded 584 g/m². The quality of rice from harvests using the new techniques also matched the quality obtained by conventional practices (NARO 2012).

Variance analysis of the results showed no significant difference in yield or quality due to the presence or absence of puddling, or difference in planting density.

Discussion

This study evaluated the impact of new and conventional rice cultivation techniques on global warming by measuring GHGs per unit area. Cultivation techniques that were evaluated include conventional practice, sparse planting cultivation, and non-puddling cultivation.

The experiments showed no significant differences in methane gas emissions between the sparse planting plot and conventional plot. While the number of seedlings was

reduced, thereby reducing emissions during some processes such as nursery operations, overall emission reductions were small. Using LCA, we were able to calculate that GHGs were mitigated by merely 3%.

Methane gas emissions from the non-puddling plot, however, were only 64% of those from the puddling (or conventional planting) plot; in other words, GHG emissions were mitigated by 31%.

Table 3 lists the current GHG emission test results with the values reported in previous studies. Methane emissions at 5,520 kg CO₂eq/ha for the puddling plot are larger than those in the corresponding technique at 4,120 kg CO₂eq/ha as reported by Harada et al., both of which were measured in the same Ogata plot. Meanwhile, emissions from the non-puddling plot were valued at 3,290 kg CO₂eq/ha, and thus significantly smaller than the corresponding value of 4,190 kg CO₂eq/ha (reported by Hayashi et al. 2010).

In the experiment conducted by Harada et al., irrigation for both the puddling plot and non-puddling plot began at the same time prior to transplantation. Conversely in our study, irrigation began just before transplantation to delay irrigation of the non-puddling plot.

In another test that measures the oxidation-reduction potential (Eh) of paddy fields in the Ogata plot, the drop rate of Eh was slow in the non-puddling test area, which is a result of delayed irrigation. The minimum value, therefore, remained higher than for the puddling area (Ito et al. 2013). Even in this test, since irrigation occurred in the same order, just before transplantation, the drop in Eh for the non-puddling plot is behind that for the puddling plot, and the resulting high numerical value continues, therefore methane emissions were believed to actually decrease.

Nitrous oxide was measured in 2015. The total emissions during this period were less than those in previous years. There was no significant difference due to the presence or absence of puddling, or the difference in planting density. No significant gas evolution reaction was observed before irrigation and after drainage.

Methane emissions are known to be reduced when removing rice straw from a paddy field (Yagi & Minami 1990). Table 3 lists only those experiments where rice straw had not been removed. The effect due to the presence or absence of a plow inclusive of rice straw was excluded.

Originally, a large proportion of the methane gas contribution originated from the paddy fields. The ratio of methane emissions in our present study (comparing our conventional plot with our sparse planting plot and non-puddling plot) is calculated to range from 81% to 87% between the sites' total GHG emissions, thereby showing a relatively large value difference compared with the value reports of other studies.

This leads to our conjecture that the quantity of GHG reductions could be greatly reduced by introducing these

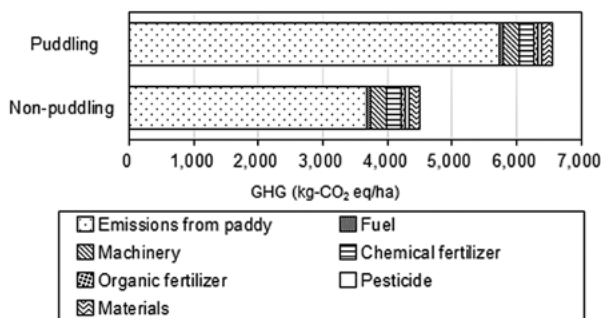


Fig. 6. Emissions for each greenhouse gas source in puddling plot (b) and non-puddling plot (c) (Average value of 2011-2013)

Table 3. GHG emissions and methane emissions in rice cultivation

Target		① GHG emissions kg CO ₂ eq/ha	② CH ₄ emissions kg CO ₂ eq/ha	②/① %	Remarks
This study	Conventional	6340	5520	87.1	Ogata
	Sparse planting, puddling	5870	5030	85.7	Large-scale management
	Sparse planting, non-puddling	4050	3290	81.2	Until drying and preparation
Harada et al.	Soil puddling	4290	4120	96.0	Ogata Large-scale management
	Non-tillage	2520	2350	93.3	Fertilizer machinery
	Non-puddling	4390	4190	95.4	manufacturing is excluded. Pesticides: only herbicide
Tsuruta, Ozaki	5100	3990	78.2		
Hirai et al.	Farmer A	6530	4490	68.8	Fukuoka, rice terrace
	Farmer B	6610	4490	67.9	Until drying and preparation
Kurosawa et al.	Conventional	5870	3360	57.2	Shiga, medium-sized mechanized system
	Environmental protection type	5160	3360	65.1	Until drying and preparation
Hokazono et al.	Conventional	9000	4700	52.2	
	Sustainable	7400	4700	63.5	Until shipment
	Organic	8100	4700	58.0	
Masuda et al.	Conventional	4660	1470	31.5	Shiga, Until shipment
	Reduce fertilizer & pesticide	4980	1940	39.0	Machinery manufacturing is excluded.

cultivation techniques to large operations. For example, sparse planting cultivation can be introduced into almost all rice fields. If sparse planting cultivation were introduced to 50% of the nation's paddy fields, it would reduce emissions by 369,655 t-CO₂eq/year. Non-puddling cultivation can only be introduced to paddy fields made of heavy clay, such as on reclaimed land. The possible area for introducing non-puddling nationwide is currently unknown. However, introducing sparse planting cultivation and non-puddling cultivation to 50% of the paddy fields in Ogata would make it possible to reduce emissions by 11,565 t-CO₂eq/year in that village alone.

Conclusion

In this study, we used LCA to assess new techniques that could be introduced into rice cultivation. Our findings are as follows:

① In sparse planting cultivation, GHG emissions are reduced by 3%. If irrigation is carried out prior to transplantation, non-puddling cultivation can mitigate GHG emissions by 31%. Emission reductions from non-puddling cultivation are high. We can thus conclude that the largest proportion of such reductions result from mitigation processes that occur in the paddies. However, that conclusion does not mean we should

avoid reductions through other means.

② If sparse planting cultivation were introduced to 50% of the rice paddy fields in Japan, greenhouse gas emissions could be reduced by an estimated 370,000 t-CO₂eq/year. By introducing sparse planting and non-puddling (irrigation just before transplantation) to 50% of the paddy fields in Ogata alone, emissions could be reduced by 10,000 t-CO₂eq/year.

Scientists have warned us of the inevitable future of global warming. In an effort to reduce GHG emissions and the resulting global warming, we must implement agricultural techniques that mitigate GHG emissions and which also perform well at higher temperatures. This study aims to evaluate cultivation techniques and also show the need for the further development of other cultivation techniques. For the development of new technology, efforts to evaluate and accurately calculate GHG emissions will become increasingly necessary in the future.

References

- Akita Prefecture (2009) *Sakumotubetu gijutu & keiei shiho* (Index of a technique and the management according to the crops). 2008 version [In Japanese].
Akita Prefecture: Bi-no-Kuni Akita. <http://www.pref.akita.lg.jp/www/contents/1204536315794/index.html>

- Blengini, G. A. & Busto, M. (2009) The life cycle of rice: LCA of alternative agri-food chain management systems in Vercelli (Italy). *Journal of Environmental Management*, **90**, 1512-1522.
- EDF (Environment and Development Foundation) (2016): PCR Library, http://pcr-library.edf.org.tw/product_category/agriculture.asp
- Eduardo A. et al. (2015) Greenhouse gas emissions from conventional and organic cropping systems in Spain. I. Herbaceous crops, *Agron. Sustain. Dev.*, **35**, 713-724.
- FAO: Helping countries reduce agricultural greenhouse gas emissions. <http://www.fao.org/news/story/en/item/180351/icode/>
- Harada, H. et al. (2007) Reduction in greenhouse gas emissions by no-tilling rice cultivation in Hachirogata polder, northern Japan: Life-cycle inventory analysis. *Soil Science and Plant Nutrition*, **53**, 668-677.
- Harada, H. et al. (2011) Effect of no-puddling and organic fertilizer application on water pollutant loads from paddy fields. *Nippon dojohiryogaku zasshi (Jpn. Soc. Soil Sci. and Plant Nutr.)*, **82**, 97-104.
- Hayashi, K. et al. (2011) Potential of organic farming as viewed from LCA. *Nogyo oyobi engei (Agriculture and horticulture)*, **86**, 537-540 [In Japanese].
- Hayashi, M. et al. (2010) Effect of Organic Matter Application on Greenhouse Gases Emissions from Paddy Soil. *Tohoku nogyo kenkyu (Tohoku Agric. Res.)*, **63**, 15-16.
- Hirai, Y. et al. (2012) Energy consumption and greenhouse gas emissions associated with rice production in rice terraces. *Shisutemu nougaku (Jour. of the Japanese Agric. Syst. Soc.)*, **28**, 47-56 [In Japanese with English summary].
- Hokazono, S. et al. (2009) Potentialities of organic and sustainable rice production in Japan from a life cycle perspective. *Agronomy Res.* **7** (Special issue I), 257-262.
- 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. *Journal of cleaner production*, **28**, 101-112.
- Ito, C. et al. (2013) Caused by the irrigation immediately before implantation in non-puddling cultivation, the effect of the suppression of methane gas generation and rice growth. *Akita Prefecture Agricultural Experiment Station Research Times*, **52**, 27-28 [In Japanese].
- Japan Agricultural Mechanization Association (2012) 2012/2013 *Agricultural Machine and Facilities Manual*. Japan Agricultural Mechanization Association, Tokyo, JAPAN.
- Kimura, M. et al. (1991) Methane Emission from Paddy Field (Part 1) Effect of Fertilization, Growth Stage and Midsummer Drainage: Pot Experiment. *Environ. Sci.*, **4**, 265-271.
- Kumano, S. et al. (1985) Studies on Puddling in Mechanically Transplanted Rice Cultivation. *Bull. of the Tohoku National Agricultural Experiment Station*, **72**, 1-53 [In Japanese with English summary].
- Kurosawa, M. et al. (2007) Estimation of Energy Consumption and Environmental Impact Reduction by Introducing Sustainable Agriculture to Rice Paddy Field Cultivation. *Jour. of Life Cycle Assessment, JAPAN*, **3**, 232-238 [In Japanese with English summary].
- Masuda, K. & Tomioka, M. (2013) Life Cycle Assessment of Greenhouse Gas Emissions from Environmentally Friendly Rice Production. *Nouringyo mondai kenkyu (Jour. of Rural Problems)*, **190**, 219-224 [In Japanese with English summary].
- Mingxin, W. et al. (2010) Life Cycle Assessment of a Rice Production System in Taihu Region, China. *The International Journal of Sustainable Development and World Ecology*, **17**, 157-161.
- Nakayama, H. & Sato, N. (2001) Improvement of Plant Growth and Properties of Soil in Non-Puddling Paddy Field. *Tohoku nogyo kenkyu (Tohoku Agricultural Research)*, **54**, 51-52 [In Japanese].
- NARO (2010) *Tohoku nogyo kenkyu seika joho (Tohoku agric. Res. Info.)*. <http://www.naro.affrc.go.jp/org/tarc/seika/jyouhou/H22/suitou/H22suitou016.html>
- NARO (2012) *Tohoku nogyo kenkyu seika joho (Tohoku agric. Res. Info.)*. <http://www.naro.affrc.go.jp/org/tarc/seika/jyouhou/H24/kankyuu/H24kankyuu009.html>
- NIAES (2012) [*global warming countermeasures*] *New water management technology manual to control the emissions of methane generated from paddy field*. www.niaes.affrc.go.jp/techdoc/methane_manual.pdf
- Tsuruta, H. & Ozaki, Y. (1999) A life cycle assessment in rice paddy fields for greenhouse gases and water quality. *Norin suisan gijutu kenkyu journal (Res. journal of food and agric.)*, **22**, 20-25 [In Japanese].
- Yagi, K. & Minami, K. (1990) Effect of Organic Matter Application on Methane Emission from Some Japanese Paddy Fields. *Soil Sci. Plant Nutr.*, **36**, 599-610.