Comparison of soil fertility and the N, P and K balance in the paddy fields under conventional rice straw application versus cow dung compost application in mixed crop–livestock systems

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ABSTRACT

After the rice harvest in Japan, rice straw (RS) is usually cut by combine harvester and incorporated into the soil to improve its fertility. In mixed crop–livestock systems, however, RS is collected and used as livestock feed, and cow dung compost (CDC) is then applied to the soil. This system utilizes the residual organic matter from both rice production and livestock husbandry to make each product. CDC application is also considered to improve the fertility of paddy soil. But, the nutrient input from CDC and the effect of CDC application on soil fertility vary among regions and/or soil types. We compared soil fertility between RS application (RS treatment, avg. 32 years) and RS removal plus CDC application (CDC treatment, avg. 21 years) in 79 paddy fields in Mamurogawa town, Yamagata Prefecture, a cold temperate region of Japan, and measured the nutrient contents in the applied RS and CDC. The total C content of RS was significantly higher than that of CDC, whereas the N, P, K, and Si contents of CDC were significantly higher than those of RS. However, there was no significant difference in paddy soil fertility—as measured by soil organic C, total N, CEC, available N, P, and Si, exchangeable K, Ca, and Mg, base saturation percentage, pH, and bulk density—between the treatments. The soil fertility of most fields was adequate by RS or CDC treatment. Thus, leaving RS in paddy fields or removing it and then adding CDC to the paddy fields has a similar effect in maintaining adequate soil fertility for single rice production or rice–livestock production systems

To clarify the result of higher nutrient input from CDC but non-significant difference in soil fertility between treatments, we investigated on the nutrients (N, P, and K) balance in the RS and CDC treatment. From 79 selected fields, we chose 10 pairs fields (RS treatment and CDC treatment are nearby) to conduct this research. We measured the nutrient inputs (organic matter,

fertilizer, and N fixation in case of N) and the nutrient outputs (plant uptake and leaching) and calculated the nutrient balance of the pair fields. The result showed that: **(1) N balance**: The N fertilizer contributed the highest percentage to the total N input followed by organic matter and the lowest one was N fixation. The N fertilizer and N fixation in the RS treatment were non-significant difference with those in the CDC treatment. CDC contribute significantly higher N to the fields than RS, but the total N input was non-significant difference between treatments. The plant N uptake was higher in the CDC treatment, but the difference was not significant. Plant N uptake was the main output, accounting for 98% of total N output. The N leaching loss did not contribute significantly to the total output. The N balance was positive and non-significant difference between treatments. Therefore, non-significant differences in total N input, total N output, and N balance between treatments were the reason for non-significant difference in soil total N and available N of paddy field. **(2) P balance:** P input from CDC to the field was higher than that from RS, while fertilizer P in the CDC treatment was lower than that in the RS treatment. The higher amount of P input from CDC was depleted by the higher amount of fertilizer P applied in the RS treatment, which lead to the same level of total P input between treatments. The plant P uptake was the main output, accounting for 99 % to the total P output. The P leaching loss was small and negligible. The difference in plant P uptake and P leaching between treatment was not significant, which lead to non-significant difference in total P output. Overall, the non-significant difference in soil available P between treatments come from non-significant difference in total P input, total P output, and P balance between treatments. **(3) K balance:** The contribution of organic matter in total K input was higher than that of fertilizer. The difference in K input from organic matter and fertilizer between treatments was not significant, which resulted in non-significant difference in total K input to the paddy field.

The plant K uptake was the main output, accounting for 90% of total K output. It was non-significant difference between treatments. The leaching loss was a significant amount and should be considered as a main output of K from the paddy field. The RS and CDC treatments resulted in the same level of K leaching loss. The total K output, therefore, was non-significant difference between treatments. Overall, the non-significant difference in total K input, total K output, and K balance were the reason for the non-significant differences in soil exchangeable K.

Aside from the main research on the nutrients balance, we also measured the nutrients (N, P, K, Si, Ca, and Mg) and total C concentration in the plow layer water and leaching water to understand the changing of nutrients and soluble C during cropping season and how they move through from paddy field in the RS and CDC treatments. We found that in plow layer water the concentration of all of nutrients and C excepted for P increased after transplanting, reached to the peak, and decreased after that. The plenty of input before and/or at transplanting by organic matter and fertilizer and poor rice plant uptake resulted in the higher concentration in the plow layer water at early growth stage. Plant nutrients uptake, emission, and soil adsorption can explain to the decrease in the nutrient concentration in plow layer water. The increasing in the concentration of K, Si, Ca, and Mg in leaching water may result in the sharply decreased in their concentration in the plow layer water. In case of N and C, the concentration in the plow layer water did not have relationship with the concentration in leaching water. P is a special nutrient, absorbed firmly in soil, so that there was few P existing in plow layer and leaching water. The concentration of N, P, K, and C in plow layer water and leaching water were similar in the RS and CDC treatments, and the concentration of Si, Ca, and Mg in plow layer water and leaching water were higher in the RS treatment than the CDC treatment.

Overall, the RS and CDC treatments resulted in the same level and at fertile level of soil fertility. The input of nutrients from CDC was higher than that from RS but the total input, total output of the CDC treatment was non-significant difference with that of the RS treatment. This led to non-significant difference in nutrients balance between treatments. Therefore, the non-significant difference in total nutrients input and output, and the nutrient balance were the reason for non-significant difference in soil fertility between treatments. The amount of fertilizer P in this area can be reduced especially in the CDC treatment. And, the removal of RS resulted in negative K balance if there is no CDC application. Although the N, P, and K balance were positive, total N and P, available N and P, and exchangeable K in soil did not increase for three years of the study duration in both the RS and CDC treatments.

I. GENERAL INTRODUCTION

1.1. Rice production in the world and in Japan

Rice (*Oryza sativa* L.) is an important primary food crop in the world, being the staple food of more than half of world's population. As the world population increased, the total rice consumption also witnessed an increasing, from 437 million metric tons in 2008 to 490 million metric tons in 2019 (FAO, 2019). Most of rice has been consumed by Asian countries, but recently the rice consumption in African and south American countries gradually increased. To meet the demand for rice, the total rice production area continuously increased from 147 million ha in 1990 to 167 million ha in 2017. The expansion of the production area and the increase in the yields results in the steady increase in total production quantity from 519 million tons in 1990 to 770 million tons in 2017 (FAO, 2019). By being highest rice consumption continent, Asia also contributes the largest amount of rice production to the world total rice production accounting for 90.7 % (Fig. 1) (FAO, 2019). Among countries, China and India have largest rice production area, highest grain production, and highest rice consumption due to their huge population (Fig.2) (FAO, 2019). Therefore, from those data, rice production will still increase and keep an important position in agricultural system of the world.

In Japan, rice production has been practiced in long time, and it is an important crop in agriculture, about 54% of the total farms are used for paddy rice production with the main varieties being improved japonica (MAFF, 2019). However, the number of Japanese households and farm population has declined in recent decades which also caused the decline in rice production from 2.07 million ha in 1990 to 1.47 million ha in 2017, and the production quantity also decreased from 13.1 million tons to 9.8 million tons, respectively. However, Japanese rice consumption is still in 9th place in the world (Fig. 3) (Statista, 2019). So, the rice farming is still important part in Japanese agricultural system.

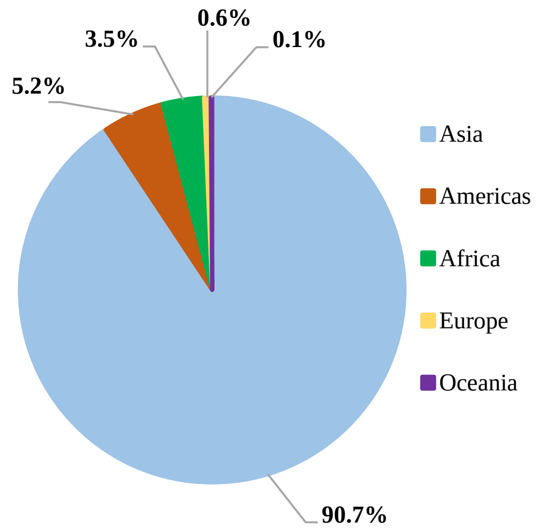


Figure 1. Production share of rice paddy by regions (avg. 1994 – 2017)

(accessed FAO data in Oct. 2019)

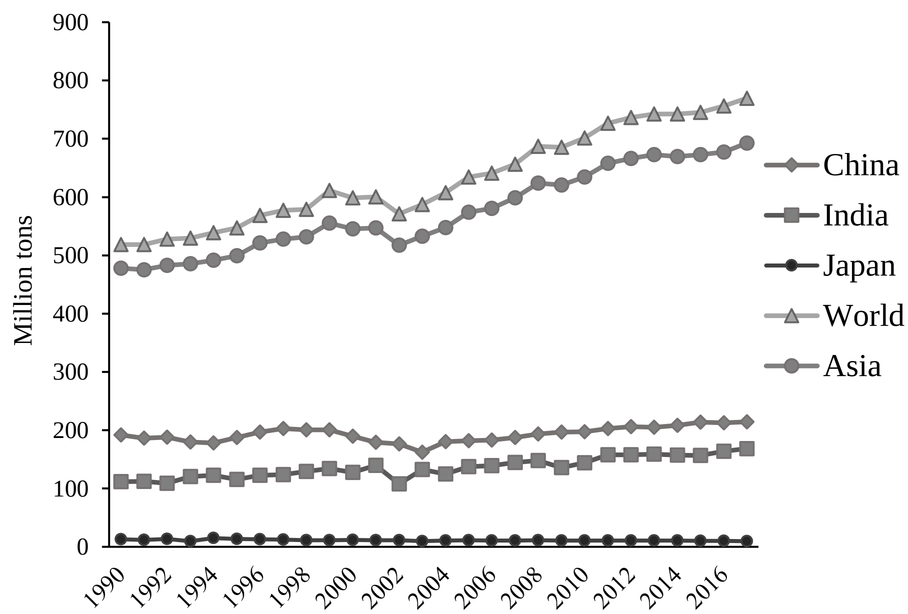


Figure 2. Rice production in the world and parts of Asia from 1990 to 2017

(accessed FAO data in Oct. 2019)

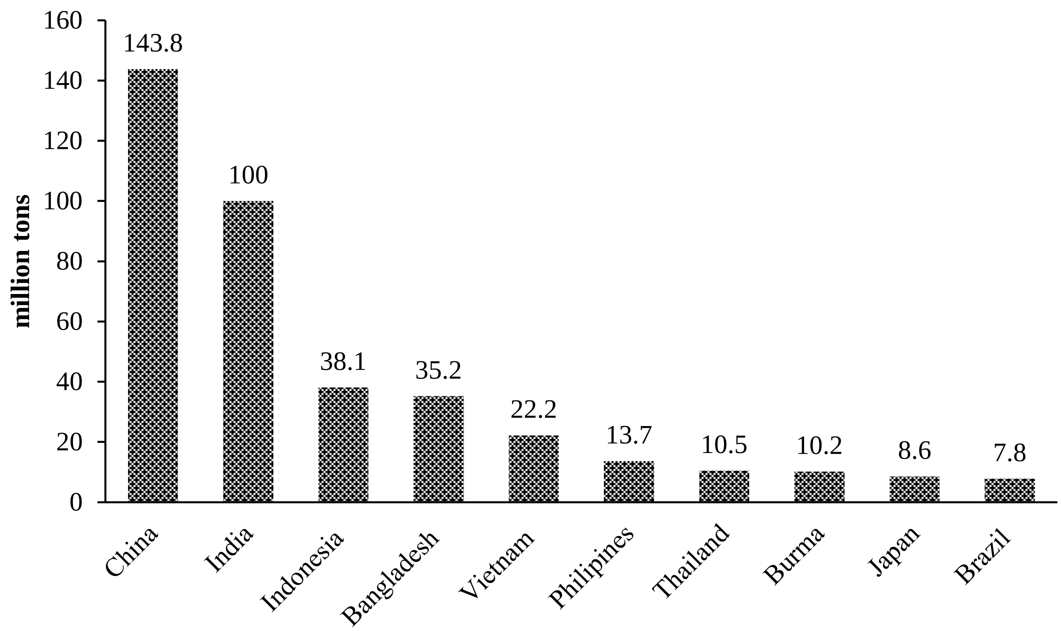


Figure 3. Top ten highest rice consumption countries in the world in 2019

(Statista accessed, 2019)

1.2. The usage of rice straw (RS) in rice production area and its effects to soil fertility and environment

RS is a abundant biomass biproduct in rice production areas. It has been used in various ways such as incorporation into the soil, feed for animals, fuels, mushroom production, munching for vegetable, and burning. RS is a good source of input nutrient to the field. It contains about 0.6–0.8% of nitrogen (N), 0.10–0.15% of phosphorus (P), and 1.5–2.0% of potassium (K) in dry matter base (Dobermann and Fairhurst 2000). Therefore, the practice of remaining rice straw on the field after harvest maintains the nutrient in the field.

Soil fertility is the ability of soil to supply nutrient to plant, and it is evaluated by chemical, physical, and biological properties. To keep a sustainable agriculture system, maintaining soil fertility is important point. However, in tropical areas where rice is produced two or three times in a year such as Vietnam, Thai, Philippine, etc., RS is usually burned after the first season or collected for other purposes such as feed or bedding for livestock, munching for crop, fuels, and for mushroom production. It is because the duration between two cropping seasons is short and this duration is not enough for RS decompose. Among those practices, burning is the common practice because it is convenient and cost-effective method. However, the burning causes almost complete N loss, P loss of about 25%, and K loss of 20% even the nutrients lost also depends on the burning method (Dobermann and Fairhurst 2002). Besides, open field burning RS also emit large amount of CO_2, CO, CH_4, and N_2O, which cause atmospheric pollution (Miura and Kanno 1997; Gadde *et al.* 2009). The usage of RS for munching, fuels, and mushroom production cause the loss of nutrient from the field.

In the temperate area such as Japan, Korea, and China where rice is cultivated once a year, the practice of RS incorporation into the soil is popular and has been proven to increase soil fertility (Nie *et al*. 2007; Liao *et al*. 2013; Cheng *et al*. 2016; Takakai *et al.* 2019). The application of RS, however, also increases greenhouse gas (GHG) emissions during the cropping season (Naser *et al*. 2007; Bhattacharyya *et al*. 2012; Liu *et al*. 2015; Zhang *et al*. 2017), especially in cold areas where RS cannot decompose during winter (Naser *et al*. 2007; Nakajima *et al*. 2016). Thus, the application of RS in paddy field is not environmentally-friendly-way of using RS.

In mixed crop-livestock system, RS is taken to feed cows and cow dung compost (CDC) is then applied to the field. This system can be applied in areas where rice production and cow husbandry occur nearby. It is because the waste of cow husbandry is not suitable to transport in long-distance (Tarumoto 2001; Tanigawa *et al.* 2006). This mixed crop-livestock system can solve the environmental problem of gas emission and pollution caused by animal waste.

Different from RS, CDC is composted before applied to the field which can reduce the methane emission (Yagi and Minami 1990; Kumagai *et al*. 2010; Das and Adhya 2014). The usage of RS as feed also can reduce the cost for livestock husbandry.

Therefore, in the view of maintaining soil fertility, environmental aspect, economical aspect, the use of RS as feed for cow in mixed crop–livestock system is the best way of using RS. However, the effect of CDC application on soil fertility in mixed crop–livestock system in comparing to RS application is still not well-known and the results is different among regions and/or soil types.

1.3. The importance of understanding nutrient balance in paddy fields and their relationship with soil fertility

To maintain soil fertility, the nutrient balance information is important. The nutrient balance provides information on how much nutrient input to the field, how much nutrient loss through field, and how much nutrient stay in the field. In paddy field, the sources of nutrient input are fertilizer, organic matters, irrigation water, rainfall, and N fixation in case of N. The sources of nutrient output are plant uptake, leaching, runoff, and denitrification and ammonium volatilization in case of N. By understanding nutrient balance, we know how much nutrient need to apply to the field to keep the positive nutrient balance in the field, and how to reduce the side effect of rice production on environment such as gas emission or ground water pollution by nutrient leaching.

To understand the effect of organic matter on soil fertility, the information of input and output provided by other than organic matter is necessary. Among input sources, fertilizer and organic matter can be managed the application amount and timing by farmers. The higher nutrient input from CDC to the field may let farmers to reduce the amount of fertilizer. Since green revolution the chemical fertilizer is main input nutrient to the field. The overuse of chemical fertilizer, however, economically increased the cost of rice production and cause environmental pollution such as leaching to ground water or denitrification and ammonia volatilization in case N. By understanding the nutrient balance, it is possible to minimize the fertilizer amount and maintain soil fertility.

1.4. Objectives

The objectives of this research are (1) to compare the soil fertility of paddy fields under conventional RS application and CDC application in mixed crop-livestock system to understand the effect of mixed crop-livestock system on paddy soil fertility, (2) to understand the nutrients balance of paddy fields under conventional RS application and CDC application in mixed crop-livestock system to optimize the fertilizer management to maintain soil fertility economically with environmental conservation.

II. CHAPTER I: Comparison of paddy soil fertility under conventional rice straw application versus cow dung compost application in mixed crop–livestock systems in a cold temperate region of Japan

2.1. Introduction

RS is a good source of nutrients for paddy fields, and its incorporation improves soil fertility (Nie *et al*. 2007; Liao *et al*. 2013; Cheng *et al*. 2016; Takakai *et al.* 2019). However, RS application also increases GHG emissions during the cropping season (Naser *et al*. 2007; Bhattacharyya *et al*. 2012; Liu *et al*. 2015; Zhang *et al*. 2017), especially in cold areas where RS cannot decompose during winter (Naser *et al*. 2007; Nakajima *et al*. 2016). In contrast, CDC is decomposed before being applied to fields, which leads to less GHG emissions from paddy fields than from those receiving RS (Yagi and Minami 1990; Kumagai *et al*. 2010; Das and Adhya 2014). Thus, CDC appears to be the better organic matter to apply to paddy fields in terms of GHG emissions, especially in cold temperate regions of Japan. CDC application also improves the fertility of paddy soil (Maeda and Hirai 2002; Sumida *et al.* 2002; Miura and Kusaba 2013; Shahid *et al*. 2013).

With regard to solving the issues of feed for livestock and environmental problems such as fecal waste and GHG emissions, CDC application in mixed crop–livestock systems is preferable to conventional RS application in Japan. Few studies, however, have compared soil fertility under CDC application in mixed crop–livestock systems to that under conventional RS application in farmers' paddy fields. Hasegawa *et al.* (2005) made this comparison in organic rice paddy fields; they found that available P in soil was higher in CDC fields than in RS fields, but the other parameters had no significant differences. However, that study was not conducted in conventional fields, but rather in fields managed organically without chemical fertilizer by a group of farmers who have their own management standards to grow rice. Outside of mixed crop–livestock systems, there are many long-term experiments in research fields that have compared the effect of RS application to that of CDC application on paddy soil fertility. Most of these studies reported better soil fertility under CDC application than RS application (Shiga *et al.* 1985b; Izuoka *et al.* 1996; Sakai *et al.* 1999; Maeda and Hirai 2002), but some noted that whether soil fertility was better under CDC or RS application depended on the soil parameters (Katou *et al.* 1985; Shibahara *et al.* 1999). National survey data of Japan showed that CDC supplies more nutrients to fields than RS (Miura and Kusaba 2013). Therefore, CDC applied fields in most mixed crop–livestock systems may have better soil fertility than conventional RS applied fields.

The effect of CDC application on soil fertility depends on its application rate and nutrient content. The application rate of CDC varies among regions (Leon *et al.* 2012; Miura and Kusaba 2013). CDC nutrient content is significantly affected by the other materials used during composting, such as rice husks and wood chips (Kohyama *et al.* 2006), with differences in the ratio or type of other materials resulting in different nutrient content. The effect of organic matter application on paddy soil fertility is influenced by the soil type (Uwasawa 1991; Miura and Kusaba 2013). Thus, the nutrient input from CDC and the difference in soil fertility under conventional RS application versus CDC application in mixed crop–livestock systems need to be assessed separately in each region and for each soil type.

The objectives of this research were to understand (1) the nutrient input of CDC produced in the mixed crop–livestock system in Mamurogawa by comparing the nutrient contents and applied amount of CDC and RS and (2) the contribution of the mixed crop–livestock system to paddy soil fertility by comparing the soil fertility of paddy fields under conventional RS application versus CDC application. We conducted this research from two points of view: (1) assessing the general soil fertility in all paddy fields in this area and (2) comparing neighboring field pairs to exclude the effect of various soil environmental conditions.

2.2. Materials and methods

2.2.1. Study area

The research was conducted in farmers' fields in Mamurogawa town, northern Yamagata Prefecture, Japan, in 2016. Mamurogawa (38°51′N, 140°15′E; 374 km^2) is surrounded by mountains on all sides. Rice paddies occupy the sediment that was carried by several small rivers from the mountains. Rice is grown once a year, starting in late April or early May, and is harvested in September or October. From November to March, the fields are covered by snow (JMA 2019). From 1981 to 2010, the average annual precipitation was 2711.0 mm and the annual mean temperature was 10.0 °C (JMA 2019).

2.2.2. Field selection and information

The study sites were 79 rice paddy fields managed by farmers. The fields were selected according to the usage of RS and CDC, as assessed by interviewing farmers. In the RS treatment (41 fields), RS was conventionally applied to the fields. In the CDC treatment (38 fields), RS was removed and then CDC was applied to the fields. The average duration of the RS treatment was 32 years and that of CDC treatment was 21 years. The soil types of the study fields were Non-allophanic Andosols, Wet Andosols, Regosolic Andosols, Gley Lowland soils, Gray Lowland soils, and Brown Lowland soils (National Agriculture and Food Research Organization 2019). In the RS treatment, 21 fields had Andosols and 20 fields had Lowland soils. In the CDC treatment, 15 fields had Andosols and 23 fields had Lowland soils. Fertilizer was used in both treatments at the conventional rate for each farmer and each rice cultivar. Several rice cultivars were grown in the study fields; 'Haenuki', 'Tsuyahime', 'Hitomebore', 'Akitakomachi', 'Koshihikari', 'SD1', and 'Himenomochi' as edible rice, 'Dewasansan' and 'Miyamanishiki' as sake rice, and 'Fukuhibiki' and 'Bekogonomi' as forage. Among the 79 fields, there were 14 neighboring field pairs (RS and CDC treatments nearby). The detail information of the fields was showed in the Table S1 and Table S2.

Table S1. Fields information (all fields) of rice straw (RS) and cow dung compost (CDC) treatments

Field name	GPS data		Plow layer (cm)	RS applied rate (t ha^{-1}) dry weight	Applied duration (years)	Rice cultivar	Soil Type‡
RSM1	N 38º52'41.2"	E 140º15'20.7"	17.5	3.9	42	Haenuki	Gley L.
RSM2	N 38º52'45.0"	E 140º16'20.3"	21.2	4.5	40	Akitakomachi	Reg. A.
RSM3	N 38º52'56.7"	E 140º17'02.8"	14.7	4.0	40	Tsuyahime	Reg. A.
RSM4	N 38º51'08.0"	E 140º13'45.2"	15.7	5.3	3	Tsuyahime	Gley L.
RSI1	N 38º52'18.2"	E 140º15'23.6"	18.7	5.9	35	Tsuyahime	Gley L.
RSI2	N 38º50'43.9"	E 140º16'50.7"	15.8	5.0	40	SD1	Wet A.
RSI3	N 38º50'42.3"	E 140º16'51.2"	18.1	4.5	40	Akitakomachi	Wet A.
RSI4	N 38º50'53.9"	E 140º17'18.8"	12.8	4.0	5	Himenomochi	Wet A.
RST1	N 38º52'13.4"	E 140º16'51.3"	15.5	4.1	40	Hitomebore	Gley L.
RST2	N 38º52'30.8"	E 140º18'30.4"	15.5	6.7	40	Haenuki	Gley L.
RST3	N 38º51'43.5"	E 140º17'44.4"	15.3	5.0	35	Tsuyahime	Wet A.
RST4	N 38º51'43.6"	E 140º16'00.5"	16.7	4.9	35	Tsuyahime	Wet A.
RSH1	N 38º51'03.4"	E 140º16'26.3"	17.8	5.2	40	Haenuki	Wet A.
RSH2	N 38º50'57.4"	E 140º16'45.1"	19.8	4.2	40	Mochi	Wet A.
RSH3	N 38º51'28.0"	E 140º16'17.9"	15.8	2.7	40	Himenomochi	Wet A.
RSS3	N 38º50'46.8"	E 140º14'23.6"	19.0	5.3	18	Hitomebore	Gley L.
RSS4	N 38º50'32.2"	E 140º14'03.8"	16.7	4.2	35	Mochi	Gley L.
RSS5	N 38º50'45.1"	E 140º14'30.1"	20.7	4.2	40	Tsuyahime	Gley L.
RSMa2	N 38º51'56.3"	E 140º18'12.8"	18.7	4.6	4	Haenuki	Gley L.
RSMa3	N 38º52'03.1"	E 140º18'15.8"	14.8	3.6	35	Himenomochi	Gley L.
RSMa4	N 38º52'02.6"	E 140º18'17.3"	15.6	4.3	4	Himenomochi	Gley L.
RSMa5	N 38º51'57.3"	E 140º17'59.1"	17.0	6.4	40	Haenuki	Non-a. A.
RSN1	N 38º55'09.9"	E 140º16'53.9"	16.2	4.5	40	Hitomebore	Wet A.
RSN2	N 38º57'24.2"	E 140º17'19.7"	14.7	4.1	13	Dewasansan	Reg. A.
RSN3	N 38º58'04.8"	E 140º24'34.9"	23.0	6.0	40	Akitakomachi	Gray L.
RSN4	N 38º55'04.8"	E 140º15'53.1"	14.2	4.8	9	Koshihikari	Reg. A.
RSN41	N 38º54'53.6"	E 140º15'55.2"	14.7	4.0	9	Koshihikari	Reg. A.
RSN42	N 38º55'17.2"	E 140º15'56.5"	14.6	4.7	9	Hitomebore	Wet A.
RSN43	N 38º55'28.6"	E 140º15'58.3"	14.5	4.1	40	Hitomebore	Reg. A.
RSN5	N 38º58'00.0"	E 140º24'57.2"	18.2	3.0	40	Himenomochi	Gray L.
RSN6	N 38º58'05.0"	E 140º24'42.8"	19.0	3.8	40	Akitakomachi	Gray L.
RSN8	N 38º55'04.8"	E 140º16'25.0"	18.0	3.7	40	Haenuki	Gley L.
RSN9	N 38º55'10.0"	E 140º16'59.5"	17.2	4.0	40	Haenuki	Wet A.
RSN10	N 38º55'07.5"	E 140º17'09.0"	18.7	4.8	40	Hitomebore	Wet A.
RSN11	N 38º55'03.2"	E 140º16'47.0"	22.5	4.7	40	Koshihikari	Wet A.
RSN12	N 38º55'00.3"	E 140º16'15.5"	14.3	4.2	40	Koshihikari	Gley L.
RSN13	N 38º58'17.0"	E 140º20'32.7"	18.7	4.9	40	Haenuki	Gley L.
RSN14	N 38º58'17.5"	E 140º20'06.3"	16.5	4.2	40	Himenomochi	Gley L.
RSN15	N 38º55'08.0"	E 140º16'37.3"	17.0	3.7	40	Hitomebore	Gley L.
RSN18	N 38º56'23.7"	E 140º16'11.3"	14.1	6.9	30	Koshihikari	Wet A.
RSN19	N 38º57'41.2"	E 140º17'05.9"	16.8	4.4	13	Hitomebore	Gley L.

Field name	GPS data		Plow layer (cm)	CDC applied rate (t ha^{-1})		Applied duration (years)	CDC storage status	Rice cultivar	Soil Type‡
				Fresh weight	Dry weight				
CDM1	N 38º52'50.3"	E 140º15'14.9"	16.0	30	8.7	49	Outdoor	Akitakomachi	Gray L.
CDM1.1	N 38º52'49.1"	E 140º15'14.0"	15.7	20	4.7	40	Indoor	Haenuki	Gray L.
CDM2	N 38º52'44.6"	E 140º16'22.9"	14.7	20	4.1	25	Outdoor	Himenomochi	Reg. A.
CDM5	N 38º53'00.8"	E 140º15'55.1"	15.8	15	3.6	4	Indoor	Hitomebore	Gley L.
CDM6	N 38º52'10.7"	E 140º15'47.0"	15.5	25	5.4	60	Outdoor	Haenuki	Brown L.
CDM7	N 38º52'32.5"	E 140º15'58.2"	14.0	15	3.6	4	Indoor	Akitakomachi	Brown L.
CDI1	N 38º51'16.3"	E 140º16'26.9"	15.5	15	3.5	37	Outdoor	Hitomebore	Wet A.
CDI2	N 38º51'16.1"	E 140º16'36.9"	16.7	15	3.5	37	Outdoor	Haenuki	Wet A.
CDI3	N 38º50'53.5"	E 140º17'19.4"	15.2	15	4.0	40	Indoor	Haenuki	Wet A.
CDI4	N 38º50'45.3"	E 140º17'00.4"	15.3	15	4.0	5	Indoor	SD1	Wet A.
CDT1	N 38º50'55.4"	E 140º15'51.0"	11.8	20	4.8	10	Indoor	Himenomochi	Wet A.
CDT2	N 38º52'03.9"	E 140º18'03.4"	14.8	20	4.8	5	Outdoor	Miyamanishiki	Non-a. A.
CDH1	N 38º51'08.9"	E 140º16'10.2"	16.0	20	5.4	37	Indoor	Hitomebore	Wet A.
CDH2	N 38º51'13.8"	E 140º16'15.4"	15.3	20	5.4	37	Indoor	Haenuki	Wet A.
CDH3	N 38º51'07.5"	E 140º16'08.4"	16.7	20	5.4	37	Indoor	Tsuyahime	Wet A.
CDS1	N 38º50'46.7"	E 140º14'19.1"	17.5	25	5.4	12	Outdoor	Haenuki	Gley L.
CDMa3	N 38º52'02.8"	E 140º17'59.2"	16.3	15	4.0	51	Indoor	Haenuki	Non-a. A.
CDN2	N 38º57'25.7"	E 140º17'18.9"	16.3	10	2.3	9	Outdoor	Hitomebore	Reg. A.
CDN3	N 38º57'59.7"	E 140º24'59.6"	16.0	15	3.4	5	Outdoor	Bekogonomi	Gray L.
CDN4	N 38º55'04.0"	E 140º15'52.9"	15.0	20	6.1	9	Indoor†	Koshihikari	Reg. A.
CDN4.1	N 38º55'03.5"	E 140º15'55.4"	15.3	20	6.1	9	Indoor†	Koshihikari	Reg. A.
CDN4.2	N 38º58'12.8"	E 140º24'18.3"	15.3	15	3.4	5	Outdoor	Bekogonomi	Gray L.
CDN4.3	N 38º58'19.5"	E 140º23'42.0"	15.5	15	3.4	3	Outdoor	Akitakomachi	Gray L.
CDN5	N 38º58'36.3"	E 140º22'41.3"	16.3	15	3.4	8	Outdoor	Hitomebore	Gray L.
CDN6	N 38º58'28.5"	E 140º21'09.3"	16.7	15	3.4	8	Outdoor	Haenuki	Brown L.
CDN7	N 38º58'16.8"	E 140º20'07.0"	15.0	15	3.4	3	Outdoor	Haenuki	Gley L.
CDN8	N 38º57'31.7"	E 140º17'13.4"	18.0	10	2.3	9	Outdoor	Hitomebore	Reg. A.
CDN9	N 38º57'21.3"	E 140º17'00.4"	14.2	10	2.3	9	Outdoor	Hitomebore	Gley L.
CDN10	N 38º57'50.5"	E 140º18'05.1"	19.7	10	2.4	40	Indoor	Fukuhibiki	Gley L.
CDN11	N 38º57'50.1"	E 140º18'04.1"	15.3	10	2.4	40	Indoor	Fukuhibiki	Gley L.
CDN12	N 38º57'48.9"	E 140º18'02.2"	18.3	10	2.4	40	Indoor	Fukuhibiki	Gley L.
CDN13	N 38º55'08.0"	E 140º16'36.2"	17.0	20	7.1	29	Indoor	Haenuki	Gley L.
CDN14	N 38º58'05.8"	E 140º18'17.5"	20.2	10	2.4	25	Indoor	Akitakomachi	Gley L.
CDN15	N 38º58'06.4"	E 140º18'15.6"	15.7	10	2.4	25	Indoor	Koshihikari	Gley L.
CDN16	N 38º57'17.2"	E 140º17'06.8"	13.0	10	2.3	9	Outdoor	Hitomebore	Gley L.
CDN17	N 38º57'10.3"	E 140º16'54.5"	18.0	10	2.3	9	Outdoor	Hitomebore	Gley L.
CDN18	N 38º57'08.2"	E 140º16'57.2"	15.0	10	2.3	9	Outdoor	Hitomebore	Gley L.
CDN19	N 38º57'39.9"	E 140º17'05.4"	14.3	10	2.3	9	Outdoor	Hitomebore	Gley L.

†The composting was done in indoor, and we sampled after it was moved on the field. ‡Reference data is National Agriculture and Food Research Organization 2019: Japan soil inventory, soil map. https://soil-inventory.dc.affrc.go.jp/figure.html (January 2019) (in Japanese). Non-a. A., Non-allophanic Andosols; Wet A., Wet Andosols; Reg. A., Regosolic Andosols; Gley L., Gley Lowland soils; Gray L., Gray Lowland soils; Brown L., Brown Lowland soils

Table S2. Fourteen field pairs of rice straw (RS) and cow dung compost (CDC) treatments

Pair number	RS treatment	CDC treatment
1	RSM1	CDM1.1
2	RSM2	CDM2
3	RSI2	CDI4
4	RSI4	CDI3
5	RSH1	CDH3
6	RSS5	CDS1
7	RSMa5	CDMa3
8	RSN2	CDN2
9	RSN5	CDN3
10	RSN4	CDN4
11	RSN6	CDN4.2
12	RSN14	CDN7
13	RSN15	CDN13
14	RSN19	CDN19

2.2.3. Soil, RS, and CDC sampling

After harvest in late October 2016, soil samples were taken in the plow layer with an auger (5 cm diameter) at six points and then bulked. The depth of the plow layer was identified manually and measured with a ruler. Soil samples were dried at 35 °C in a forced-air oven, treated to remove stones and plant residue, ground in a ceramic mortar, and passed through a 2-mm sieve. The samples were then used for chemical analysis. Part of each sample was ground finely by a grinder (TI-100, Heiko Seisakusho Ltd., Tokyo, Japan) to measure soil organic carbon (SOC) and total N. Soil bulk density was measured at three points in each field by taking 100-cm^3 cores in the plow layer.

Applied RS in the RS treatment was collected from three points (in the middle and at two sides) in each field after harvest in October 2016. At each point, the rectangle sampled area was decided and marked by pile and string, then all RS on the soil surface excluding rice stubble in the chosen area was collected, and the collection area was measured and recorded. The samples were dried in a forced-air oven at 80 °C, ground in a grinder (TI-100), and then used for chemical analysis. The amount of RS applied was calculated by dividing the dry weight of collected RS by the collected area. Because stubble also remained in the CDC treatment, it was not considered to be applied RS in the RS treatment.

CDC was sampled before being applied to the fields in April 2016. Samples were dried in a forced-air oven at 60 °C, ground in a grinder (TI-100), and then used for chemical analysis. The amount of CDC applied was obtained by interviewing farmers. In the study area, CDC comprises cow dung, rice husks, wood chips, and feed wastes that are composted for 6 to 12 months. The application rate and nutrient content of each CDC in the study area was considered to be the same every year, as we assumed that farmers did not change their rice cultivation practices or their method for producing CDC.

2.2.4. Chemical analyses

SOC and soil total N and the total N and total carbon (C) in RS and CDC were analyzed on a Sumigraph NC-220-F Analyzer (Sumika Chemical Analysis Service Ltd., Tokyo, Japan). To measure total P and total K in RS and CDC, the materials were first digested with H_2SO_4–H_2O_2 (Mizuno and Minami 1980). The concentration of P was measured by the vandomolybdophosphoric acid method (Kuo 1996). The concentration of K was measured by flame atomic absorption spectrometry (Spectr-AA 220-FS, Varian Australia Pty Ltd., Mulgrave, Australia). Total silicon (Si) in RS and CDC was extracted in 1.5 M hydrofluoric acid–0.6 M hydrochloric acid solution, and the Si concentration was measured by using the molybdenum yellow method (Saito *et al*. 2005).

Soil cation exchange capacity (CEC) was determined following extraction of air-dried soil with 1 M ammonium acetate (pH 7.0; Harada 1984). Available N was determined by anaerobic incubation of air-dried soil at 30 °C for 4 weeks followed by extraction with 2 M KCl at a soil:KCl ratio of 1: 10 (w/v). The NH_4^+-N content in solution extracted to measure CEC and available N was determined by steam distillation (Bremner 1965). Available P was determined by Truog's method (Nanzyo 1997). Exchangeable K, calcium (Ca), and magnesium (Mg) in air-dried soil were extracted with 1 M ammonium acetate (pH 7.0; Harada 1984) and, measured by flame atomic absorption spectrometry (Spectr-AA 220-FS). To determine available Si, air-dried soil was incubated in distilled water (1:6 w/w soil:water) at 40 °C for 1 week, and filtered through No.5 C filter paper (Toyo Roshi, Co. Ltd., Tokyo, Japan) (Nonaka and Takahashi 1988), and the concentration of Si was measured by the molybdenum blue method (Yoshida 1986). Soil pH (H_2O) was determined in a suspension with an air-dried soil to water (w/w) ratio of 1:2.5 (Kamewada 1997).

For each nutrient, we calculated the amount supplied to the field from RS and CDC as nutrient supplied (kg ha^{-1}) = nutrient content (g kg^{-1}) × dry weight of RS or CDC supplied (t ha^{-1}).

The soil nutrient pool was calculated as amount of nutrient in the soil (kg ha^{-1}) = soil nutrient content (g kg^{-1}) × plow layer depth (cm) × bulk density (g cm^{-3}) × 10^{-2}.

2.2.5. Statistical analysis

Welch's *t*-test was used to compare the nutrient contents of RS and CDC, nutrient input from RS and CDC, and the soil fertility of the two treatments in all fields and in neighboring field pairs. The analysis was performed with the Analysis ToolPak in Excel for Office 365 (Microsoft, Redmond, WA, USA). A P value < 0.05 was considered to indicate a significant difference.

2.3. Results

2.3.1. Nutrient content in RS and CDC

Table 2.1 shows the nutrient content of RS and CDC applied to all fields and to the 14 field pairs. The total C of RS was higher than that of CDC in the all-fields dataset and the14-field-pairs dataset, but the difference was significant only in the former case ($P < 0.01$). In contrast, the total N, total P, total K, and total Si contents of CDC were significantly higher than those of RS in both the all-fields dataset and the 14-field-pairs dataset. CDC contained total N and total K at 2 times, total P at 5 times, and total Si at 1.3 times higher than those of RS. The C/N ratio of RS was nearly double that of CDC, and the difference was significant in both the all-fields dataset and the 14-field-pairs dataset.

Table 2.1. Carbon and nutrients content of rice straw (RS) and cow dung compost (CDC) applied

Treatment	Total C ($g C kg^{-1}$)	Total N ($g N kg^{-1}$)	C/N	Total P ($g P kg^{-1}$)	Total K ($g K kg^{-1}$)	Total Si ($g Si kg^{-1}$)
All fields						
RS (n = 41)	413 ± 15	5.9 ± 0.8	70.7 ± 9.3	1.0 ± 0.2	6.2 ± 1.8	45.1 ± 10.8
CDC (n = 38)	395 ± 24	13.2 ± 2.9	31.0 ± 5.1	5.3 ± 2.6	11.3 ± 5.4	58.9 ± 12.0
P value	*< 0.01*	*< 0.01*	*< 0.01*	*< 0.01*	*< 0.01*	*< 0.01*
14 neighboring field pairs						
RS (n = 14)	411 ± 18	5.8 ± 0.9	72.3 ± 10.3	1.0 ± 0.3	6.5 ± 2.1	45.2 ± 13.7
CDC (n = 14)	396 ± 25	13.3 ± 2.8	30.6 ± 4.6	5.2 ± 2.6	11.2 ± 5.8	58.9 ± 11.6
P value	*0.09*	*< 0.01*	*< 0.01*	*< 0.01*	*0.01*	*< 0.01*

Values are mean ± SD. The *P* value is the probability level of two-tailed Welch's *t*-test.

2.3.2. Nutrient input from RS and CDC

Table 2.2 shows the rates of RS and CDC application and the nutrient inputs from RS and CDC in the two datasets. In the all-fields dataset, the average dry weight of RS applied was 4.6 t ha^{-1}, significantly higher than that of CDC at 3.9 t ha^{-1} ($P < 0.05$). In the 14-field-pairs dataset the rates of application of RS (4.4 t ha^{-1}) and CDC (4.5 t ha^{-1}) were similar. In the all-fields dataset, the total C input from RS was significantly higher than that from CDC ($P < 0.01$). In the 14-field-pairs dataset, the trend was opposite, although the difference was not significant ($P = 0.94$). In both datasets, the nutrient inputs (total N, total P, total K, and total Si) from CDC were significantly higher than those from RS, with the exception of total Si in the all-fields dataset.

Table 2.2. Application rates of rice straw (RS) and cow dung compost (CDC) and carbon and nutrients inputs from RS and CDC

Treatment	Application rate† (t ha^{-1})	Total C (kg C ha^{-1})	Total N (kg N ha^{-1})	Total P (kg P ha^{-1})	Total K (kg K ha^{-1})	Total Si (kg Si ha^{-1})
All fields						
RS (n = 41)	4.6 ± 0.9	1882 ± 375	26.8 ± 5.0	4.4 ± 1.1	28.4 ± 9.9	206.5 ± 64.9
CDC (n = 38)	3.9 ± 1.5	1545 ± 635	52.6 ± 27.7	21.6 ± 16.9	46.5 ± 34.4	227.2 ± 98.7
P value	*0.03*	*< 0.01*	*< 0.01*	*< 0.01*	*< 0.01*	*0.28*
14 neighboring field pairs						
RS (n = 14)	4.4 ± 0.8	1793 ± 341	24.9 ± 3.8	4.4 ± 1.1	27.8 ± 9.7	198.4 ± 70.3
CDC (n = 14)	4.5 ± 1.8	1811 ± 771	61.0 ± 28.5	23.5 ± 16.1	53.9 ± 39.2	265.5 ± 110.1
P value	*0.75*	*0.94*	*<0.01*	*<0.01*	*0.03*	*0.07*

Values are mean ± SD. The *P* value is the probability level of two-tailed Welch's *t*-test.

†Dry weight.

2.3.3. Soil fertility of paddy fields under RS or CDC treatment.

Soil fertility is evaluated on the basis of many indicators of soil chemical, physical, and biological properties. We investigated SOC, total N, C/N ratio, CEC, available N, available P, exchangeable K, exchangeable Ca, exchangeable Mg, base saturation percentage, available Si, pH, and bulk density (Table 2.3). In the all-fields dataset, the CDC treatment had higher values than the RS treatment in SOC, total N, C/N ratio, CEC, available N, exchangeable K, exchangeable Ca, exchangeable Mg, base saturation percentage, pH, and bulk density, whereas the RS treatment had higher values in soil available P and available Si. However, the differences were not significant for any of the parameters. In the 14-field-pairs dataset, the CDC treatment had higher SOC, total N, CEC, available N, exchangeable Ca, exchangeable Mg, and bulk density values than the RS treatment, whereas the RS treatment had higher values in base saturation percentage and available Si; the soil C/N ratio, available P, exchangeable K, and pH were comparable between treatments. None of the parameters showed significant differences between treatments.

Table 2.3. Soil fertility of paddy fields under conventional rice straw (RS) application and cow dung compost (CDC) application in mixed crop–livestock systems

Treatment	SOC ($g\ C\ kg^{-1}$)	TN ($g\ N\ kg^{-1}$)	C/N	CEC ($cmol_c\ kg^{-1}$)	AN ($g\ N\ kg^{-1}$)	AP ($g\ P\ kg^{-1}$)	Ex. K ($g\ K\ kg^{-1}$)	Ex. Ca ($g\ Ca\ kg^{-1}$)	Ex. Mg ($g\ Mg\ kg^{-1}$)	BS (%)	ASi ($mg\ Si\ kg^{-1}$)	pH (H_2O)	BD ($g\ cm^{-3}$)
All fields													
RS (n = 41)	47.8 ± 23.3	3.63 ± 1.34	12.7 ± 2.0	22.3 ± 6.8	0.24 ± 0.05	0.16 ± 0.06	0.18 ± 0.13	1.73 ± 0.60	0.28 ± 0.10	52.6 ± 12.5	27.2 ± 10.4	5.6 ± 0.3	0.74 ± 0.12
CDC (n = 38)	50.5 ± 17.6	3.87 ± 1.05	12.8 ± 1.4	24.3 ± 7.8	0.25 ± 0.05	0.14 ± 0.06	0.20 ± 0.12	2.13 ± 1.31	0.31 ± 0.14	55.0 ± 15.5	24.5 ± 11.8	5.7 ± 0.3	0.76 ± 0.11
P value	*0.57*	*0.37*	*0.81*	*0.23*	*0.20*	*0.11*	*0.45*	*0.09*	*0.22*	*0.45*	*0.30*	*0.07*	*0.60*
14 neighboring field pairs													
RS (n = 14)	47.7 ± 22.6	3.58 ± 1.23	12.8 ± 2.5	22.0 ± 7.5	0.22 ± 0.04	0.14 ± 0.05	0.21 ± 0.18	1.72 ± 0.64	0.27 ± 0.11	53.4 ± 15.5	24.0 ± 10.7	5.7 ± 0.3	0.74 ± 0.11
CDC (n = 14)	51.1 ± 21.6	3.89 ± 1.32	12.8 ± 1.7	23.0 ± 4.7	0.24 ± 0.04	0.14 ± 0.06	0.21 ± 0.12	1.80 ± 0.57	0.30 ± 0.10	51.4 ± 10.9	23.6 ± 13.0	5.7 ± 0.3	0.78 ± 0.15
P value	*0.69*	*0.53*	*0.92*	*0.69*	*0.41*	*0.83*	*0.99*	*0.73*	*0.50*	*0.71*	*0.94*	*0.69*	*0.45*

SOC, soil organic carbon; TN, total nitrogen; C/N, carbon/ nitrogen ratio; CEC, cation exchange capacity; AN, available nitrogen; AP, available phosphorus; Ex. K, exchangeable potassium; Ex. Ca, exchangeable calcium; Ex. Mg, exchangeable magnesium; BS, base saturation percentage; ASi, available silicon; BD, bulk density. Values are mean ± SD. The *P* value is the probability level of two-tailed Welch's *t*-test.

2.3.4. Plow-layer depth, SOC, and nutrient pools of paddy fields under RS or CDC treatment

Table 2.4 reports the pool of SOC and nutrients in plow-layer soil of paddy fields under RS or CDC treatment. The plow-layer depth of the RS treatment was higher than that of the CDC treatment in both datasets with the significant difference in all-fields dataset. In both datasets, the CDC treatment had higher SOC, total N, available N, exchangeable K, and exchangeable Mg than the RS treatment, whereas the RS treatment had higher available P and available Si. In the all-fields dataset, exchangeable Ca was greater in the CDC treatment than in the RS treatment, but in the 14-field-pairs dataset, the opposite was observed. In both datasets, however, no significant differences in the SOC and nutrient pools were found between treatments.

Table 2.4. Plow layer depth, soil organic carbon (SOC), and nutrient pools of paddy soil under conventional rice straw (RS) application and cow dung compost (CDC) application in mixed crop–livestock systems

Treatment	Plow layer depth (cm)	SOC (kg C ha^{-1})	TN (kg N ha^{-1})	AN (kg N ha^{-1})	AP (kg P ha^{-1})	Ex. K (kg K ha^{-1})	Ex. Ca (kg Ca ha^{-1})	Ex. Mg (kg Mg ha^{-1})	ASi (kg Si ha^{-1})
All fields									
RS (n = 41)	17.0 ± 2.3	56251 ± 22190	4320 ± 1147	293 ± 53	194 ± 70	208 ± 118	2111 ± 719	344 ± 145	34 ± 14
CDC (n = 38)	15.9 ± 1.6	58284 ± 17034	4498 ± 965	299 ± 54	163 ± 66	231 ± 143	2520 ± 1566	370 ± 168	29 ± 15
P value	*0.02*	*0.65*	*0.46*	*0.62*	*0.05*	*0.44*	*0.15*	*0.48*	*0.14*
14 neighboring field pairs									
RS (n = 14)	17.0 ± 2.3	56419 ± 20998	4319 ± 1045	277 ± 47	178 ± 57	233 ± 148	2139 ± 910	337 ± 152	31 ± 17
CDC (n = 14)	15.7 ± 0.9	59244 ± 20270	4559 ± 1129	284 ± 37	165 ± 69	254 ± 167	2131 ± 634	356 ± 125	29 ± 16
P value	*0.05*	*0.72*	*0.56*	*0.68*	*0.61*	*0.73*	*0.98*	*0.72*	*0.69*

SOC, soil organic carbon; TN, total nitrogen; AN, available nitrogen; AP, available phosphorus; Ex. K, exchangeable potassium; Ex. Ca, exchangeable calcium; Ex. Mg, exchangeable magnesium; ASi, available silicon. Values are mean ± SD. The *P* value is the probability level of two-tailed Welch's *t*-test.

2.4. Discussion

2.4.1. Nutrient contents of RS and CDC

In the all-fields dataset, the total C content of CDC was lower than that of RS (Table 2.1). The other materials (rice husks, wood chips, feed waste) used in making CDC have a C content similar to that of RS (i.e., > 410 g kg^{-1}). However, cow dung usually has a C content of < 300 g kg^{-1} (Wani *et al.* 2013; Kumar *et al.* 2017). Thus, the C content in cow dung lowers the C content of CDC relative to RS. The C lost as gas or leachate during composting is another reason for the lower total C content in CDC. Mishima *et al.* (2012) estimated that 38% of C is lost during composting in cattle manure. Wood chips are used in making CDC in the study area because the local timber industry produces abundant wood chips. Wood chips contain a high percentage of C and are difficult to decompose because of the high content of lignin (Shiga *et al.* 1985a). The C content of CDC produced in this area is about 400 g kg^{-1}, which is higher than the average C content of CDC in Japan (Livestock Industry's Environmental Improvement Organization 2005), and it is likely because of the high percentage of wood chips used in its production.

Nutrient contents (N, P, K, and Si) of CDC were significantly higher than those of RS in both datasets (Table 2.1). The higher nutrient contents in CDC likely resulted from the high nutrient content of cow dung, because the other materials (rice husks, wood chips, and feed waste) used in composting have nutrient contents similar to those of RS. The nutrient contents of CDC had larger variation than those of RS; the CDC applied in this study was made by several farmers, which results in different sources and percentages of the other materials. The variation in K content of both RS and CDC was high. The K in organic matter exists mostly in soluble forms and is easily washed out by rainfall (Rosolem *et al.* 2005; Jin *et al.* 2015).

Hasegawa *et al.* (2005) noted that the concentration of K in CDC stored indoors was more than 6 times that of CDC stored outdoors. In the present study, CDC was stored both indoors and outdoors and RS was collected on the fields before or after exposure to the rain. In addition, the C/N ratio of RS was ≥ 70 and that of CDC was ~30; in the decomposition process in soil, RS immobilizes soil N, and thus net N mineralization is less in RS than in CDC (Shiga *et al.* 1985a; Nishida *et al.* 2003).

The application rate of CDC in this area ranged from 10 to 30 t ha^{-1} in fresh weight (Table S1), which is the same or higher than the recommended application rate for Yamagata Prefecture (2008). In the all-fields dataset, the C input from CDC was significantly lower than that from RS (Table 2.2), owing to the lower rate of CDC application in dry weight and the lower C content in CDC than in RS. In contrast, the N, P, and K inputs from CDC were greater than those from RS, owing to the higher nutrient contents in CDC (Table 2.1). This result is comparable with that of Miura and Kusaba (2013), and it agrees with the hypothesis that CDC supplied more nutrients to the field than RS. The Si inputs from CDC and RS were similar, likely reflecting the higher Si content and the lower rate of CDC application. In the 14-field-pairs dataset, however, the CDC application rate was not significantly different from that of RS, so the trend of nutrient input was the same as the nutrient contents. Overall, the C input tended to be higher in RS-applied fields and the N, P, and K inputs were significantly higher in CDC-applied fields.

2.4.2. Paddy soil fertility parameters under conventional RS application and CDC application in mixed crop–livestock systems

The soil fertility under RS and CDC treatments was not significantly different in the all-fields dataset or the 14-field-pairs dataset (Table 2.3). This finding indicates that the effects of RS and CDC on soil fertility are not influenced by variation in the fields' environmental conditions including soil types.

Table 2.5. Standard values used to evaluate the fertility of paddy soil

Soil fertility indicator	Fertility level	References
SOM	20 g SOM kg^{-1} dry soil (Lowland soils)	MAFF (2008)
TN	–	–
CEC	12 $cmol_c$ kg^{-1} dry soil (Lowland soils), 15 $cmol_c$ kg^{-1} dry soil (Andosols)	MAFF (2008)
AN	0.08 to 0.20 g N kg^{-1} dry soil	MAFF (2008)
AP	0.04 g P kg^{-1} dry soil	MAFF (2008)
Ex .K	0.08 g K kg^{-1} dry soil	Dobermann and Fairhurst (2000)
Ex. Ca	0.40 g Ca kg^{-1} dry soil	Dobermann and Fairhurst (2000)
Ex. Mg	0.24 g Mg kg^{-1} dry soil	Dobermann and Fairhurst (2000)
BS	70 to 90 % (Lowland soils), 60 to 90 % (Andosols)	MAFF (2008)
ASi	62.48 mg Si kg^{-1} dry soil	Calculated from Imaizumi and Yoshida (1958); Sumida (1992); Kato *et al*. (2002).
pH	6.0 to 6.5	MAFF (2008)
BD	–	–

SOM, soil organic matter (calculated as 1.724×soil organic carbon); TN, total nitrogen; CEC, cation exchange capacity; AN, available nitrogen; AP, available phosphorus; Ex. K, exchangeable potassium; Ex. Ca, exchangeable calcium; Ex. Mg, exchangeable magnesium; BS, base saturation percentage; ASi, available silicon; BD, bulk density.

Although the C input from RS was greater than that from CDC (Table 2.2), SOC was not different between treatments (Table 2.3). A higher loss of C in the RS treatment explains this result. Nishida *et al.* (2003) reported that C in RS is decomposed more rapidly than that in CDC after field application. In the present research, the C content in CDC comes from wood chips or rice husk, which have higher lignin content than RS and are thus difficult to decompose (Shiga *et al.* 1985a). The N input from organic matter was higher in the CDC treatment (Table 2.2), but soil total N was not significantly different between treatments (Table 2.3). This could be explained by lower net N mineralization in the RS treatment due to the high N immobilization resulting from the high C/N ratio of RS (Table 2.1) and greater loss of N in the CDC treatment through plant nutrient uptake, leaching, and emission. In this research, however, we did not investigate plant nutrient uptake (rice yield), leaching, or emission. To elucidate the true causes, it will be necessary to measure those outputs in the RS and CDC treatments. Another reason for the lack of a significant difference in SOC and total N between the RS and CDC treatments may be the relatively small input into the large soil volume: the C input from RS or CDC was about 3% of SOC, and the N input accounted for about 1% of soil total N (data not shown). So, the difference in C or N input between RS and CDC was ≤ 1% of SOC or soil total N.

SOC (or soil organic matter, SOM) and total N constitute heterogeneous mixtures of organic substances and are widely used as the main parameters for evaluating soil fertility (Huang *et al.* 2009). Table 2.5 lists the standard values used to evaluate the fertility of paddy soil. In the present study, SOC ranged from 18.0 to 95.3 g C kg^{-1} (31.0–64.3 g kg^{-1} SOM) in the RS treatment and from 18.4 to 85.4 g C kg^{-1} (31.7–147.3 g kg^{-1} SOM) in the CDC treatment. Soil total N ranged from 1.65 to 6.66 g N kg^{-1} in the RS treatment and from 1.72 to 5.76 g N kg^{-1} in the CDC treatment. The SOM content of paddy soil in this study was quite high in comparison with the standard value of fertile soil. We propose three possible causes for this:

(1) the continuous addition of organic matter to paddy soil from RS or CDC, (2) the slow rate of decomposition of SOM as a result of the region's long cold winter and snow cover (JMA 2019), and (3) the distribution of Andosols in study fields, because Andosols contain higher SOC and total N than those of Lowland soils.

The CEC of the CDC treatment was not significantly different from that of the RS treatment (Table 2.3). CEC had significant positive correlations with SOC and soil total N (Table 2.6). SOM carries a negative charge, which can hold cations. Thus, if the SOM content is greater, there will be more available space for cation exchange. The lack of a difference in SOC and soil total N between the RS and CDC treatments would result in the nonsignificant difference of CEC between treatments.

Soil CEC ranged from 5.8 to 35.7 $cmol_c$ kg^{-1} in the RS treatment and from 10.7 to 49.3 $cmol_c$ kg^{-1} in the CDC treatment. Compared with the standard fertility values for CEC, 93% of the fields in the RS treatment and 92% of those in the CDC treatment had higher values, meaning that both treatments resulted in a CEC level representative of fertile soil.

The available N content (Table 2.3) and the amount of available N in soil (Table 2.4) of the CDC treatment were not different from those of the RS treatment. These findings, however, are incompatible with the higher total N input from CDC than from RS (Table 2.2). Available N had significant positive correlations with SOC and soil total N (Table 2.6). Soil organic N is the initial material necessary for N mineralization, which produces available N. Therefore, the nonsignificant difference of soil SOC and soil total N between the RS and CDC treatments directly contributed to this result, rather than the higher N input from CDC.

Soil available N ranged from 0.14 to 0.36 g N kg^{-1} in the RS treatment and from 0.17 to 0.39 g N kg^{-1} in the CDC treatment. The available N of all fields in both treatments were in the range of or higher than the standard fertility value. Thirty-two percent of fields in the RS treatment and 16% of those in the CDC treatment had an available N level representative of fertile soil, and the remaining fields had plenty of available N.

The soil available P content (Table 2.3) and the amount of available P in soil (Table 2.4) of the CDC treatment were not different from those of the RS treatment. This finding is not compatible with the higher P input from CDC (Table 2.2). The availability of P in soil is dependent on the soil type (Andosols or Lowland soils) and soil pH. The soil pH was similar between treatments, however. Andosols adsorb soil P strongly, which results in a lower ratio of available P to total P in Andosols in comparison to Lowland soils. If the CDC treatment have more Andosols than the RS treatment, the higher P input from CDC will be adsorbed by soil then resulted in same level of soil available P with that of the RS treatment. But, in this study the numbers of fields with Andosols and Lowland soils in the RS treatment were similar (21 and 20), and those in the CDC treatment were 15 and 23, respectively. In the 14 neighboring field pairs, the soil type of the RS and CDC treatments in each pair was the same. Thus, the comparison of available P between the RS and CDC treatments was not affected by more distribution of Andosols in the CDC treatment. Therefore, the incompatible result between P input and soil available P can be explained by two hypotheses: (1) the higher P input from CDC increased soil total P but not available P, and (2) there was greater loss of P from the CDC treatment than from the RS treatment. Nagumo *et al.* (2013) reported that soil available P is difficult to increase by long-term P input from inorganic fertilizer or organic matter, even if the soil total P is increased, which supports the first hypothesis. P cannot be lost by decomposition and leaching, like C and N can, because it usually exists in the soil in compounds with aluminum, Ca, or iron. Many studies have reported that the amount of P leaching from paddy fields is very small (Hasegawa 1992; Nanzyo 1996; Cho *et al.* 2002; Shan *et al.* 2005; Maruyama *et al.* 2008), and plant nutrient uptake is the main loss of P from the fields (Hasegawa 1992; Nanzyo 1996; Maruyama *et al.* 2008). Thus, further research on the form of P in soil and the P balance of the RS and CDC treatments is needed to clarify the issue.

Soil available P ranged from 0.07 to 0.31 g P kg^{-1} in the RS treatment and from 0.06 to 0.32 g P kg^{-1} in the CDC treatment. Values in all fields in both treatments were higher than the standard value indicating soil fertility.

There were no significant differences in soil exchangeable K content (Table 2.3) or the amount of exchangeable K in soil (Table 2.4) between the RS and CDC treatments. This was not compatible with the higher total K input from CDC than from RS (Table 2.2). The greater loss of K from the fields via plant nutrient uptake and leaching in the CDC treatment than the RS treatment may explain this result. To clarify the issue, we need to perform further research on the K balance in paddy fields.

Soil exchangeable K ranged from 0.06 to 0.77 g K kg^{-1} in the RS treatment and from 0.05 to 0.53 g K kg^{-1} in the CDC treatment. Compared with the standard fertility value, the 93% of the fields in the RS treatment and 84% of those in the CDC treatment had higher exchangeable K.

Soil exchangeable Ca and exchangeable Mg of the CDC treatment showed no significant difference from those of the RS treatment (Tables 2.3, 2.4). Both values had significant positive correlations with CEC (Table 2.6). Thus, the lack of a difference in CEC between the RS and CDC treatments could contribute to the nonsignificant differences in these cations. Similarly, soil base saturation percentages were nonsignificant difference in the RS and CDC treatments (Table 2.3). Soil base saturation percentage had significant positive correlations with exchangeable Ca and exchangeable Mg (Table 2.6). The lack of differences in CEC and exchangeable cations between the two treatments led to the nonsignificant difference in soil base saturation.

Soil exchangeable Ca ranged from 0.43 to 3.57 g Ca kg^{-1} in the RS treatment and from 0.56 to 6.97 g Ca kg^{-1} in the CDC treatment. All of the fields in the RS and CDC treatments had higher exchangeable Ca than the standard fertility value. Soil exchangeable Mg ranged from 0.08 to 0.70 g Mg kg^{-1} in the RS treatment and from 0.13 to 0.69 g Mg kg^{-1} in the CDC treatment. Sixty-one percent of the fields in the RS treatment and 68% of those in the CDC treatment had higher exchangeable Mg than the standard fertility value. Base saturation percentage of soil ranged from 29.4% to 80.8% in the RS treatment and from 27.7% to 94.7% in the CDC treatment. Only 12% of fields in the RS treatment and 18% of those in the CDC treatment had a base saturation percentage representative of fertile soil. Thus, all of the fields reached an adequate level of exchangeable Ca and most of the fields had adequate levels of exchangeable K and exchangeable Mg, but most of the fields did not achieve sufficient base saturation percentage by RS application or CDC application in mixed crop–livestock systems.

Soil available Si content (Table 2.3) and the amount of soil available Si (Table 2.4) in the CDC treatment were not different from those in the RS treatment, which likely reflects the nonsignificant difference in Si input from RS and CDC (Table 2.2).

Soil available Si ranged from 10.8 to 51.4 mg Si kg^{-1} in the RS treatment and from 11.0 to 49.9 mg Si kg^{-1} in the CDC treatment. A Si concentration of 51 g Si kg^{-1} in rice shoot at maturity is recognized as the critical level needed to achieve healthy growth and good yield in Japan (Imaizumi and Yoshida 1958; Sumida 1992). Based on the regression formula reported by Kato *et al.* (2002) between Si concentration of rice shoot and soil available Si, at least 62.48

mg Si kg^{-1} of soil available Si is recommended. However, all of the study fields had a lower value. Since soil mineralogical properties determine the amount of soil available Si (Makabe *et al.* 2009; Yanai *et al.* 2016), properties of the soil in the research area caused the low soil available Si. A large uptake of Si by rice plants also could explain this result. Total Si uptake through leaf and stem of rice plants in the RS treatment equaled 165% of the amount of available Si in the soil (data not shown). Even though all the Si in leaf and stem is returned to the fields in the RS treatment, the Si uptake by rice grain makes the balance of Si negative every year.

Both soil pH and bulk density of the CDC treatment were not significantly different from those of the RS treatment (Table 2.3). Soil pH had significant positive correlations with soil CEC, exchangeable Ca, exchangeable Mg, and base saturation percentage, and bulk density had significant negative correlations with SOC and soil total N (Table 2.6). The nonsignificant differences of CEC, exchangeable Ca, exchangeable Mg, and base saturation percentage between the RS and CDC treatments would contribute to the nonsignificant difference of soil pH, and the lack of differences in SOC and soil total N would contribute to the nonsignificant difference of soil bulk density between treatments.

Soil pH affects the availability of nutrients in soil through desorption and absorption processes. Soil pH ranged from 5.1 to 6.1 in the RS treatment and from 5.2 to 6.4 in the CDC treatment. Compared with the standard pH value representative of fertile soil, only 15% of the fields in the RS treatment and 29% of those in the CDC treatment were within the ideal range. Sources of acidity that lower pH include rainfall, fertilizer application, plant nutrient uptake, weathering of minerals, and decomposition of organic matter. Thus, both RS application and CDC application in mixed crop–livestock systems cause soil fertility problems due to improper soil pH.

Table 2.6. Linear correlation coefficients (r) of the relationships between soil fertility indicators

	SOC	TN	CEC	AN	AP	Ex. K	Ex. Ca	Ex. Mg	BS	ASi	pH	BD
SOC	1											
TN	0.96**	1										
CEC	0.45**	0.47**	1									
AN	0.56**	0.62**	0.51**	1								
AP	0.29**	0.37**	0.03	0.22*	1							
Ex. K	0.20	0.18	0.10	0.12	0.00	1						
Ex. Ca	0.20	0.25*	0.77**	0.41**	0.16	−0.05	1					
Ex. Mg	−0.12	−0.05	0.64**	0.30**	−0.03	0.09	0.72**	1				
BS	−0.22	−0.20	−0.04	0.03	0.22	−0.01	0.54**	0.45**	1			
ASi	−0.02	0.08	0.03	0.18	0.60**	−0.19	0.26*	0.23*	0.31**	1		
pH	0.24*	0.19	0.40**	0.08	0.23*	0.09	0.63**	0.34**	0.51**	0.07	1	
BD	−0.80**	−0.84**	−0.57**	−0.65**	−0.33**	−0.06	−0.37**	−0.16	0.11	−0.15	−0.14	1

SOC, soil organic carbon; TN, total nitrogen; CEC, cation exchange capacity; AN, available nitrogen; AP, available phosphorus; Ex. K, exchangeable potassium; Ex. Ca, exchangeable calcium; Ex. Mg, exchangeable magnesium; BS, base saturation; ASi, available silicon; BD, bulk density.
** $P < 0.01$, * $P < 0.05$.

Bulk density of soil ranged from 0.53 to 0.98 g cm^{-3} in the RS treatment and from 0.60 to 1.1 g cm^{-3} in the CDC treatment. Bulk density of Andosol is about 0.5–0.8 g cm^{-3} and that of sandy soil is about 1.1–1.8 g cm^{-3} (Inubushi 2001). The soils in the study fields are Andosols and gravelly to fine-textured Lowland soils, and the bulk density is within the expected range.

This study revealed no significant differences in SOC, total N, CEC, available N, available P, exchangeable K, exchangeable Ca, exchangeable Mg, base saturation percentage, available

Si, pH, or soil bulk density between the RS and CDC treatments. This result rejected our hypothesis that higher nutrient input from CDC leads to better soil fertility in the CDC treatment than the RS treatment. To clarify the incompatible result between nutrient inputs from RS and CDC and the soil fertility, it is necessary to conduct further research on the nutrient balance. Compared to the standard values, the application of either RS or CDC in mixed crop–livestock systems in this study area maintained most of the soil fertility indicators at a sufficient level for healthy rice growth.

2.5. Conclusion

According to the data gathered in all fields, RS had a higher C content but lower nutrient contents (N, P, K, and Si) than CDC. Consequently, C input was higher in the RS treatment and N, P, and K inputs were higher in the CDC treatment. However, the effect of CDC application on soil fertility was not significantly different than that of conventional RS application. There are several possible reasons for this result: (1) Trends were obscured by the large variation of soil environmental condition across the many study fields. (2) Input sources other than RS or CDC to paddy fields have a greater effect on soil fertility. (3) Difference exist in the amount of nutrient output from the plow layer between RS- and CDC-applied fields. The first possible cause can be rejected from the comparisons of neighboring field pairs with the same environmental conditions; results were similar to those when comparing all fields. The second and third reasons, however, should be investigated further. The soil fertility of most of the study fields was adequate, whether they received RS or CDC application. Based on our findings regarding soil fertility after RS or CDC application, it is possible to recommend that farmers in this area expand mixed crop–livestock systems.

III. CHAPTER II: Comparison of the nitrogen balance in paddy fields under conventional rice straw application versus cow dung compost application in mixed crop–livestock systems

3.1. Introduction

N is the most essential nutrient element for rice plants, and the capacity of paddy soils to supply N has a great impact on rice yield. Even when a paddy field receives sufficient fertilizer application, the N uptake by rice plants from mineralization of soil N exceeds that from fertilizer (Koyama *et al.* 1973; Shoji *et al.* 1986; Wada *et al.* 1986; Hasegawa 1992), with about 60% of N uptake by rice plants coming from soil and the other 40% from fertilizer. Therefore, to improve rice plant N uptake, it is important to increase soil total N and available N.

In chapter I, we found that the application of CDC in a mixed crop–livestock system supplied more N to the fields than RS, but soil total N and available N were not significant difference between treatments (Nguyen *et al.*, 2019). However, the status of soil total N and available N are not only controlled by N input from RS and CDC but also other N inputs, N outputs, and the N balance of the field. To explain our previous findings, it is important to investigate the N inputs, N outputs, and N balance in RS- and CDC-applied fields in mixed crop–livestock systems.

Aside from RS or CDC, fertilizer, N fixation, irrigation water, and rainfall are additional sources of N inputs to paddy fields. Since the Green Revolution, chemical fertilizer has been an important N input used in rice fields to increase yield. The amount of fertilizer N applied depends on the rice variety, target yield, and soil fertility. CDC application may lead to less N application in the form of fertilizer. In paddy fields, N fixation contributes a significant amount of N to the soil. Studies have shown that RS application not only supplies N to the soil, it also enhances N fixation in the fields (Yoneyama *et al.* 1977; Adachi *et al.* 1989; Oyediran *et al.* 1996; Kondo and Yasuda 2003b; Tanaka *et al.* 2006). The effect of CDC application on N fixation is being debated, however, as it was reported to both increase N fixation (Wada *et al.* 1978; Kondo and Yasuda 2003a) and not increase N fixation (Tanaka *et al.* 2006). The presence of mineral N inhibits microbial N fixation (Yoshida *et al.* 1973; Rajaramamohan Rao 1976; Kyaw *et al.* 2005). Tanaka *et al.* (2006) reported that CDC application resulted in higher microbial biomass N and available N, which inhibited N fixation. In the present study, how N fixation in CDC-applied fields differs from that in RS-applied fields is another question we examine. Irrigation water can be a significant source of N. In Japan, the N input from irrigation was estimated to be 15 to 30 kg ha^{-1} per year (Hasegawa 1992; Kyuma 2004). However, most of the nitrate from irrigation water is lost due to denitrification (Kyaw *et al*. 2005). Rainfall supplies an insignificant amount of N to paddy fields, only about 5 to 6 kg ha^{-1} per year (Hasegawa 1992; Kyuma 2004). Thus, the N inputs from irrigation water and rainfall are viewed as negligible in this study. In addition, the N inputs from these sources were likely the same in the RS- and CDC-applied fields, because we compared neighboring field pairs.

The N output from paddy fields includes plant N uptake, leaching loss, denitrification, ammonia volatilization, and runoff. Plant N uptake is the largest output of N from fields, and it depends on rice variety and soil N availability. RS and CDC application improves plant N uptake by increasing the sources of N mineralization in the soil. In addition, CDC contains inorganic N, because it is decomposed before application. The inorganic N provided by CDC may result in higher plant N uptake and/or higher N leaching loss, the latter of which is the main cause of N loss from paddy fields (Takeda *et al.* 1991; Choudhury and Kennedy 2005; Peng *et al.* 2011). N loss due to leaching is not only an economic concern but also an environmental one, as it causes groundwater pollution. Therefore, clarifying N leaching loss is not only relevant to the nutrient balance but also to the effect of RS and CDC application on the environment. The loss of N via denitrification is influenced by many soil factors, including oxygen, organic matter, pH, temperature, and redox potential (Kyuma 2004). N_2 and N_2O are the main outputs of denitrification, and the latter is a serious greenhouse gas. The N loss due to denitrification of chemical fertilizer has been reported as about 20% (Ito and Iimura 1983; Hasegawa 1992) and 14–46% (Yamamuro 1986). Reports indicate, however, that the amounts of N loss due to denitrification of chemical fertilizer in RS- and CDC-applied fields are similar (Yamamuro 1981, 1986). Ammonia volatilization occurs at high pH and high temperature, and it is a critical problem in tropical countries (Mikkelsen and De Datta 1979). Under sunshine, the pH of ponding water can increase to more than 7.0 and ammonia volatilization will occur. However, Hayashi *et al*. (2006) showed that very little ammonia volatilization occurs from Japanese paddy fields (about 1.4% of applied N), even though they observed higher volatilization occurring during daytime when ponding water has a high pH and a high ammonium concentration. The occurrence of negligible ammonia volatilization in Japanese paddy fields was also reported by Mitsui *et al.* (1954) and Okuda *et al.* (1960). Runoff loss happens when large rain events cause overflow or drainage. The loss of N due to runoff in Japanese rice paddies was estimated to be 0.6 kg ha^{-1} (Kyuma 2004), which is a negligible amount. Thus, we did not consider N loss due to denitrification, ammonia volatilization, or runoff in this study.

The objective of the present research was to clarify why the higher N input from CDC than RS does not result in a difference in the soil total N and available N between treatments. We investigated this question by measuring the total N inputs, total N outputs, and N balance of adjacent paddy fields that received conventional RS treatment or CDC application in a mixed crop–livestock system.

3.2. Materials and methods

3.2.1. Experimental sites discription

The experiment was conducted in the same area as introduced in the chapter I.

3.2.2. Fields selection and treatments

In chapter I, 79 paddy fields were selected based on the application of RS or CDC in 2016. In the RS treatment, RS was applied in the conventional manner to the fields. In the CDC treatment, RS was removed, used as livestock feed, and then CDC was applied to the fields. From the 79 fields, we selected 10 neighboring field pairs under RS and CDC treatments to eliminate variation in environmental conditions and soil properties. In 2017, the full data sets were collected for only 8 of the field pairs due to miscommunication with some farmers. In 2018, data were collected for all 10 field pairs. The average duration of the RS treatments was 33 years and that of the CDC treatments was 21 years. The soil types of the study fields were Non-allophanic Andosols, Wet Andosols, Regosolic Andosols, Lowland Paddy soils, Gley Lowland soils, and Gray Lowland soils (NARO 2019). The following rice cultivars were grown in the study fields: ‘Haenuki’, ‘Hitomebore’, ‘Koshihikari’, ‘SD1’, ‘Tsuyahime’, ‘Yukiwakamaru’, ‘Himenomochi’ (as edible rice), ‘Dewasansan’ (as sake rice), and ‘Fukuhibiki’ and ‘Yumeaoba’ (as forage). The detail information of the fields is showed in Table S3.

Table S3. Field information of rice straw (RS) and cow dung compost (CDC) treatment

Number ⸸	Field name	GPS data		Plow layer (cm)	Applied duration (years)	Rice cultivar 2017/2018	Soil Type‡
RS treatment							
1	RSM1	N 38º52'41.2"	E 140º15'20.7"	17.5	43	Haenuki/ Haenuki	Gley L.
2	RSH1	N 38º51'03.4"	E 140º16'26.3"	17.8	41	Tsuyahime/Tsuyahime	Wet A.
3	RSI2	N 38º50'43.9"	E 140º16'50.7"	15.8	41	SD1/ Tsuyahime	Wet A.
4	RSMa5	N 38º51'57.3"	E 140º17'59.1"	17.0	41	Haenuki / Yumeaoba	Non-a. A.
5	RSN4	N 38º55'04.8"	E 140º15'53.1"	14.2	10	Koshihikari/ Koshihikari	Reg. A.
6	RSN15	N 38º55'08.0"	E 140º16'37.3"	17.0	41	Haenuki/ Haenuki	Gley L.
7	RSN2	N 38º57'24.2"	E 140º17'19.7"	14.7	14	Dewasansan/ Dewasansan	Reg. A.
8	RSN19	N 38º57'41.2"	E 140º17'05.9"	16.8	14	Hitomebore/ Hitomebore	Gley L.
9	RSN13	N 38º58'17.0"	E 140º20'32.7"	18.7	41	Haenuki / Fukuhibiki	Gley L.
10	RSN5	N 38º58'00.0"	E 140º24'57.2"	18.2	41	Himenomochi/ Himenomochi	Gray L.
CDC treatment							
1	CDM1.1	N 38º52'49.1"	E 140º15'14.0"	15.7	41	Haenuki/ Haenuki	Gray L.
2	CDH3	N 38º51'07.5"	E 140º16'08.4"	16.7	38	Tsuyahime/ Tsuyahime	Wet A.
3	CDI4	N 38º50'45.3"	E 140º17'00.4"	15.3	6	SD1/ Yukiwakamaru	Wet A.
4	CDMa3	N 38º52'02.8"	E 140º17'59.2"	16.3	52	Haenuki/ Haenuki	Non-a. A.
5	CDN4	N 38º55'04.0"	E 140º15'52.9"	15.0	10	Koshihikari/ Koshihikari	Reg. A.
6	CDN13	N 38º55'08.0"	E 140º16'36.2"	17.0	30	Hitomebore/ Haenuki	Gley L.
7	CDN2	N 38º57'25.7"	E 140º17'18.9"	16.3	10	Hitomebore/ Hitomebore	Reg. A.
8	CDN19	N 38º57'39.9"	E 140º17'05.4"	14.3	10	Hitomebore/ Hitomebore	Gley L.
9	CDN7	N 38º58'16.8"	E 140º20'07.0"	15.0	4	Haenuki/ Haenuki	Gley L.
10	CDN3	N 38º57'59.7"	E 140º24'59.6"	16.0	6	Fukuhibiki/ Yumeaoba	Gray L.

‡Non-a. A., Non-allophanic Andosols; Wet A., Wet-Andosols; Reg. A., Regosolic Andosols; Gley L., Gley Lowland soils; Gray L., Gray Lowland soils; Brown L., Brown Lowland soils.

⸸ The same number in the RS and CDC treatment represent for the field pair.

3.2.3. Data collection, sampling and analysis

a. Organic matter

RS and CDC were the forms of organic matter applied in this research. A rice plant sample was collected from each field at harvest by cutting whole rice plants above the soil surface and separating them into leaf, stem, and panicle. The samples were then dried at 80°C in a forced-air oven, ground finely with a grinder (TI-100, Heiko Seisakusho Ltd., Tokyo, Japan), and then used for total N analysis on a Sumigraph NC-220-F Analyzer (Sumika Chemical Analysis Service, Tokyo, Japan). The weight of leaf and stem minus stubble was calculated as the rate of RS application, because stubble remains in the fields in both the RS and CDC treatments. The weight of stubble was calculated as 13% of the total weight of leaf and stem (including stubble), following the methods of Ogawa *et al.* (1988) and Hayano *et al.* (2013). CDC was sampled before being applied in April of 2017 and 2018, and the samples were separated into two parts. One part was dried at 60°C in a forced-air oven, ground finely with a grinder (TI-100), and then used for total N analysis on a Sumigraph NC-220-F Analyzer. The other part was dried at 105°C in a forced-air oven to calculate the moisture content of fresh CDC, which was then used to calculate the application rate on a dry weight basis. The fresh weight of applied CDC was obtained by interviewing the farmers. Total N input to the fields from organic matter was calculated by multiplying the application rate of RS and CDC by the total N content in RS and CDC, respectively.

b. Fertilizer

Commercial fertilizer was applied to the fields as basal and top-dressing at the conventional rate for each farmer and rice cultivar. The amount of N fertilizer applied was obtained by interviewing farmers in November of 2017 and 2018.

c. Biological N fixation

The biological N fixation was determined as the enrichment of organic N in the 0–5 mm soil layer during the cropping season, based on a ^{15}N tracer study by Reddy and Patrick (1979) showed that N fixation activity occurs at 0–5 mm in paddy fields. Organic N enrichment was calculated as the difference between organic N in the 0–5 mm soil layer at the various sampling times and at transplanting.

At transplanting, soil was sampled from the plow layer and divided into two parts. One part was extracted with 2M KCl at a soil:KCl ratio of 1:10 (w/v) to determine inorganic N by steam distillation (Bremner 1965). The other part was dried at 35°C in a forced-air oven, ground finely with a grinder (TI-100), and total N was determined by semi-micro-Kjeldahl method followed by steam distillation (Bremner 1965). Organic N was calculated as total N minus inorganic N.

To collect the 0–5 mm soil layer during the cropping season, plow-layer soil was collected from five points in each field right after transplanting and the subsamples were mixed together; the soil was then used to fill polyvinyl chloride (PVC) pipes of 15 cm length and 13.14 cm diameter. Each pipe was covered by a net at the bottom to allow movement of water but not soil and set between the two rows of transplanted hills. The soil surface inside the pipe was set equal with the field soil surface. From each pipe, the 5 mm soil layer was collected five times: at 28 days after transplanting (DAT) (mid-tillering), 42 DAT (panicle initiation), 70 DAT (heading), 100 DAT (ripening), and 120–130 DAT (harvest). It was then dried at 35°C in a forced-air oven, weighed, ground finely with a grinder (TI-100), and total N was determined by semi-micro-Kjeldahl method followed by steam distillation (Bremner 1965). At the same time, the soil in the plow layer near each pipe was collected, passed through a 2-mm sieve, and extracted with 2M KCl at a soil:KCl ratio of 1:10 (w/v) to measure inorganic N by steam distillation (Bremner 1965).

The organic N content was calculated as total N minus inorganic N at each sampling time. The increase in the content of organic N between each sampling time and transplanting is the content of N fixation. The amount of N fixation in the pipe was calculated by multiplying the

N fixation content and the dry weight of soil in the 0–5 mm soil layer. Among sampling times, the highest amount of N fixation was considered as the amount of N fixation in the whole cropping season.

d. Leaching loss

The leached water was sampled using a ceramic cup (10 cm length and 8 mm diameter, sealed at one end) connected to a silicon tube (7 mm inner diameter, 9 mm outer diameter). The ceramic cup was inserted vertically at 30–40 cm depth from the soil surface in the middle of four rice hills at three positions in each field after transplanting. The silicon tubes were extended upward to 20 cm above the soil surface to prevent flow of ponded water into the tube. The end of each silicon tube was covered with a plastic bag to prevent rainfall and insects from entering the pipe. Sampling of leached water began 3 or 4 days after the ceramic cup was set and continued at 1- or 2-week intervals thereafter. The leached water was pumped up by using a 50-ml plastic cylinder. The pH of the sampled water was measured, then pH was adjusted to 2.0–3.0 by adding concentrated HCl, and the sample was stored in a refrigerator. Total N in leached water was measured with a total organic carbon analyzer with total nitrogen measuring unit (TOC-VCSN with TNM-1; Shimadzu Corporation, Kyoto, Japan).

The amount of leached water was measured by using three pairs of PVC pipes of 5.6 cm diameter set near the ceramic cup. In each pair, one pipe without a cap at the bottom was buried until the bottom reached 35 cm deep from the soil surface to measure the amount of water loss through evaporation and leaching, and the other was capped at the bottom and was buried until the bottom reached 15 cm deep from the soil surface to measure the amount of water loss though evaporation only. The top of both pipes was set at 10 cm above the soil surface. The amount of water loss in the pipes was measured several times per week. The cumulative N loss due to leaching was calculated by multiplying the N concentration by the leached water volumes.

e. Plant N uptake

At harvest, we sampled the aboveground parts of rice plants, which were separated into stem, leaf, and panicle, and dried at 80°C in a forced-air oven to measure the dry weight. The sample was then ground finely with a grinder (TI-100), and total N in the sample was analyzed with a Sumigraph NC-220-F Analyzer. The amount of N uptake by rice plants was calculated by multiplying the weight of whole plants minus stubble by the N content. The weight of stubble was calculated as 13% of the total weight of leaf and stem (including stubble) (Ogawa *et al.* 1988; Hayano *et al.* 2013).

f. Soil sampling and analysis

After havest in late October 2017 and 2018, soil samples were collected from the plow layer with an auger (5 cm diameter) at six points and then bulked. The depth of the plow layer was identified manually and measured with a ruler. Soil samples were dried at 35°C in a forced-air oven, treated to remove stones and plant residue, ground in a ceramic mortar, and passed through a 2-mm sieve. Part of each sample was ground finely with a grinder (TI-100), then total N of the sample was analyzed with a Sumigraph NC-220-F Analyzer. Available N was determined by anaerobic incubation of air-dried soil at 30°C for 4 weeks followed by extraction with 2 M KCl at a soil:KCl ratio of 1:10 (w/v). The NH_4^+-N content in solution extracted to measure available N was determined by steam distillation (Bremner 1965).

3.2.4. Statistical analysis

Welch's *t*-test was used to compare the N input, N output, N balance, soil total N, and available N between the RS and CDC treatments. The analysis was performed with the Analysis ToolPak in Excel for Office 365 (Mircosoft, Redmond, WA, USA). A P value < 0.05 was considered to indicate a significant difference.

3.3. Results

3.3.1. Soil total N and available N

Table 3.1. Soil total N and available N of paddy fields in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018

Treatment	Total N ($g\ kg^{-1}$)	Available N ($g\ kg^{-1}$)
2017		
RS (n = 8)	3.72 ± 1.13	0.22 ± 0.06
CDC (n = 8)	4.08 ± 1.42	0.21 ± 0.05
P (t-test)	0.58	0.85
2018		
RS (n = 10)	3.66 ± 1.18	0.29 ± 0.05
CDC (n = 10)	4.03 ± 1.45	0.26 ± 0.05
P (*t*-test)	0.53	0.13

Values are mean ± SD. The P value is the probability level of a two-tailed Welch's *t*-test.

Soil total N of the RS treatment was 3.72 and 3.66 $g\ kg^{-1}$ and that of the CDC treatment was 4.08 and 4.03 $g\ kg^{-1}$ in 2017 and 2018, respectively (Table 3.1). Although soil total N of the

RS treatment was lower than that of the CDC treatment in both years, the differences were not significant (P = 0.58 and 0.53). In both treatments, soil total N in 2018 was similar to that of 2017. Available N of the RS treatment (0.22 and 0.29 g kg^{-1}) was higher than that of the CDC treatment (0.21 and 0.26 g kg^{-1}) in both years, but not significantly so (P = 0.85 and 0.13). Soil available N accounted for less than 10% of the soil total N in both treatments.

3.3.2. N input from organic matter

Table 3.2. N content and N input from rice straw (RS) and cow dung compost (CDC) in 2017 and 2018

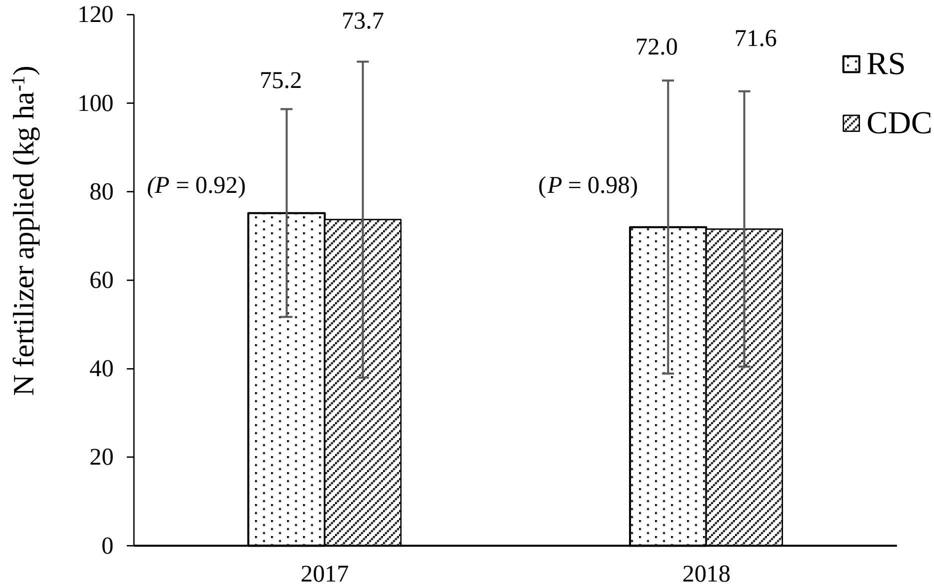
Treatment	Application rate ($t\ ha^{-1}$)	N content ($g\ kg^{-1}$)	N input ($kg\ ha^{-1}$)
2017			
RS (n = 8)	5.4 ± 1.4	5.3 ± 0.7	29.8 ± 9.3
CDC (n = 8)	4.4 ± 0.9	11.9 ± 2.3	52.0 ± 11.6
P (t-test)	0.11	< 0.01	< 0.01
2018			
RS (n = 10)	5.5 ± 1.0	5.4 ± 0.8	31.2 ± 9.3
CDC (n =10)	4.1 ± 1.1	13.3 ± 1.0	54.3 ± 15.5
P (t-test)	< 0.01	< 0.01	< 0.01

Values are mean ± SD. The P value is the probability level of a two-tailed Welch's t-test.

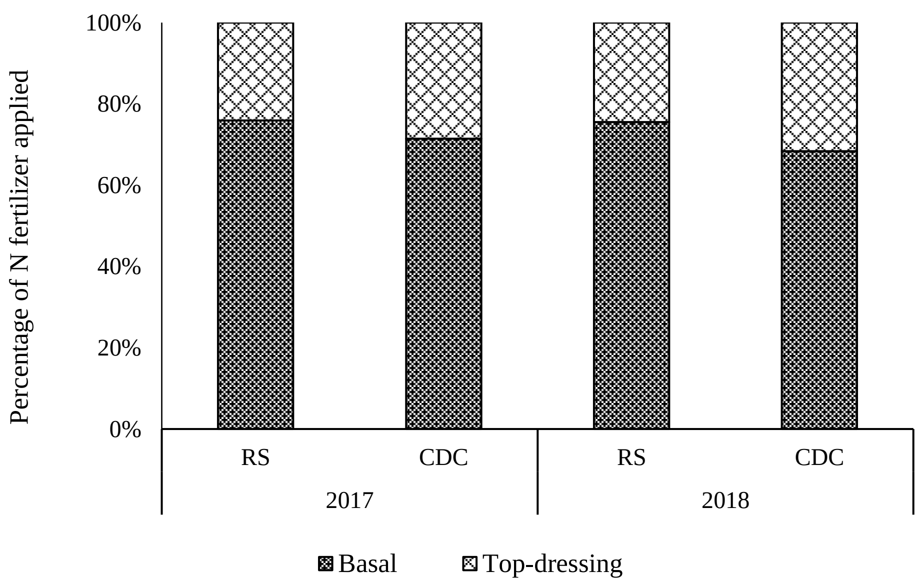
Table 3.2 reports the rate of RS and CDC application, N contents, and the amounts of N input from RS and CDC to the fields in 2017 and 2018. The application rates of RS on a dry weight basis (excluding stubble) were 5.4 and 5.5 t ha^{-1} in 2017 and 2018, respectively, which were higher than those of CDC (4.4 and 4.1 t ha^{-1}), although the difference was significant only in 2018. The N contents of RS in 2017 and 2018 were 5.3 and 5.4 g kg^{-1}, respectively, which were significantly lower than those of CDC (11.9 and 13.3 g kg^{-1}). The variation in N content of CDC was larger than that of RS. The amount of N input was calculated by multiplying the application rate by the N content. The N inputs from RS were 29.8 and 31.2 kg N ha^{-1} and those from CDC were 52.0 and 54.3 kg N ha^{-1} in 2017 and 2018, respectively. The difference in N input between RS and CDC was significant in both years ($P < 0.01$), by about 22 kg ha^{-1} in 2017 and 23 kg ha^{-1} in 2018. The N content of organic matter made a large contribution to the N input.

3.3.3. N input from fertilizer

In most fields, fertilizer was applied two times, as a basal application (before or at transplanting) and a top-dressing (panicle initiation stage). Some fields received only basal fertilizer, and some fields received top-dressing multiple times. The total N fertilizer applied in the RS treatment was higher than that in the CDC treatment, with rates of 75.2 and 73.7 kg ha^{-1}, respectively, in 2017 and 72.0 and 71.6 kg ha^{-1} in 2018, but the differences were not significant (P = 0.92 and 0.98) (Fig. 3.1a). The amount of N application varied among fields in both treatments. The percentages of N fertilizer applied as basal and top-dressing were about 75% and 25% in the RS treatment and about 70% and 30% in the CDC treatment (Fig. 3.1b).



(a)



(b)

Figure 3.1. The total fertilizer N application amount of rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018 (a), and the percentage of N fertilizer applied as basal and top-dressing in cases in which both basal and top-dressing fertilizer were applied (b). Vertical bars are SD. The *P* value is the probability level of a two-tailed Welch's *t*-test.

Table 3.3. N balance in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018

Parameter	2017			2018		
	RS (kg ha^{-1})	CDC (kg ha^{-1})	*P* (*t*-test)	RS (kg ha^{-1})	CDC (kg ha^{-1})	*P* (*t*-test)
N input						
Organic matter	29.8 ± 9.3	52.0 ± 11.6	< 0.01	31.2± 9.3	54.3 ± 15.5	< 0.01
Fertilizer	75.2 ± 23.5	73.7 ± 35.7	0.92	72.0 ± 33.1	71.6 ± 31.1	0.98
N fixation	22.7 ± 9.4	24.1 ± 7.7	0.76	27.0 ± 10.7	30.9 ± 8.5	0.38
Total	127.8 ± 30.8	149.8 ± 43.2	0.34	130.2 ± 39.7	156.7 ± 39.7	0.22
N output						
Plant uptake	87.5 ± 21.3	103.4 ± 22.5	0.17	86.8 ± 18.5	89.6 ± 23.2	0.77
Leaching	2.4 ± 0.9	2.8 ± 1.8	0.32	1.9 ± 1.7	1.5 ± 0.7	0.59
Total	89.9 ± 21.1	106.2 ± 22.7	0.16	88.6 ± 18.1	91.0 ± 23.2	0.78
N balance	37.8 ± 21.8	43.5 ± 34.9	0.70	41.6 ± 29.5	65.7 ± 37.5	0.20

Values are mean ± SD. The *P* value is the probability level of a two-tailed Welch's *t*-test.

3.3.4. Biological N fixation

The organic N content in the 0–5 mm soil layer tended to increase after transplanting, reached a peak at 28 or 42 DAT in both treatments and in both years, and then remained stable during the cropping season (Fig. 3.2). In 2017 the organic N contents were similar in the RS and CDC treatments at all sampling times, whereas in 2018 the CDC treatment showed higher organic N content at all sampling times, although the differences between treatments were not significant.

The amounts of N fixation were 22.7 and 27.0 kg ha^{-1} in the RS treatment and 24.1 and 30.9 kg ha^{-1} in the CDC treatment in 2017 and 2018, respectively (Table 3.3). The amount of N fixation in the RS treatment was lower than that of the CDC treatment in both years, but the difference was not significant. The differences in the amount of N fixation between RS and CDC treatment were about 1 kg ha^{-1} in 2017 and about 4 kg ha^{-1} in 2018.

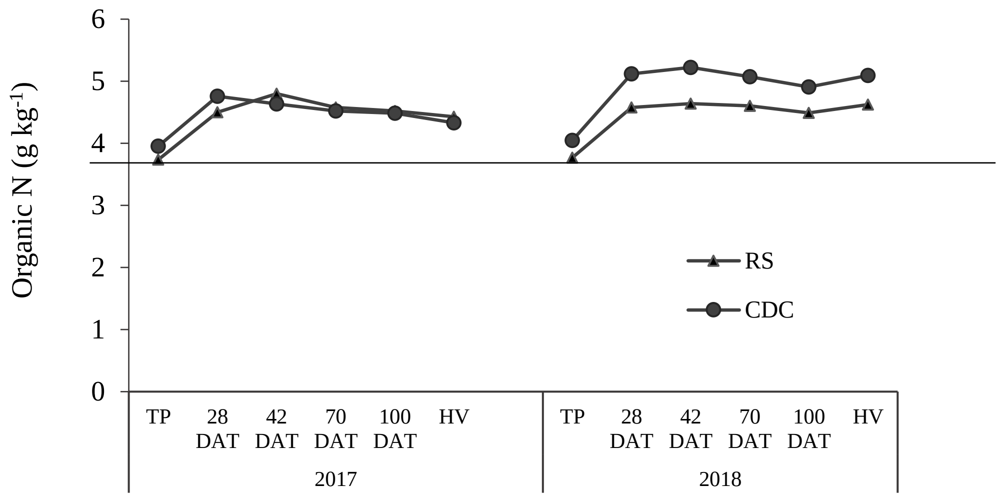


Figure 3.2. Organic N content in the 0–5 mm soil layer of rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018. TP: transplanting; DAT: days after transplanting; HV: harvest.

3.3.5. N leaching loss

The amount of water leached ranged from 1.90 to 3.65 mm day^{-1} in the RS treatment and from 2.13 to 3.26 mm day^{-1} in the CDC treatment in 2017, with respective ranges of 1.68–2.70 mm day^{-1} and 2.05–2.93 mm day^{-1} in 2018 (Fig. 3.3). The amount of water leached in the CDC treatment was greater than that in the RS treatment but not significantly so. The amount of water leached varied during the cropping season in both treatments and in both years.

The water was sampled once per week until 10 weeks after transplanting (WAT) and once every 2 weeks after that in 2017 and once every 2 weeks in 2018. The concentration of total N in leached water was the highest in the early growth stage, then gradually decreased with time in both treatments in 2017. In the early growth stage, the concentration of total N in the CDC treatment was higher than that in the RS treatment, but after 7 WAT the total N concentration in both treatments fluctuated at a low level. In 2018, the concentration of total N in leached water fluctuated slightly and remained at a low level during the cropping season. The concentration of total N in the RS treatment was similar to that of the CDC treatment at all sampling times (Fig. 3.3). The average total N concentration in leached water over both years was 0.88 mg L^{-1} in the RS treatment and 0.92 mg L^{-1} in the CDC treatment.

From the amount of water leached and the concentration of total N in leached water, we calculated the amount of cumulative N loss due to leaching. The values were 2.4 and 1.9 kg ha^{-1} in the RS treatment and 2.8 and 1.5 kg ha^{-1} in the CDC treatment in 2017 and 2018, respectively (Table 3.3). The amount of N loss due to leaching in the CDC treatment was higher than in the RS treatment in 2017, and the opposite result was seen in 2018, but the differences were not significant.

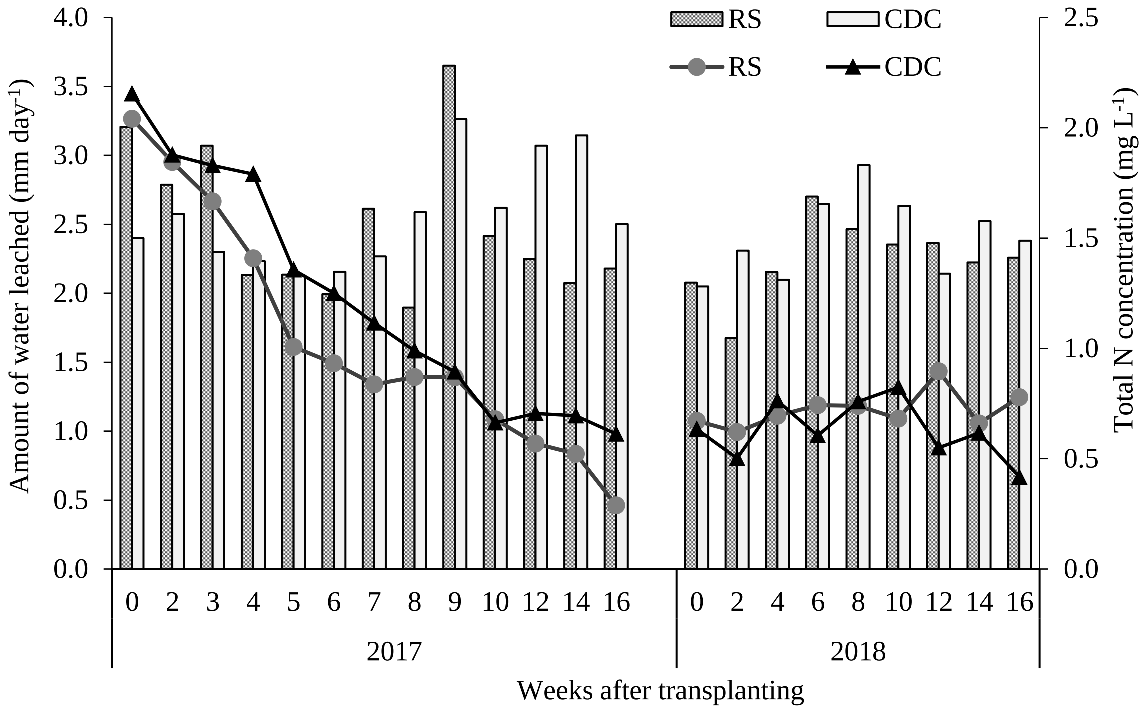


Figure 3.3. Amount of water leached (bar graph) and total N concentration in leached water (line graph) in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018.

3.3.6. Plant N uptake

Table 3.4 shows the N content in rice plants at harvest and the total N uptake by rice plants in 2017 and 2018. The N contents of all parts of rice plants in the RS treatment were lower than those in the CDC treatment, except for grain in 2018. The N content of each part was similar between the two years. Most of the N taken up by plants was distributed to the panicle. Total N uptake by plants in the RS treatment was calculated as 87.5 and 86.8 kg ha^{-1} in 2017 and 2018, respectively, which is lower than the values in the CDC treatment (103.4 and 89.6 kg ha^{-1}), although the difference was not significant. The difference in plant N uptake between treatments was about 16 kg ha^{-1} in 2017 and 3 kg ha^{-1} in 2018.

Table 3.4. N content and N uptake by rice plants, by plant part, in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018

	N content (g kg^{-1})		N uptake (kg ha^{-1})		*P* (*t*-test)
	RS	CDC	RS	CDC	
2017 (*n* = 8)					
Stem	4.1 ± 0.5	5.0 ± 1.3	18.2 ± 4.8	24.9 ± 6.0	
Leaf	11.7 ± 1.5	12.9 ± 2.5	11.6 ± 5.1	15.3 ± 5.9	
Grain	9.1 ± 0.7	9.7 ± 1.0	57.7 ± 12.7	63.3 ± 13.0	
Total			87.5 ± 21.3	103.4 ± 22.5	0.17
2018 (*n* = 10)					
Stem	4.3 ± 0.7	4.7 ± 1.1	19.5 ± 5.3	21.8 ± 6.6	
Leaf	10.3 ± 1.1	10.7 ± 2.3	11.8 ± 4.5	12.0 ± 3.9	
Grain	9.6 ± 0.9	9.1 ± 0.9	55.5 ± 11.5	55.8 ± 14.1	
Total			86.8 ± 18.5	89.6 ± 23.2	0.77

Values are mean ± SD. The *P* value is the probability level of a two-tailed Welch's *t*-test.

3.3.7. N balance

The N in organic matter (RS or CDC), N fertilizer, N fixation, and plant N uptake were the main contributors to the N balance of paddy fields, whereas N loss through leaching was negligible. The total N input to the RS treatment was 127.8 and 130.2 kg ha^{-1} in 2017 and 2018, respectively, which is about 22 and 27 kg ha^{-1} lower than the inputs to the CDC treatment (Table 3.3), but the differences were not significant. Among N input sources, fertilizer contributed the most, accounting for 55% of total N inputs in the RS treatment and 45% in the CDC treatment, followed by organic matter (24% for RS and 36% for CDC), and the remainder was from N fixation. The total output of N was also lower in the RS treatment (89.9 and 88.6 kg ha^{-1}) than in the CDC treatment (106.2 and 91.0 kg ha^{-1}) in 2017 and 2018. The differences in the total N output between the RS and CDC treatments, about 16 kg ha^{-1} in 2017 and 2 kg ha^{-1} in 2018, were not significant. The N balance of the RS treatment was positive in both years (37.8 and 41.6 kg ha^{-1}) and lower than that of the CDC treatment (43.5 and 65.7 kg ha^{-1}), but not significantly so.

3.4. Discussion

3.4.1. Effects of variation of soil total N and soil types on the present results

Soil total N and available N were not significantly different between treatments (Table 3.1). There was, however, a large variation in the soil total N because the soil types of the study fields included Andosols and Lowland soils. Soil total N ranged from 2.6 to 5.4 g kg^{-1} in Andosols and from 1.6 to 5.9 g kg^{-1} in Lowland soils, and the average soil total N of Andosols was 1.3 times higher than that of Lowland soils. There was a concern regarding the effect of variation in soil total N or soil types on the non-significant difference in soil total N between treatments, but we confirmed that soil total N was not significantly different between treatments, even when we compared it separately in Andosols and in Lowland soils. In addition, in each field pair, the soil total N and soil type of the RS treatment was almost the same as that of the CDC treatment, as they were adjacent fields. Thus, the variation in soil total N and soil types in this study was not an obstacle to comparing the results.

3.4.2. Sources of N input to the fields

The N input from CDC was significantly greater than that of RS, due to the higher N content in CDC than in RS (Table 3.2). This is comparable with the result reported by Nguyen *et al.* (2019).

The N input from both RS and CDC showed large variation among fields, ranging from 16.0 to 43.5 kg ha^{-1} in the RS treatment and from 31.1 to 76.6 kg ha^{-1} in the CDC treatment. In the RS treatment, the variation of N input from RS arose from variation in the amount of RS applied and the N content of RS among fields due to differences in rice varieties and N fertilizer application rates. In the CDC treatment, the variation of N input from CDC was due to different CDC application rates and N contents of CDC. The application rate ranged from 3.9 to 8.6 t ha^{-1} in the RS treatment and from 2.1 to 5.3 t ha^{-1} in the CDC treatment. The N content in RS ranged from 4.2 to 6.7 g kg^{-1} and that in CDC ranged from 10.2 to 14.8 g kg^{-1}. Several rice varieties were grown in the study area, and CDC was obtained from several different sources. The application rate of RS in this study is comparable with that reported by Cheng *et al.* (2016) in the same region. The N input from RS or CDC contributed a significant amount to the total N inputs, accounting for 24% in the RS treatment and 36% in the CDC treatment.

The N fertilizer contributed the highest amount to the total N input, accounting for 55% in the RS treatment and 45% in the CDC treatment. The rate of N fertilizer application is decided based on rice variety and each farmer's approach, and it ranged from 16.7 to 145.0 kg ha^{-1} in the RS treatment and from 30.0 to 143.0 kg ha^{-1} in the CDC treatment. The fertilizer was applied at a higher rate to forage rice and rice used in making sake than to edible rice. In a special N management practice known as *Tokubetsu-saibai* in Japanese, chemical inorganic N fertilizer is applied at half the rate of conventional N management. The N fertilizer application rate in the RS treatment was similar to that of the CDC treatment, but the total N input from CDC was higher than that from RS.

Although the CDC treatment resulted in higher N fixation than the RS treatment, the difference was not significant (Table 3.3). Thus, the two treatments had a similar effect on N fixation, a result that is comparable with the findings of Kondo and Yasuda (2003a) but not with those of Tanaka *et al.* (2006). The higher soil available N in CDC-applied fields than in RS-applied fields was the reason for the lower N fixation in CDC-applied fields reported by Tanaka *et al.* (2006). In this study, however, there were no differences in soil available N (Table 4) or the N concentration in plow-layer water (data not shown) between treatments, which explained the above result. The N input from N fixation was lower than that from RS or CDC and fertilizer, but it still made a significant contribution to total N input. The amount of N fixation in this study ranged from 11.9 to 51.8 kg ha^{-1} in the RS treatment and from 13.2 to 48.0 kg ha^{-1} in the CDC treatment. This result was comparable to the 15–50 kg N ha^{-1} input from N fixation reported by Koyama and App (1979) and to the 25–35 kg ha^{-1} reported by Ono and Koga (1984) using an analysis of enriched N in the surface soil. The N fixation activity occurred mostly during the 4 to 6 WAT (Fig. 3.2), which is comparable with the results estimated by Kyaw *et al*. (2005) and Tanaka *et al.* (2006) using incubation experiments.

Total N input from the RS treatment was lower than that from the CDC treatment (Table 3.3), but the difference was not significant, despite the significant difference in N input from RS and CDC. In addition, the N input from sources other than RS or CDC (i.e., fertilizer and N fixation) was similar between treatments.

3.4.3. Sources of N output from the fields

Plant N uptake was the main output of N from the fields, accounting for 98% of total N output and 67% of total N input. The RS treatment had lower plant N uptake than the CDC treatment in both years, but not significantly so (Table 3.3). Rice plants take up N in inorganic forms that originate from soil N mineralization, decomposition of organic matter, and N fertilizer. The N fertilizer application rate (Fig. 3.1) and N concentration in plow-layer water (data not shown) were similar between treatments. Thus, the plant N uptake depends on the inorganic N generated by RS and CDC decomposition. Considering the results of plant N uptake, available N delivered from CDC decomposition may be greater than that from RS decomposition, but not at a significant level. The N uptake by rice plants mostly went to grain, at more than half in both treatments.

The N leaching loss was calculated from the amount of water leached and the total N concentration in the leached water. The amount of water leached obviously depends on soil texture. The paddy soils in the study fields include coarse- and fine-textured Lowland soils and Andosols (NARO 2019), which results in variation in the degree of leaching among fields. Organic matter application reduces water leaching (Luo *et al.* 2011). In this study, the CDC and RS treatments had similar amounts of water leached in both years (Fig. 3.3), which confirms that the application of CDC had the same effect on reducing water leaching as RS incorporation. In contrast, the concentration of N in leached water mainly depends on the availability of N in the plow layer, and it increases with a higher N fertilizer application rate (Kyaw *et al*. 2005; Peng *et al.* 2011; Wang *et al.* 2014). In 2017, N fertilizer was applied at the same rate in both treatments, and >70% of N fertilizer was spread as a basal application before or at transplanting. This situation may have contributed to the similar total N concentration in leached water between treatments and the higher concentration of total N in leached water at the early growth stage after transplanting (Fig. 3.3). The amount of N leaching loss in this study was quite small and ranged from 0.5 to 6.2 kg ha^{-1} in the RS treatment and from 0.6 to 6.0 kg ha^{-1} in the CDC treatment. The differences in the amount of leached water and N fertilizer application amount may be the reason for this variation. The N leaching loss in this area was lower than the results reported by Takeda *et al.* (1991), Cho *et al.* (2000), and Peng *et al.* (2011). Our result can be explained by the effect of organic matter application on reducing the N leaching loss. Shibahara *et al.* (1994) and Luo *et al.* (2011) reported that organic matter application decreased the percolation loss of N from paddy fields.

Overall, plant N uptake was the largest output of N from the fields, whereas N loss due to leaching was insignificant. The total N output was similar between the two treatments.

3.4.4. N balance

The N balance was the same in both treatments and in both years (Table 3.3). Although the N input to the CDC treatment from organic matter (CDC) was significantly higher than in the RS treatment, the total N input was not significantly different between treatments. In addition, the output of N was similar between treatments, which resulted in a non-significant difference in the N balance. The N input from RS and CDC are important sources that kept the N balance positive in the RS and CDC treatments. If there were no RS or CDC application, the N balance would have been negative in the RS treatment in 34% of the fields and in the CDC treatment in 63% of the fields. Therefore, when RS is removed to feed cows, the application of CDC is important to retain a positive N balance in paddy fields.

Overall, the non-significant difference in N balance between treatments could explain the non-significant difference in soil total N and available N. Soil total N did not increase even though the N balance was positive in both years. This can be explained by the small contribution of the positive N balance to the large pool of soil total N, accounting for about 1% (data not shown).

3.5. Conclusion

The N input from organic matter, fertilizer, and N fixation contributed significantly to the N balance of paddy fields. Fertilizer contributed the greatest N input to the fields, followed by organic matter and N fixation. The N input from CDC was significantly higher than that from RS, but farmers applied the same amount of N fertilizer to both treatments. The application of RS or CDC resulted in the same amount of N fixation. The greater amount of N input from CDC than that from RS did not contribute enough to make the difference in total N input between treatments significant.

Although the N output from the CDC treatment was higher, it was not significantly different from that of the RS treatment. Plant N uptake was the main output from the fields, accounting for 98% of the total N output. The N leaching loss did not contribute significantly to the total output. The plant N uptake and N leaching loss were non-significant difference between treatments.

The non-significant difference in N input and N output between treatments resulted in a non-significant difference in N balance as well. Thus, we conclude that the non-significant difference in total N input, total N output, and N balance together caused the non-significant difference in soil total N and available N between treatments.

IV. CHAPTER III: Comparison of the phosphorus balance in paddy fields under conventional rice straw application versus cow dung compost application in mixed crop–livestock systems

4.1. Introduction

P is an essential nutrient for plant as its function in energy storage and transfer. This energy is used in growth and reproductive processes. P exists in organic and inorganic forms in soil and the available P, which is a part of inorganic form, is measured to evaluate the amount of plant available P from soil. Thus, soil available P is important indicator to evaluate the soil fertility. Since green revolution, chemical fertilizer P has been main input source of available P for plant.

In Japan, about 30% of total produced fertilizer P is consumed in the paddy field (Nishio, 2002; Mishima *et al.* 2003). This high rate of fertilizer P application has led to the excessively P accumulation in soil. National scale investigation on soil available P in paddy field in Japan reported that 80% of the paddy fields contain higher available Truog-P than diagnostic standard in surface soil (44 mg kg $^{-1}$ as P) (Obara and Nakai, 2004). To produce fertilizer P, however, most of P resources is imported and this source is going to be depleted in near future. Therefore, to cope with this situation, a good fertilizer P management practice and the alternative source of fertilizer such as organic matter is necessary. organic matter is necessary for the sustainable agricultural system. And, understanding P balance in paddy field is important information to have good management of fertilizer P to keep rice yield and maintain soil available P.

In rice production area, RS is the most available source of P. In Japan, RS is usually cut and sprayed on the field at harvest, then incorporated into the soil in the next season. The application of RS in combination with fertilizer (NPK) has been proven to increase soil available P (Beaton *et al*. 1992; Wang *et al.* 2005). In mixed crop–livestock system, however, CDC is the available source of P because RS is removed from the fields to feed cows. CDC or manure application in combination with fertilizer has been also proven to increase soil available P (Lee *et al*. 2004; Bhattacharyya *et al*. 2015). In our previous research, we found that CDC supply more total P to the field than RS but the available P in soil was not different between treatments (Nguyen *et al.* 2019). The availability of P in soil is not only depended on the input from RS and CDC but also other factors such as other sources of P input, P output, and P balance of the fields. To identify the reason for our previous observation (Nguyen *et al.* 2019), we investigated on the total P input, total P output, and P balance of the RS and CDC treatments.

Aside from RS or CDC, fertilizer, irrigation water, and rainfall are additional source of P input to the fields. Fertilizer P is considered as the largest source of P input, because high fertilizer P inputs in intensive crop areas have been practice for several decades. The difference in the P input from RS and CDC may lead farmers to apply different amount of fertilizer P for two treatments. The P input from irrigation water and rainfall, however, were proven to be small and negligible in P balance, which is estimated to be less than 1 kg ha^{-1} in Japanese paddy field (Nanzyo 1996; Maruyama *et al.* 2008). Besides, the RS treatment and CDC treatment in this research are nearby, and they receive the same source of irrigation water, so we consider that those inputs are the same between treatments. Thus, we did not measure the input from irrigation water and rainfall in this research.

The output of P from the field include plant P uptake, runoff, and leaching. Plant P uptake is considered as the main loss of P from the paddy field (Hasegawa 1992; Nanzyo 1996; Maruyama *et al.* 2008). The different in the input of P from RS and CDC may result in difference in plant P uptake between treatments. Runoff loss of P is occurred when large rain events or surface drainage before transplanting. The loss of P due to runoff in Japanese rice paddies was estimated to be less than 2 kg ha^{-1} (Nanzyo 1996), which is a negligible amount. P leaching loss is usually insignificant (Hasegawa 1992; Kyuma 2004) as the P is widely considered to be firmly fixed onto the soil particles. However, high P accumulation enhances a potential loss of P through leaching in paddy rice field (Zhang *et al.* 2003; Shan *et al*. 2005; Ooya *et al.* 2007). And, the difference in input from RS and CDC may result in difference in the soluble P in plow layer water and lead to difference in leaching loss.

The objective of the present research to investigate on the P balance of paddy field to consider the minimum amount of fertilizer P application to maintain soil available P and to clarify the reason why the higher P input from CDC than RS does not result in a difference in the available P between treatments. We investigated this question by measuring the total P inputs, total P outputs, and P balance of adjacent paddy fields that received conventional RS treatment or CDC application in a mixed crop–livestock system.

4.2. Materials and methods

4.2.1. Experimental sites discription

The experiment was conducted in the same area as introduced in the chapter I.

4.2.2. Fields selection and treatments

The experiment was conducted on the same fields as introduced in chapter II.

4.2.3. Data collection, sampling and analysis

a. Organic matter

RS and CDC samples were the same with the one collected in chapter II. To measure total P in

RS and CDC, the materials were first digested with H_2SO_4–H_2O_2 (Mizuno and Minami 1980). The concentration of P was measured by the vandomolybdophosphoric acid method (Kuo 1996). The amount of total P input was calculated by multiplying the total P content with rate of RS and CDC applied.

b. Fertilizer

The amount of P fertilizer was obtained by asking farmers.

c. Plant P uptake

The plant sample was the same sample with the one collected in chapter II. To measure total P in plant sample, the materials were first digested with H_2SO_4–H_2O_2 (Mizuno and Minami 1980). The concentration of P was measured by the vandomolybdophosphoric acid method (Kuo 1996).

d. Leaching loss

The amount of water leaching was taken from the experiment introduced in chapter II. The leaching water sample was the same sample with the one collected in chapter II. To determine the total P in leaching water, the sample was digested with potassium peroxodisulphate ($K_2S_2O_8$), then the P concentration in digested solution was measured by molybdenum blue method (Matsuhisa 2005).

e. Soil total P and available P

The soil sample was the same with the one collected in the chapter II. The available P was determined by Truog's method (Nanzyo 1997). The total P in soil was digested with concentrated H_2SO_4 plus H_2O_2 (30%) (Gasparatos and Haidouti 2001), then P concentration in digested solution was measured by vandomolybdophosphoric acid method (Kuo 1996).

4.2.4. Statistical analysis

Welch's *t*-test was used to compare the P input, P output, P balance, soil total P, and available P between the RS and CDC treatments. The analysis was performed with the Analysis ToolPak in Excel for Office 365 (Mircosoft, Redmond, WA, USA). A *P* value < 0.05 was considered to indicate a significant difference.

4.3. Results

4.3.1. Soil total P and available P

Table 4.1. Soil total P and available P of paddy fields in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018

Treatment	Total P (mg P kg^{-1})	Available P (mg P kg^{-1})
2017		
RS (*n* = 8)	2815.4 ± 974.3	82.3 ± 32.1
CDC (*n* = 8)	2997.3 ± 1533.1	75.0 ± 33.6
P (t-test)	0.782	0.663
2018		
RS (*n* = 10)	2807.7 ± 979.1	77.3 ± 28.8
CDC (*n* = 10)	2980.4 ± 1533.2	81.1 ± 47.6
P (*t*-test)	0.768	0.832

Values are mean ± SD. The *P* value is the probability level of a two-tailed Welch's *t*-test.

Soil total P in the RS treatment was 2815.4 and 2807.7 mg kg^{-1} in 2017 and 2018, respectively, which was lower than those in the CDC treatment (2997.3 and 2980.4 mg kg^{-1}), even the difference was not significant (Table 4.1). Soil available P in the RS treatment was 82.3 and 77.3 mg kg^{-1} in 2017 and 2018, respectively, and that in the CDC treatment was 75.0 and 81.1 mg kg^{-1}. In 2017, soil available P in the RS treatment was higher than that of the CDC treatment, while the opposite was seen in 2018. The difference between treatments was not significant in both years. Soil total P and available P in both treatments did not increase after two year during this study and was almost the same between two years.

4.3.2. P input from organic matter

Table 4.2. P content and P input from rice straw (RS) and cow dung compost (CDC) in 2017 and 2018

	Application rate ($t\ ha^{-1}$)	P content ($g\ kg^{-1}$)	P input ($kg\ ha^{-1}$)
2017			
RS (n = 8)	5.4 ± 1.4	1.3 ± 0.6	6.9 ± 2.5
CDC (n = 8)	4.4 ± 0.9	5.2 ± 5.1	21.6 ±19.3
P (t-test)	0.11	0.07	0.07
2018			
RS (n = 10)	5.5 ± 1.0	1.4 ± 0.5	7.8 ± 2.6
CDC (n = 10)	4.1 ± 1.1	4.8 ± 1.3	19.5 ± 6.3
P (t-test)	< 0.01	< 0.01	< 0.01

Values are mean ± SD. The *P* value is the probability level of a two-tailed Welch's *t*-test.

Table 4.2. shows the P content and P input from RS and CDC to the field in 2017 and 2018. The total P content of RS was 1.3 and 1.4 g kg^{-1} in 2017 and 2018, respectively, which was lower than that of CDC (5.2 and 4.8 g kg^{-1}), but the difference was significant only in 2018. There was a large variation in the total P content in CDC in 2017. The amount of P input from RS was 6.9 and 7.8 kg ha^{-1} in 2017 and 2018, respectively, which was lower than that from CDC (21.6 and 19.5 kg ha^{-1}). The difference in amount of P input from RS and CDC was 14.5 and 11.7 kg ha^{-1} but the difference was significant only in 2018, too.

4.3.3. P input from fertilizer

Table 4.3. The P balance in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018.

	2017			2018		
	RS (kg ha^{-1})	CDC (kg ha^{-1})	*P* t-test	RS (kg ha^{-1})	CDC (kg ha^{-1})	*P* t-test
P Input						
Organic matter	6.9 ± 2.5	21.6 ± 19.3	0.070	7.8 ± 2.6	19.5 ± 6.3	< 0.01
Fertilizer	50.5 ± 25.9	32.3 ± 10.6	0.099	43.8 ± 26.3	29.4 ± 11.7	0.140
Total	57.4 ± 24.0	52.0 ± 17.2	0.609	51.6 ± 24.7	48.9 ± 13.3	0.768
P Output						
Plant uptake	19.9 ± 4.1	22.1 ± 6.3	0.421	23.3 ± 5.2	22.6 ± 4.4	0.718
Leaching	0.17 ± 0.1	0.15 ± 0.2	0.718	0.21 ± 0.1	0.25 ± 0.2	0.547
Total	20.1 ± 4.1	22.3 ± 6.2	0.423	23.6 ± 5.2	22.8 ± 4.5	0.733
Balance	37.3 ± 27.0	29.7 ± 17.6	0.515	28.1 ± 28.2	26.1 ± 12.7	0.847

Values are mean ± SD. The *P* value is the probability level of two-tailed Welch's t-test.

The fertilizer P applied to the RS treatment was 50.5 and 43.8 kg ha^{-1} in 2017 and 2018, respectively, and it was higher than that to the CDC treatment (Table 4.3). The difference in the amount of fertilizer P between treatments was about 18 and 14 kg ha^{-1} in 2017 and 2018, respectively, even the difference was not significant. There was large variation in the rate of P fertilizer application in both treatments. Different varieties received different amount of P fertilizer. Most of P fertilizer was applied as basal.

4.3.4. Plant P uptake

Table 4.4. P content and P uptake of whole rice plant and each plant part in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018

	P concentration (g kg^{-1})		P uptake (kg ha^{-1})		*P* (t-test)
	RS	CDC	RS	CDC	
2017 (n = 8)					
Stem	1.3 ± 0.6	1.4 ± 0.5	5.8 ± 2.1	7.5 ± 4.0	
Leaf	1.3 ± 0.7	1.2 ± 0.4	1.2 ± 0.5	1.4 ± 0.7	
Grain	2.1 ± 0.2	2.0 ± 0.1	13.0 ± 2.2	13.2 ± 3.0	
Total			19.9 ± 4.1	22.1 ± 6.3	0.42
2018 (n = 10)					
Stem	1.4 ± 0.5	1.4 ± 0.4	6.2 ± 2.2	6.4 ± 1.8	
Leaf	1.4 ± 0.4	1.3 ± 0.2	1.5 ± 0.5	1.4 ± 0.4	
Grain	2.7 ± 0.2	2.4 ± 0.1	15.6 ± 3.4	14.8 ± 3.1	
Total			23.4 ± 5.2	22.6 ± 4.4	0.72

Values are mean ± SD. The *P* value is the probability level of a two-tailed Welch's *t*-test.

Table 4.4 shows the P content and P uptake of whole rice plant and each plant part in the RS and CDC treatment. The P content in stem, leaf, and grain was almost the same between treatments. The P content in the grain was highest. The total P uptake in the RS treatment was almost the same with that of the CDC treatment in both years and it ranged from 19.9 to 23.4 kg ha^{-1}. Most of the P uptake by rice plant come to grain, accounting for 66% and 63% of total P uptake in the RS treatment and CDC treatment, respectively. Very few P come to leaf at harvest in both treatments.

4.3.5. P leaching

The total P concentration in leaching water was very low, ranged from 0.02 to 0.17 mg L^{-1} (Fig. 4.1). The total P concentration in the RS treatment was higher than that of the CDC treatment in the period from 3 to 8 WAT in 2017 and from 2 to 6 WAT in 2018. In 2017, the total P concentration increased sharply from 0.05 mg L^{-1} in the RS treatment and 0.02 mg L^{-1} in the CDC treatment at 2 WAT to the peak of 0.17 and 0.10 mg L^{-1} at 5 WAT. After that it decreased sharply until 9 WAT, then kept at constant level until 16 WAT. In 2018, total P concentration got peak at 2 WAT at level of 0.15 and 0.13 mg L^{-1} in the RS treatment and CDC treatment, respectively. After that P concentration continuously decreased until 8 WAT in the RS treatment and 12 WAT in the CDC treatment, then kept constant until 16 WAT.

The accumulative P leaching in the RS treatment was 0.17 and 0.21 kg ha^{-1} in 2017 and 2018, respectively, and that in the CDC treatment was 0.15 and 0. 25 kg ha^{-1} (Table 4.3). The difference in the P leaching amount between treatments was not significant in both years. This amount of P leaching was about 1% of total output.

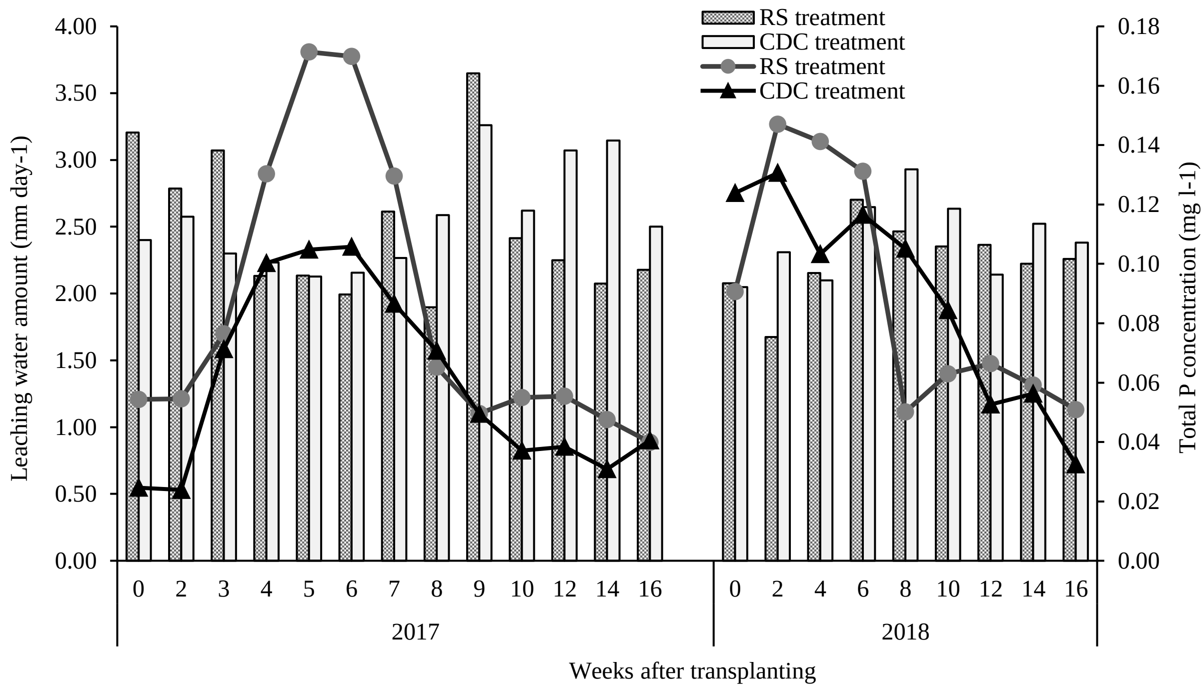


Figure 4.1. Amount of water leached (bar graph) and total P concentration in leached water (line graph) in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018.

4.3.6. P balance

Table 4.3 shows the P balance of the RS treatment and CDC treatment. The total P input of the RS treatment was almost the same with that of the CDC treatment, which was almost doubled the total P output. This result lead to positive P balance in both treatments. The P balance in the RS treatment was 37.3 and 28.1 kg ha^{-1} in 2017 and 2018, respectively, which was higher than that in the CDC treatment (29.7 and 26.1 kg ha^{-1}). The difference between treatment was small and not significant. There was a large variation in the P balance in the RS treatment. Most of the fields in both treatments have positive P balance, excepted for 2 fields in the RS treatment in 2018.

4.4. Discussion

4.4.1. The soil total P in the RS and CDC treatment

In our previous study (Nguyen *et al.* 2019), we found that CDC supplied more P to the field than RS, but the soil available P was non-significant difference between treatments. One possible reason for this result is the higher soil total P in the CDC treatment than RS treatment. It is because soil available P do not reflect the total P in soil, and soil available P is difficult to increase even the soil total P increase (Nagumo *et al.* 2013). In this study, we confirmed the non-significant difference result in soil available P between treatments and measured soil total P in the pair fields. We found that both soil available P and total P in the RS treatment was non-significant difference from that of the CDC treatment (Table 4.1). Thus, we can confirm that the higher input from CDC did not result in higher soil total P in the CDC treatment than the RS treatment. There must be other reasons for this inconsistent result.

Soil total P (Takeda *et al.* 2004; Yanai *et al.* 2012) and soil available P (Obara and Nakai 2004) vary among soil types and among regions. The comparison of this study, however, was done in the pair fields which have the same soil type. Therefore, the result of the present study was not affected by the difference in soil types and variation in the environmental condition.

4.4.2. Source of P input to the fields

P input from RS and CDC accounted for 18 and 39% of total P input in the RS and CDC treatments, respectively. The P input from CDC to the fields was significantly higher than that from RS, with the difference was 13 kg ha^{-1} (Table 4.2). This result was similar with the one reported by other researches (Yan *et al.* 2007; Polthanee *et al.*2008; Liu *et al.* 2010; Nagumo *et al*. 2013; Nguyen *et al.* 2019). The higher total P content in CDC than in RS was the reason for higher input from CDC, because the applied rate of RS in dried weight was almost the same with that of CDC. The occurrence of higher P content in CDC or manure than RS was also reported by Lee *et al.* (2004), Yan *et al.* (2007), and Lan *et al.* (2012). There was large variation in P input from CDC, and it ranged from 5.5 to 68.1 kg ha^{-1}. This variation come from variation in total P content of CDC. The different source of CDC made by different farmers could be the reason for this variation. This large variation caused the non-significant difference in P input from CDC and RS in 2017, even the average of 2017 was similar to that of 2018.

Fertilizer P was the highest input of P to the paddy field in this area (46.8 and 30.7 kg ha^{-1} in the RS and CDC treatment, respectively), accounting for 82% and 61% of the total P input in the RS and CDC treatments, respectively (Average of two years data). Based on the data of 11 long-term experiments in Asian countries Dobermann *et al.* (1996b) recommended to apply 20–25 kg P ha^{-1} to maintain rice yields of 5–6 t ha^{-1}. However, in Japan the average rate of current fertilizer P consumption in paddy rice fields was 40–47 kg ha^{-1} yr^{-1} as P (Nishio 2002, 2003; Mishima *et al.* 2003). Ninety percent of the research fields in both treatments applied higher fertilizer P than the recommended amount of Dorbermann et al. (1996). Fifty percent of the fields in the RS treatment and 30% in the CDC treatment applied higher fertilizer P than average P rate in Japan. Together with the over accumulative of P in paddy soil in Japan and in this area (available P is about 80 mg P kg^{-1}), farmer may reduce the amount of fertilizer P if no yield decline observed. To understand how many fertilizer P can be cut off to keep the same level of rice yield, we need to conduct the further research on the response of rice yield under different levels of fertilizer P application in the conventional RS application and in mixed crop–livestock system. Farmers applied lower amount of fertilizer P in the CDC treatment, with the difference was 16 kg ha^{-1}. The higher P input from CDC may cause the lower fertilizer P applied in the CDC treatment than the RS treatment. So, from this result, mixed crop–livestock can save the limited P resource by cutting off 16 kg P ha^{-1} fertilizer. The higher in P input from CDC was almost similar to the higher fertilizer P in the RS treatment, which resulted in the same level and non-significant difference of total input between treatments.

Therefore, one possible reason for the non-significant difference in soil total P and available P between treatments was non-significant difference of total P input between treatments.

4.4.3. Source of P output from the fields

Plant P uptake was the main output of P from the fields, accounting for 99% of the total P output. The plant P uptake was similar in both treatments (Table 4.4). This result may come from the similar amount of total P input between treatments. The plant P uptake accounted for 52% and 47% of total P input in the RS and CDC treatment, respectively, which means that 48% and 53% of total P input stay in the soil if we consider the other loss of P rather than leaching is small and negligible. Combing with the situation of over fertilizer P application and excess P accumulation in paddy soil in Japan, once again, we can recommend farmer to reduce the amount of fertilizer P application in this area in both the RS and CDC treatments to maintain the soil total P.

P leaching loss in this research was very small amount and non-significantly contribute to the P balance (< than 1% of total output). The amount of the P leaching ranged from 0.05 to 0.44 kg ha^{-1} in the RS treatment and from 0.04 to 0.52 kg ha^{-1} in the CDC treatment. This result is comparable with the results reported by Nanzyo (1996) (0.04 to 0.22 kg P ha^{-1}), Shan *et al.* (2005) (0.07 to 0.11 kg P ha^{-1}), Cho *et al.* (2002) (0.04 to 0.05 kg P ha^{-1}), and Maruyama *et al.* (2008) (<0.05 kg P ha^{-1}). It is because P usually stay in the soil in the compound forms with others such as Al, Fe, and Ca, which is difficult to leach to ground water. Therefore, almost half of P input was stayed in the paddy soil in this area. And, the excess P accumulation in soil did not result in more leaching loss. The application of RS or CDC did not result in the difference in the amount of P leaching.

Therefore, non-significant difference in the total P output may be one reason for the non-significant difference in the soil total P and available P between treatments.

4.4.4. P balance

The total P input was higher than total P output in both treatments and in both years, which resulted in the positive P balance (Table 4.3). The non-significant difference in total input and total output resulted in the non-significant difference of P balance between treatments. This non-significant difference in the P balance between treatments may be the reason for the non-significant difference in the soil total P and available P (Table 4.1). From the result of positive P balance in both treatments, it is possible to reduce maximum 32.2 and 28.6 kg ha^{-1} fertilizer P in the RS and CDC treatments respectively to keep the P balance in paddy rice fields in this area. This result also shows the importance of alternative P source of RS and CDC in the rice production areas.

There was large variation in the P balance of the RS treatment, especially in the 2018. The large variation in the input from P fertilizer was the reason for this large variation in P balance. There were two fields in the RS treatments have negative P balance, in which farmers applied lower amount of P fertilizer than the recommended amount (< 20 kg ha^{-1}) by Dobermann *et al.* (1996b). Thus, we can confirm that to make the P balance in paddy fields farmer should apply higher fertilizer P than the recommended amount by Dobermann *et al.* (1996b).

The soil total P and available P did not increase after two years (Table 4.1), even the positive P balance was observed in both treatments and in both years. This can be explained by the small contribution of positive P balance to the large pool of total P in the soil. The positive P balance accounted for < 1.0% of total P in soil, so the duration of two years was too short to witness the changing in soil total P.

Overall, non-significant difference in total P input, total P output, and P balance between treatments was the reason for non-significant difference in soil total P and available P.

4.5. Conclusion

Organic matter (RS or CDC) and fertilizer were the main source of P input to the paddy fields. The input of P from CDC to the field was higher than that from RS, while the fertilizer P in the CDC treatment was lower than that of the RS treatment. The higher P input from CDC may let farmer to reduce the amount of fertilizer P. Thus, the application of CDC in the mixed crop–livestock system can save the limited P source and reduce the cost for fertilizer. The higher amount of input P from CDC was almost the same with the higher amount of P fertilizer applied in the RS treatment, which lead to the same level of total P input between treatments. The amount of fertilizer P applied in this area is higher than the recommended amount, and the soil available P (about 80 mg P kg^{-1}) is also over the standard value (44 mg P kg^{-1}). Therefore, it is possible to reduce the amount of fertilizer P in this area.

The plant P uptake was the main output of P from the field and contributed 99% to the total output. This amount of P was higher than P input from RS or CDC but lower than P input from fertilizer. Thus, it may possible to reduce the amount of P fertilizer to get the same level of plant P uptake. The P leaching loss was very small and can be considered negligible to P balance of the paddy field. It may not necessary to consider P leaching loss when we measure P balance in paddy field. The difference in plant P uptake and P leaching between treatments was not significant, which lead to non-significant difference in total P output.

The non-significant difference in total P input and total P output between treatments resulted in a non-significant difference in P balance as well. We confirmed the non-significant difference of soil total P and available P between treatments in the pair fields. Thus, we conclude that the non-significant difference in total P input, total P output, and P balance together caused the non-significant difference in soil total P and available P between treatments.

V. CHAPTER IV: Comparison of the potassium balance in paddy fields under conventional rice straw application versus cow dung compost application in mixed crop–livestock systems

5.1. Introduction

RS is a good source of K because it contains 1.5–2.0% of K at harvest (Dobermann and Fairhurst 2000). And, RS contains more than 80% of absorbed K in above ground biomass of rice plant (Dobermann and Fairhurst 2000; Kyuma 2004). The application of RS increases the soil exchangeable K (Ponnamperuma 1984) and maintains the balance of soil exchangeable K (Wang *et al.* 2005). Aside from RS, CDC is also a good source of K in rice production. The application of CDC also increases soil exchangeable K (Wihardjaka *et al.* 1999). In Japan, after harvest, RS is usually cut by the combine harvester and incorporated into the soil. However, in the mixed crop-livestock system, the RS is removed to feed for cows and CDC is then supplied to the fields. This system has some advantages in compare to the conventional RS application and has increased in Japan. In our previous study (Nguyen *et al*. 2019), we found that CDC input more of K to the field than RS, but the soil exchangeable K was not significantly different between treatments. To find the answers for this inconsistent result, we investigated on the total K input, total K output, and K balance of the fields applied by RS and CDC.

RS or CDC, fertilizer, irrigation water, and rainfall are the source of K input to the paddy fields. Fertilizer is a major source of K, and it needs to be applied in adequate amount in the irrigated rice fields to get the target yield (Islam *et al.* 2015). The application amount of K fertilizer depends on rice varieties (Islam and Muttaleb. 2016), other input sources, and the availability of K in the soil. Thus, the higher input of K from CDC may lead farmers to apply less K fertilizer in the CDC treatment. Irrigation water is the source of basic cations such as K, Ca, and Mg, and readily soluble Si. In Japan, K input from irrigation water was reported as a significant amount (Katoh *et al.* 2003; Kyuma 2004; Matsuda and Kumagai 2017). In this research, since the RS and CDC treatments are nearby and they receive the same source and amount of irrigation water, the input of K from irrigation water to two treatments will be the same. Thus, we did not measure the input from irrigation water. Rainfall is a source of K into the paddy fields. Kyuma (2004) reported that the K input from rainfall is 4.4 kg ha^{-1}. The amount of input from rainfall is also considered to be the same between treatments because they are nearby. Thus, we did not measure the input from rainfall in this research.

The output of K from the paddy fields includes plant K uptake, leaching loss, and runoff. Among output, plant K uptake is the main source (Kyuma 2004). The higher in K input from CDC may lead to higher plant K uptake in the CDC treatment. K leaching loss is also a significant output of K from the field (Katoh *et al*. 2003; Kyuma 2004). The difference in the K input from RS and CDC may result in the difference of K in leaching water.

The objective of the present research was to clarify why the higher K input from CDC than RS did not result in a difference in exchangeable K in soil between treatments. We investigated this question by measuring the total K inputs, total K outputs, and K balance of adjacent paddy fields that received conventional RS treatment or CDC application in a mixed crop–livestock system.

5.2. Materials and methods

5.2.1. Experimental sites discription

The experiment was conducted in the same area as introduced in the chapter I.

5.2.2. Fields selection and treatments

The experiment was conducted on the same fields as introduced in chapter II.

5.2.3. Data collection, sampling and analysis

a. Organic matter

RS and CDC samples were the same with the one collected in chapter II. To measure total K in RS and CDC, the materials were first digested with H_2SO_4–H_2O_2 (Mizuno and Minami 1980). The concentration of K was measured by flame atomic absorption spectrometry (Spectr-AA 220-FS, Varian Australia Pty Ltd., Mulgrave, Australia). The amount of total K input was calculated by multiplying the total K content with rate of RS and CDC applied.

b. Fertilizer

The amount of K fertilizer was obtained by asking farmers.

c. Leaching loss

The amount of water leaching was taken from the experiment introduced in chapter II. The leaching water sample was the same with the one collected in chapter II. The concentration of K in leaching sample was measured by flame atomic absorption spectrometry (Spectr-AA 220-FS, Varian Australia Pty Ltd., Mulgrave, Australia).

d. Plant K uptake

The plant sample was the same sample collected in chapter II. To measure total K in plant samples, the materials were first digested with H_2SO_4–H_2O_2 (Mizuno and Minami 1980). The concentration of K was measured by flame atomic absorption spectrometry (Spectr-AA 220-FS, Varian Australia Pty Ltd., Mulgrave, Australia).

e. Soil total K and exchangeable K

The soil sample was the same with the one collected in the chapter II. Exchangeable K in air-dried soil were extracted with 1 M ammonium acetate (pH 7.0; Harada 1984) and, measured by flame atomic absorption spectrometry (Spectr-AA 220-FS)

5.2.4. Statistical analysis

Welch's *t*-test was used to compare the K input, K output, K balance, soil exchangeable K between the RS and CDC treatments. The analysis was performed with the Analysis ToolPak in Excel for Office 365 (Mircosoft, Redmond, WA, USA). A P value < 0.05 was considered to indicate a significant difference.

5.3. Results

5.3.1. Soil exchangeable K

Soil exchangeable K in the RS treatment was 189.3 and 165.9 mg kg^{-1} and in 2017 and 2018, respectively, and that in the CDC treatment was 174.0 and 189.1 mg kg^{-1} (Table 5.1). The difference between treatments and between years was not significant.

Table 5.1. Soil Non-exchangeable K and exchangeable K of paddy fields in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018

Treatment	Exchangeable K ($mg\ kg^{-1}$)
2017	
RS (*n* = 8)	189.3 ± 74.8
CDC (*n* = 8)	174.0 ± 79.2
P (t-test)	0.70
2018	
RS (*n* = 10)	165.9 ± 59.7
CDC (*n* = 10)	189.1 ± 70.8
P (*t*-test)	0.44

Values are mean ± SD. The *P* value is the probability level of a two-tailed Welch's *t*-test.

5.3.2. K input from organic matter

Table 5.2 shows the K content and input from RS and CDC in two years. The total K content in RS was 13.9 and 14.2 g kg^{-1} in 2017 and 2018, respectively, and that of CDC was 15.4 and 13.2 g kg^{-1}. The difference in total K content between treatments was not significant in both years. The variation of total K content in CDC was greater than that of RS.

The total K input from RS was 74.1 and 78.4 kg ha^{-1} in 2017 and 2018, respectively, and higher than that from CDC (64.0 and 56.4 kg ha^{-1}), even the difference was not significant. The amount of K input from CDC in 2017 was higher than that in 2018.

Table 5.2. K content and K input from rice straw (RS) and cow dung compost (CDC) in 2017 and 2018

	Application rate ($t\ ha^{-1}$)	K content ($g\ kg^{-1}$)	K input ($kg\ ha^{-1}$)
2017			
RS (n = 8)	5.4 ± 1.4	13.9 ± 1.6	74.1 ± 20.4
CDC (n = 8)	4.4 ± 0.9	15.4 ± 13.2	64.0 ± 54.9
P (t-test)	0.11	0.76	0.66
2018			
RS (n = 10)	5.5 ± 1.0	14.2 ± 1.3	78.4 ± 14.5
CDC (n = 10)	4.1 ± 1.1	13.2 ± 7.9	56.4 ± 38.0
P (t-test)	< 0.01	0.70	0.11

Values are mean ± SD. The *P* value is the probability level of two-tailed Welch's t-test.

5.3.3. K input from fertilizer

The amount of K fertilizer was almost similar between treatments in both years (Table 5.3). The amount of K fertilizer applied in the RS treatment was 61.5 and 51.0 kg ha^{-1} in 2017 and 2018, respectively, and that in the CDC treatment was 58.4 and 54.7 kg ha^{-1}. There was no significant difference between treatments in both years. The average fertilizer amount applied in 2017 was a little bit higher than that in 2018. Most of K fertilizer was applied as basal at transplanting.

Table 5.3. The K balance in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018

	2017			2018		
	RS (kg ha^{-1})	CDC (kg ha^{-1})	*P* t-test	RS (kg ha^{-1})	CDC (kg ha^{-1})	*P* t-test
Input						
Organic matter	74.1 ± 20.4	64.0 ± 54.9	0.640	78.4 ± 14.5	56.4 ± 38.0	0.113
Fertilizer	61.5 ± 18.6	58.4 ± 20.5	0.752	51.0 ± 24.2	54.7 ± 21.9	0.721
Total	135.6 ± 37.4	122.4 ± 61.3	0.613	129.3 ± 31.1	111.1 ± 43.7	0.298
Output						
Plant uptake	88.9 ± 21.6	102.6 ± 24.4	0.254	90.0 ± 16.4	90.2 ± 18.2	0.982
Leaching	7.3 ± 3.6	7.9 ± 7.7	0.844	7.0 ± 3.8	7.3 ± 4.9	0.884
Total	96.2 ± 22.5	110.5 ± 22.8	0.228	97.1 ± 18.9	97.5 ± 18.6	0.956
Balance	39.4 ± 19.8	11.9 ± 46.6	0.159	32.3 ± 25.7	13.6 ± 43.7	0.261

Values are mean ± SD. The *P* value is the probability level of two-tailed Welch's t-test.

5.3.4. Plant K uptake

Table 5.4 shows the K content and K uptake of whole rice plants and each plant part in the RS and CDC treatment. The K content in stem was the highest, followed by leaf and then the grain. The total K amount in stem was 72% and 73 % of total K uptake in the RS treatment and CDC treatment, respectively. The K contents in stem, leaf, and grain of the RS treatment were almost the same with that of the CDC treatment in both years.

In 2017, plant K uptake in the RS treatment was 88.9 kg ha^{-1}, which was lower than that of the CDC treatment at level of 102.6 kg ha^{-1}. But, in 2018 plant K uptake was almost the same between treatments at level of 90.0 and 90.2 kg ha^{-1}. The difference in plant K uptake between treatments was not significant in both years.

Table 5.4. K content and K uptake of whole rice plants and each plant part in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018

	K concentration (g kg^{-1})		K uptake (kg ha^{-1})		P (t-test)
	RS	CDC	RS	CDC	
2017 (n = 8)					
Stem	14.6 ± 1.7	14.9 ± 2.4	64.5 ± 16.8	75.2 ± 20.1	
Leaf	9.9 ± 1.5	9.7 ± 2.1	9.6 ± 4.0	11.1 ± 3.6	
Grain	2.4 ± 0.3	2.5 ± 0.3	14.8 ± 2.9	16.2 ± 2.8	
Total			88.9 ± 21.6	102.6 ± 24.4	0.254
2018 (n =10)					
Stem	14.6 ± 1.4	14.2 ± 2.1	64.4 ± 11.4	65.9 ± 14.1	
Leaf	12.6 ± 1.7	11.4 ± 1.7	13.9 ± 4.2	12.7 ± 2.9	
Grain	2.0 ± 0.3	1.9 ± 0.3	11.7 ± 2.5	11.6 ± 1.8	
Total			90.0 ± 16.4	90.2 ± 18.2	0.982

Values are mean ± SD. The *P* value is the probability level of two-tailed Welch's t-test.

5.3.5. K Leaching

The K concentration in leaching water ranged from 2.0 to 3.5 mg L^{-1} (Fig. 5.1). In 2017, the K concentration in the RS treatment gradually decreased from about 3.5 mg L^{-1} at 3 WAT to 2.0 mg L^{-1} at 16 WAT. In the CDC treatment, K concentration decreased a little from 2.6 to 2.1 mg L^{-1} in 5 WAT, before increasing to the peak of 3.3 mg L^{-1} at 9 WAT. Then it fluctuated and decreased to 2.5 mg L^{-1} at 16 WAT. In 2018, in both treatments K concentration in leaching increased from 2.3 mg L^{-1} at 2 WAT to the peak of 3.4 and 3.0 mg L^{-1} at 8 WAT in the RS and CDC treatment, respectively. After that in both treatments K concentration decreased continuously to 2.5 and 2.2 mg L^{-1} in the RS and CDC treatments, respectively.

The K leaching loss amount was the same level between treatments in both years, at level of 7.3 and 7.0 kg ha^{-1} in the RS treatment and 7.9 and 7.3 kg ha^{-1} in the CDC treatment in 2017 and 2018, respectively (Table 5.3). The leaching loss amount accounted for more than 10% of the input from fertilizer.

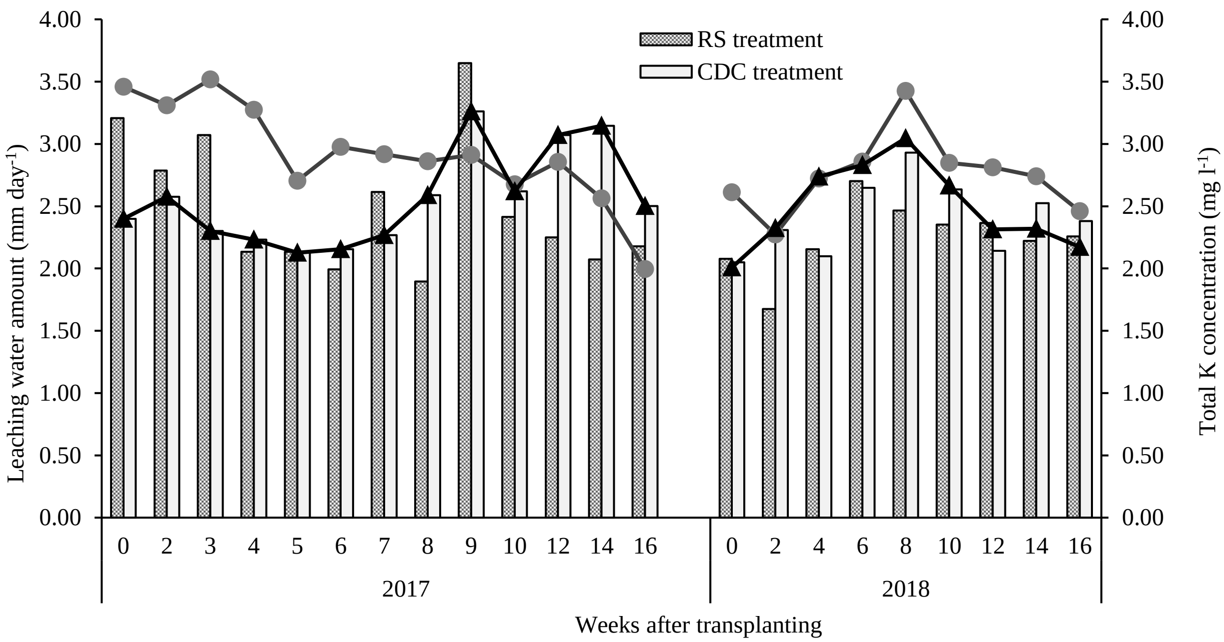


Figure 5.1. Amount of water leached (bar graph) and total K concentration in leached water (line graph) in rice straw (RS) and cow dung compost (CDC) treatments in 2017 and 2018.

5.3.6. K balance

Table 5.3. shows the K balance in the RS and CDC treatment. The total K input to the RS treatment was 135.6 and 129.3 kg ha^{-1} in 2017 and 2018, respectively, which was higher than

that of the CDC treatment (122.4 and 111.1 kg ha^{-1}). The total K input was higher than total output, which resulted in the positive K balance in both treatments. The K balance in the RS treatment was higher than that of the CDC treatment in both years, but the difference was not significant. There was large variation in the K balance of both treatments, especially in the CDC treatment. In both treatments, there were both positive and negative K balance fields. The negative balance was observed in 45% of field in the CDC treatment and that in 10% of field in the RS treatment.

5.4. Discussion

5.4.1. Source of K input to the fields

The amount of K input from RS was higher than that of the CDC even the difference was not significant (Table 5.2). The higher amount of K input from RS come from the higher rate of RS application in compare to CDC, because the K content was almost the same between RS and CDC. This result is difference from the result we got in our previous study (Nguyen *et al.* 2019). The lower in K content in RS collected in previous study than this study come from the difference in timing of RS sampling. In the previous study, RS was collected on the field after harvest, and before collected RS was let on the fields somedays. But, in the study, the RS sample was the plant sample at harvest. It has been reported that K in the RS or organic matter is easy to leach by rain (Hasegawa *et al.* 2005; Rosolem *et al.* 2005; Jin *et al.* 2015), so in the previous study, during the period from harvest to collection the K in RS was lost by leaching. There was a large variation in the amount of K input from CDC. It is because CDC in this study was made by different farmers and CDC was stored both indoor and outdoor. The CDC stored outdoor contained lower K content than that stored indoor. The contribution of K input from RS or CDC to the K balance was significant and higher than that from fertilizer (Table 5.3). Therefore, RS and CDC can be good alternative source of K to the paddy fields.

Farmer applied almost the same amount of fertilizer K to both treatment (Table 5.3), which lead to higher total K input to the RS treatment than that to the CDC treatment, even the difference was not significant. This result may be the reason for non-significant difference in soil exchangeable K between treatments.

5.4.2. Source of K output from the fields

Plant K uptake was the main K output from the fields, accounting for 93% of total output (Table 5.4). The non-significant difference in the total K input between treatments can be the reason for the non-significant difference in the plant K uptake. K leaching loss accounted for 7% of total output and was a significant K output. The amount of K leaching loss in this study was smaller than the one reported by Katoh *et al* (2003). The lower K leaching loss in this study come from the lower amount of water leaching (0.16–0.36 cm day^{-1}) comparing to (estimated 0.5–1 cm day^{-1}), because the range of K concentration in leaching was almost the same. The amount of K leaching was also similar between treatments in both years (Table 5.3). The similarity in total K input may be the reason for non-significant difference in leaching between treatments. Therefore, leaching loss should be considered when we think about K balance in the paddy fields.

Total K output was not significantly different between treatment. This result may be the reason for non-significant difference in soil exchangeable K between treatments.

5.4.3. K balance

The average value of K balance was positive in both treatments (Table 5.3), but there are still some fields having negative balance in both treatments (40% of the fields in the CDC treatment – 10% in the RS treatment). In those negative K balance fields, farmers should apply more CDC or increase the amount of fertilizer K to balance the K in the fields. The negative K balance caused by less supply of fertilizer K was also reported by some researches (Dobermann *et al.* 1996; Kumar *et al.* 1999; Mohammad 1999; Zhang *et al.* 2010). The positive K balance was seen in 90% of fields in the RS treatment and 60% in the CDC treatment, which showed that RS application is better in maintaining K balance in paddy field than CDC application.

The amount of plant K uptake was higher than K input from organic matter or fertilizer K. It means that if there was no K input from RS or CDC, all fields will have negative balance, and at level of -41 and -47 kg ha^{-1} in the RS and CDC treatment, respectively. This result showed that RS and CDC are important K input to keep the positive K balance in paddy field. And, it is necessary to apply the adequate amount of CDC to the paddy field in the mixed crop–livestock system.

The exchangeable K in soil did not increase after two years (Table 5.1), even the positive K balance was observed as average in both treatments and in both years. This can be explained by the small contribution of exchangeable K to the large pool of the soil total K (Moritsuka *et al.* 2003; Kitagawa *et al.* 2018). And, we need to evaluate nonexchangeable K in combination with exchangeable K to consider K balance and K fertility of soil (Kitagawa *et al.* 2018).

Non-significant difference in total K input and K output resulted in non-significant difference in K balance. Therefore, non-significant difference in soil exchangeable K between treatments come from the non-significant difference in total K input, K output, and K balance between treatments.

5.5. Conclusion

Organic matters (RS or CDC) and fertilizer K were the main source of K input to the paddy fields. The contribution of organic matter to total K input was higher than that of fertilizer. The difference in K input from organic matter and fertilizer between treatments was not significant, which resulted in non-significant difference in total K input to the paddy field.

The plant K uptake was the main source of K output from the fields, accounting for 93% of total K output. The plant K uptake was higher than K input from organic matter and fertilizer. So, the application of both organic matter and fertilizer is necessary to keep positive K balance in paddy fields. Therefore, after removing RS from field to feed cows, it is necessary to supply the additional organic matters such as CDC. The leaching loss was also a significant amount and should be considered when we think about K balance. The application of RS and CDC resulted in the same level of K leaching loss.

Overall, the non-significant difference in total K input, total K output, and K balance was the reason for the non-significant difference in soil exchangeable K.

VI. CHAPTER V: Comparison of the carbon and nutrients content in plow layer and in leaching water in paddy fields under conventional rice straw application versus cow dung compost application in mixed crop–livestock systems

6.1. Introduction

Irrigated paddy fields are managed flooding condition most of the time after transplanting. As the ponding water percolates downward, it carried organic matter (Esaki *et al.* 1993; Murase *et al.* 1993; Maie *et al*. 1997) as well as inorganic cations and anions from plow layer to the subsoil (Hasegawa *et al*. 1980; Tsuchiya *et al.* 1981; Kimura *et al.* 1992), which means that the concentration of nutrient in the plow layer water influence the nutrient concentration in the leaching water. The nutrient concentration in the plow layer is decided by many factors, and the input amount is one of them. In our previous study, we found that CDC supply higher nutrients but lower total C than RS (Nguyen *et al*. 2019). Therefore, the application CDC to paddy field in mixed crop–livestock system may result in lower in C and higher nutrients concentration in the plow layer from that application of RS.

Therefore, in this chapter, we wanted to understand the nutrients situation in the plow layer of paddy fields under RS versus CDC application, and the relation between the nutrient concentration in the plow layer water and that in the leaching water.

6.2. Materials and methods

6.2.1. Experimental sites discription

The experiment was conducted in the same area as introduced in the chapter I.

6.2.2. Fields selection and treatments

The experiment was conducted on the same fields as introduced in chapter II.

6.2.3. Sampling and analysis

Soil water was sampled using a ceramic cup (10 cm length and 8 mm diameter, sealed at one end) connected to a silicon tube (7 mm inner diameter, 9 mm outer diameter) in 2018. To take plow layer water, the ceramic cup was inserted vertically at 10–20 cm depth from the soil surface in the middle of four rice hills at three positions at each sampling time. To take leached water, the ceramic cup was inserted vertical at depth of 30–40 cm after transplanting and left it until the last sampling. The silicon tubes were extended upward to 20 cm above the soil surface to prevent flow of ponded water into the tube. The end of each silicon tube for taking leached water was covered with a plastic bag to prevent rainfall and insects from entering the pipe. Sampling of leached water began 3 or 4 days after the ceramic cup was set and continued at 2-week intervals thereafter. The sampling of plow layer water was also taken at the same time with leached water. The plow layer water and leached water were pumped up by using a 50-ml plastic cylinder. The pH of the sampled water was measured, then pH was adjusted to 2.0–3.0 by adding concentrated HCl, and the sample was stored in a refrigerator. The concentration of total N and C in sampled water was measured with a total organic carbon analyzer with total nitrogen measuring unit (TOC-VCSN with TNM-1; Shimadzu Corporation, Kyoto, Japan). The concentration of ammonium N in sampled water was measured by the indophenol blue method (Scheiner 1976). The concentration of total P in sampled water was digested with $K_2S_2O_8$, then the P concentration in digested solution was measured by molybdenum blue method (Matsuhisa 2005). The concentration of inorganic P in sampled water was measured by molybdenum blue method (Matsuhisa 2005). The concentration of K, Ca, and Mg in sampled water was measured by flame atomic absorption spectrometry (Spectr-AA 220–FS, Varian Australia Pty Ltd., Mulgrave, Australia). The concentration of Si in sampled water was determined by the molybdenum blue method (Yoshida 1986).

6.2.4. Statistical analysis

Welch's *t*-test was used to compare nutrients and C concentration between the RS and CDC treatments. The analysis was performed with the Analysis ToolPak in Excel for Office 365 (Mircosoft, Redmond, WA, USA). A P value < 0.05 was considered to indicate a significant difference.

6.3. Results

6.3.1. N concentration in plow layer water and leaching water

a. Total N

Total N concentration in plow layer water in both treatments increased to the peak of 2.7 mg L^{-1} in the CDC treatment and 2.6 mg L^{-1} in the RS treatment at 4 WAT, then decreased continuously to about 0.4 mg L^{-1} in the CDC treatment and 0.6 mg L^{-1} in the RS treatment at 14 WAT and increased a little after that (Fig. 6.1). The CDC treatment showed a little bit higher than the RS treatment in some sampling time, but the difference was very small and non-significant. In leaching water, total N concentration was kept at low level and ranged from 0.6 to 0.8 mg L^{-1} in the RS treatment and from 0.4 to 0.8 mg L^{-1} in the CDC treatment during cropping season. The difference between treatments was very small and non-significant.

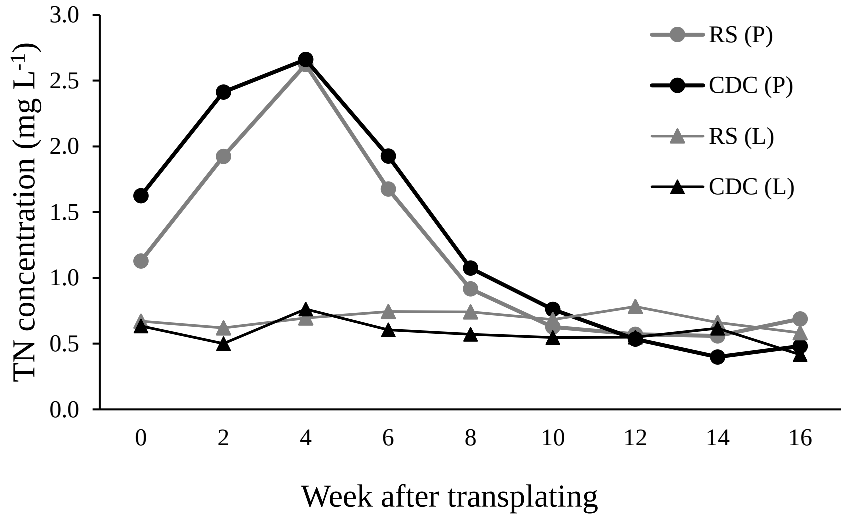


Figure 6.1. Total N (TN) concentration in soil solution of the plow layer (P) and leaching (L) in the RS and CDC treatment.

b. Ammonium N

In the RS treatment, NH_4^+-N in the plow layer water increased after transplanting to the peak of 1.5 mg L^{-1} at 4 WAT, then decreased sharply to 0.4 mg L^{-1} at 8 WAT and gradually after that to about 0.2 mg L^{-1} at 16 WAT (Fig. 6.2). This changing was the same with that of total N concentration. However, in the CDC treatment, NH_4^+-N concentration increased from about 1.6 mg L^{-1} at transplanting to peak of 2.0 at 2 WAT then continuously decreased to about 0.1 mg L^{-1} at 16 WAT. The CDC treatment showed higher value than the RS treatment in most sampling times, but the difference was not significant. In leaching water, the NH_4^+-N concentration in the RS treatment was the same with that of the CDC treatment at all sampling times, decreased continuously from about 0.49 mg L^{-1} at transplanting to about 0.09 mg L^{-1} in the RS treatment and 0.07 mg L^{-1} in the CDC treatment at 16 WAT.

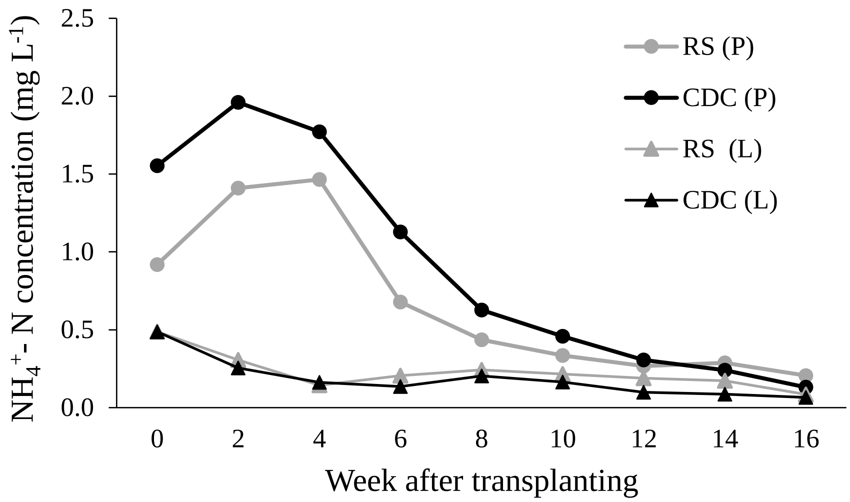


Figure 6.2. NH_4^+-N concentration in soil solution of the plow layer (P) and leaching (L) in the RS and CDC treatment.

6.3.2. P concentration in plow layer water and leaching water

Inorganic P concentration in plow layer water increased slightly from transplanting to 2 WAT and gradually decreased from 0.08 mg L^{-1} in the RS treatment and 0.09 mg L^{-1} in the CDC treatment at 2 WAT to about 0.04 and 0.03 mg L^{-1} in the RS and CDC treatment, respectively at 12 WAT, and increased a little after that (Fig. 6.3). The RS treatment showed higher value than CDC treatment, but the difference was not significant. In leaching water, the concentration of inorganic P was also decreased in both treatments at almost the same values with that in the plow layer water.

The total P in leaching water increased to peak of 0.15 mg L^{-1} in the RS treatment and 0.13 mg L^{-1} in the CDC treatment at 2 WAT, then decreased continuously to 0.05 and 0.03 mg L^{-1} in the RS treatment and CDC treatment, respectively (Fig. 6.3). The difference between treatments was not significant at all sampling times. The total P concentration in leaching water was higher than that of inorganic P concentration, so that the leaching water also contained organic P.

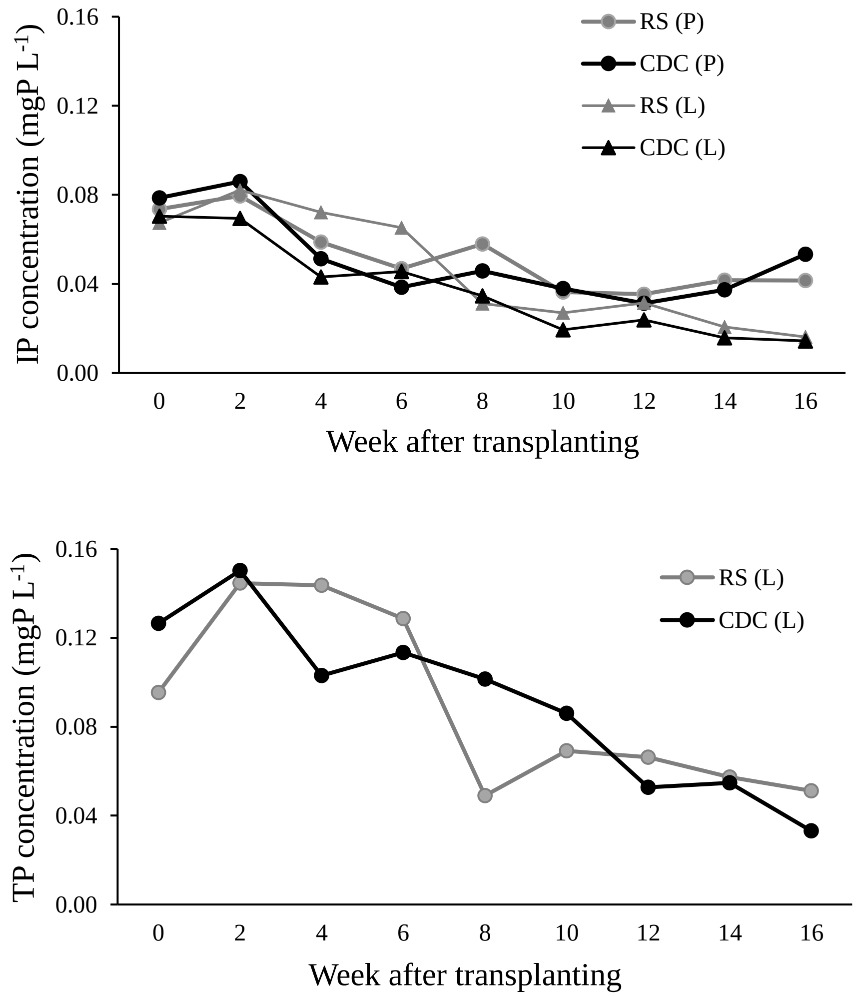


Figure 6.3. Inorganic P (IP) and total P (TP) concentration in soil solution of the plow layer (P) and leaching (L) in the RS and CDC treatment.

6.3.3. K concentration in plow layer water and leaching water

K concentration in the plow layer water increased to the peak of about 6.2 mg L^{-1} in the RS treatment and 5.7 mg L^{-1} in the CDC treatment at 2 WAT, then decreased continuously in both treatments to about 1.9 mg L^{-1} at 10 WAT and kept constant until 16 WAT (Fig. 6.4). The difference in K concentration between treatments was very small and non-significant. In leaching water, K concentration in both treatments increased to the peak of about 3.4 mg L^{-1} in the RS treatment and 3.0 mg L^{-1} in the CDC treatment at 8 WAT, then continuously decreased to 2.2 and 2.5 mg L^{-1} in the RS and CDC treatment, respectively at 16 WAT. The difference between treatments was very small and non-significant.

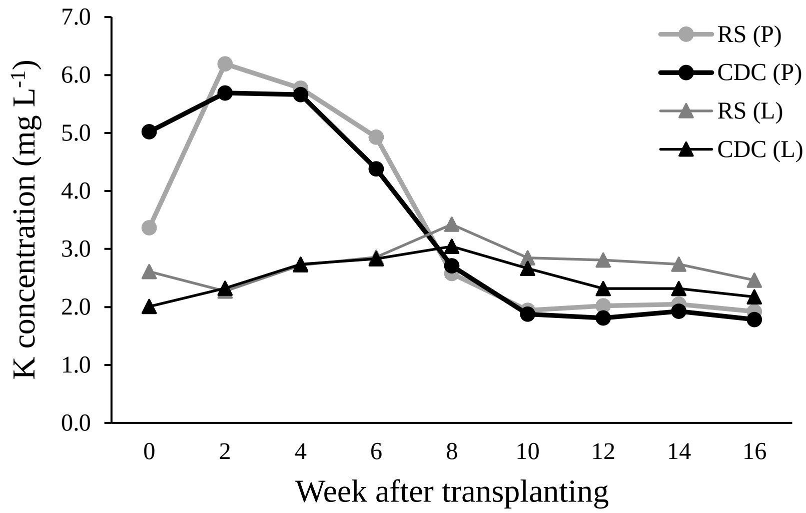


Figure 6.4. K concentration in soil solution of the plow layer (P) and leaching (L) in the RS and CDC treatment.

6.3.4. Si concentration in plow layer water and leaching water

In plow layer water, Si concentration increased from 5.2 mg L^{-1} in the RS treatment and 5.3 mg L^{-1} in the CDC treatment at transplanting to the peak of 6.2 mg L^{-1} at 4 WAT in the RS and CDC treatment, respectively (Fig. 6.5). After that, Si concentration decreased sharply to about 3.1 mg L^{-1} at 10 WAT, then fluctuated slightly until 16 WAT. The Si concentration was almost the same in both treatments at all sampling time. In leaching water, the RS treatment showed higher Si concentration than the CDC treatment at most of sampling times, even the difference was not significant. In the RS treatment, Si concentration increased to peak of about 6.1 mg L^{-}

[1] at 4 WAT, then decreased continuously to about 3.0 mg L^{-1} at 16 WAT. In the CDC treatment, Si concentration increased and reached to peak at about 5.0 mg L^{-1} at 6 WAT, then decreased continuously to about 2.9 mg L^{-1} at 16 WAT.

Until 6 WAT, the Si concentration in plow layer water was higher than that of the leaching water, but at 8 and 10 WAT, the Si concentration in leaching water was higher than that of plow layer water.

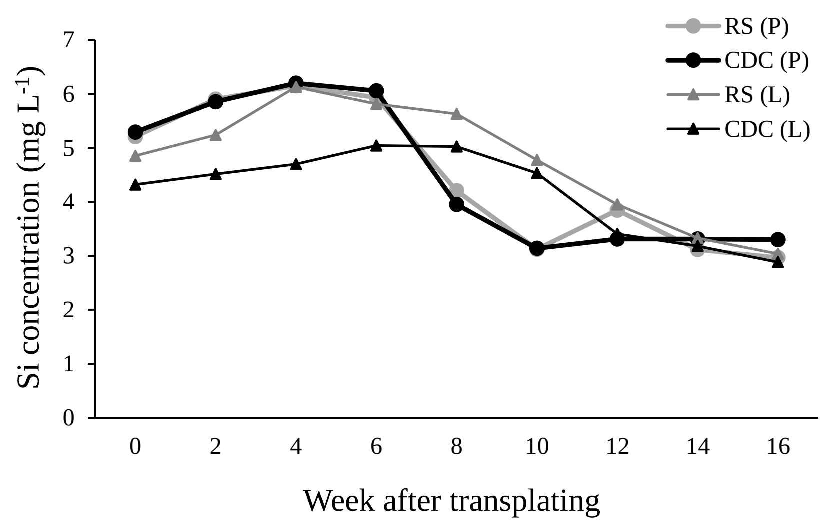


Figure 6.5. Si concentration in soil solution of the plow layer (P) and leaching (L) in the RS and CDC treatment.

6.3.5. Ca and Mg concentration in plow layer water and leaching water

In plow layer water, Ca and Mg concentration in both treatments increased to peak at 4 WAT, then decreased continuously after that (Fig. 6.6 and 6.7). The concentrations of Ca and Mg in the RS treatment were higher than that of the CDC treatment at all sampling times, even the difference was not significant. The Ca concentration ranged from 9.5 to 34.3 mg L^{-1} in the RS treatment and from 6.6 to 25.7 mg L^{-1} in the CDC treatment. The Mg concentration ranged from 2.5 to 10.8 mg L^{-1} in the RS treatment and from 1.6 to 7.7 mg L^{-1} in the CDC treatment.

In the leaching water, Ca and Mg concentration in both treatments increased slightly to peak at 6 or 8 WAT then decreased continuously to lowest at 12 or 14 WAT. The RS treatment showed higher values than the CDC treatment at all sampling time, but the difference was not significant. Ca concentration ranged from 15.9 to 21.5 mg L^{-1} in the RS treatment and from 10.9 to 18.7 mg L^{-1} in the CDC treatment. Mg concentration ranged from 5.0 to 7.1 mg L^{-1} in the RS treatment and from 3.4 to 5.6 mg L^{-1} in the CDC treatment. From 0 to 6 WAT, Ca and Mg concentration in plow layer was higher than that of the leaching water, but the opposite result was observed after 8 WAT.

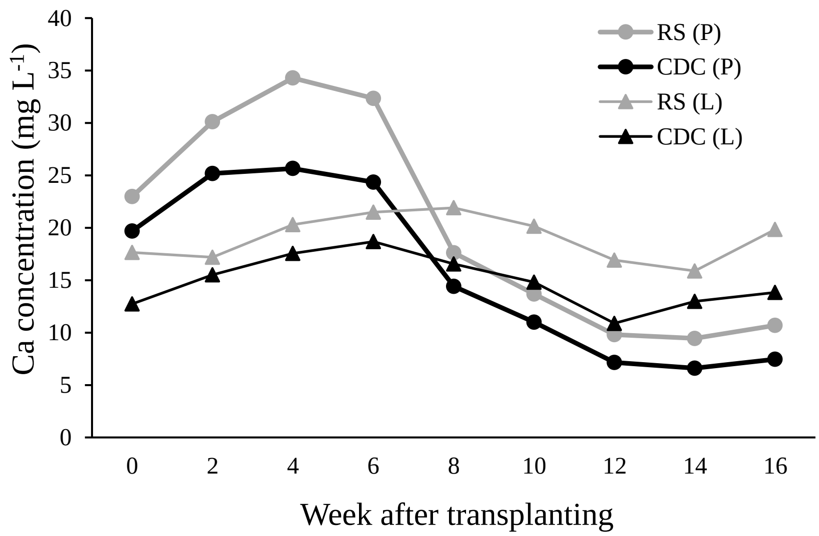


Figure 6.6. Ca concentration in soil solution of the plow layer (P) and leaching (L) in the RS and CDC treatment.

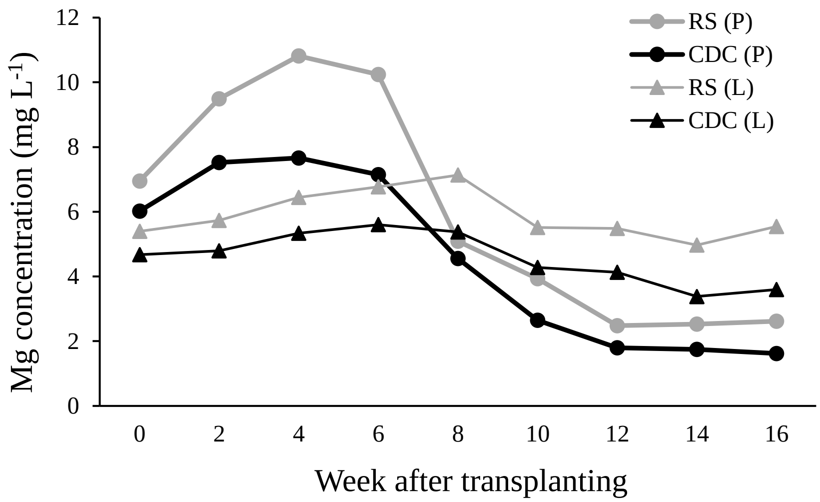


Figure 6.7. Mg concentration in soil solution of the plow layer (P) and leaching (L) in the RS and CDC treatment.

6.3.5. Total C concentration in plow layer water and leaching water

In plow layer water, total C concentration increased to the peak of about 14.3 mg L^{-1} in the RS treatment and 13.7 mg L^{-1} in the CDC treatment at 6 WAT, then decreased continuously to 5.6 mg L^{-1} in the RS treatment at 14 WAT and 5.7 mg L^{-1} in the CDC treatment at 12 WAT, and increased a little after that (Fig. 6.8). Total C concentration in the RS treatment was almost the same with that of the CDC treatment at all sampling time. In leaching water, total C concentration in the RS treatment showed higher value than that of the CDC treatment, but the difference was not significant. Total C concentration in the RS treatment ranged from 4.8 to 6.2 mg L^{-1} and that in the CDC treatment ranged from 4.5 to 6.1 mg L^{-1}.

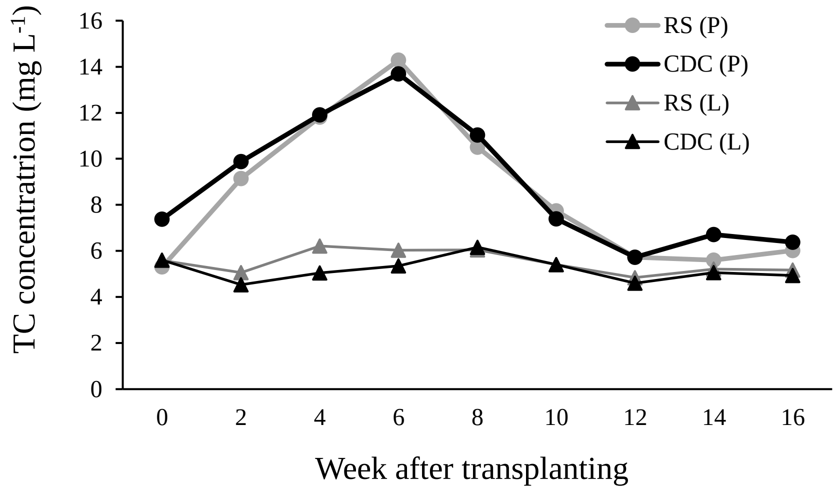


Figure 6.8. Total C (TC) concentration in soil solution of the plow layer (P) and leaching (L) in the RS and CDC treatment.

6.4. Discussion

NH_4^+-N in plow layer water was high during 0 to 4 WAT and decreased drastically after that (Fig. 6.2). The concentration of NH_4^+-N in soil solution behaves same as the amount of soil NH_4^+-N, and they have high positive correlation (Toriyama and Ishida 1987). NH_4^+-N in plow layer water or in soil consists of applied fertilizer N, mineralized N from soil organic N, and decomposed organic matter. The amount of mineralized N increases through rice cropping season (Broadbent 1979; Shoji *et al.* 1986). N uptake by rice plant increases exponentially until the maximum tiller number stage (Shoji *et al*. 1986; Wada *et al*. 1989). Therefore, the amount of NH_4^+-N of soil (Shoji *et al*. 1986; Wada *et al.* 1989) and concentration of NH_4^+-N of soil solution (Toriyama and Ishida 1987) in plow layer are high at early growth stage of rice, and then they are decreased drastically. Since soil N mineralization of paddy field is controlled by the soil temperature, the high NH_4^+-N keep until about 4 WAT in Japan or temperate region (Shoji *et al.* 1986). After transplanting until 4 WAT, the mineralization and decomposition process are strongest and produced much organic and NH_4^+-N to the soil solution, but rice plant was still small so they could not uptake all that N, which resulted in the increasing of total N concentration (Fig. 6.1). During this period, total N concentration was higher than NH_4^+-N, because some total N included soluble organic N. After 4 WAT rice plant grow quickly, bear much tiller and they uptake more N, which resulted in the decreasing in the N concentration. In plow layer, both total N and NH_4^+-N concentration increased from 0 WAT to 2 and 4 WAT but that in leaching kept constant, a result that is comparable with the findings of Luo *et al* (2011). This result meant that N in plow layer did not leach to ground water. It may be because of rice plant uptake or kept in the subsoil layer.

N input from CDC was higher than that from RS as mentioned in Chapter 2. Higher N input from CDC, however, did not result in the higher total N and NH_4^+-N concentration in the plow layer and leaching water of the CDC treatment. It is because the higher input from CDC was not large enough to make the significantly higher in total N input. And, the total N input was non-significantly different between the treatments. Thus, the non-significant difference in total N and NH_4^+-N concentration between the treatments come from the non-significant difference in total N input.

In this study the inorganic P in the plow layer soil solution was very low (Fig. 6.3). It is because P exists in the soil as negative charged phosphate ion, which is extremely reactive and binds with aluminum, iron, Ca, and other elements in all soils at relatively higher levels. Those forms of P are bind tightly with the soil clay and organic matter. This leads to low concentration of inorganic P in the plow layer solution. For this reason, the concentration of inorganic P in soil solution does not reflect the amount of P in the soil. Because of this characteristic very few of inorganic P was leaching out from plow layer, even the total P (Fig 6.3). The inorganic P in plow layer water increased slightly from transplanting to 2 WAT and decreased until 12 WAT, and then increased again until 16 WAT in both treatments. In leaching water, the concentration of inorganic P was decreased and could not detect after 10 WAT and that of total P decreased continuously during the cropping season in both treatments. After transplanting, paddy field is submerged and becomes reduction condition. In this condition, ferrous phosphate and phosphate anion are released by the reduction of ferric phosphate, and occluded phosphate is released by the reduction of hydrated ferric oxide coating (Kyuma 2004). These mechanisms resulted in availability of P in soil and rising the concentration of phosphate anion in the soil solution in plow layer. However, exponential increase of P uptake by rice plant (Nanzyo 1996) decreased the concentration of P in plow layer water and in leaching water. When the drainage started at about 8 WAT, the soil becomes oxidation condition. Under the oxidation condition, the phosphate anion is transferred to precipitated hydrated ferric oxide (Kyuma 2004), which resulted in decreasing of P concentration in plow layer water and leaching water.

We found that P input from CDC was higher than RS in the Chapter 2, but it did not result in the difference in inorganic P concentration in plow layer water and leaching water. It is because the higher P input from CDC was offset by the lower fertilizer P in the CDC treatment which resulted in the same level of total P input in both treatments. Thus, the non-significant difference in total P input was the reason for the non-significant difference in inorganic P concentration in plow layer water and leaching water.

The K concentration in the plow layer water increased to peak at 4 WAT and then decreased after that, whether in leaching water it increased continuously until 8 WAT and then decreased (Fig. 6.4). After 8 WAT, K concentration in the plow layer was lower than that in leaching water. These results showed that a part of K in the plow layer leached to ground water. During the first weeks (until 4 WAT), the large amount of K input come from fertilizer, organic matter, irrigation, and soil, but the rice plant was still small and could not uptake much K, which resulted in the increasing of K concentration. After that, however, exponential increase of K uptake by rice plant (Shoji and Mae 1984) decreased of K concentration in the plow layer water. This trend of K concentration in plow layer water is comparable with the change of exchangeable K in soil shown in Shoji and Mae (1984). After 8 WAT, the K concentration in the leaching water was higher than that in the plow layer water, which means that K in leaching water was not only supplied from plow layer but also from ground water.

We found in the previous study that K input from CDC was higher than RS (Nguyen *et al.* 2019). But, in this study, the K input from CDC was found to be the same level with that of RS and the total K input was also the same level between treatments. Therefore, the non-significant difference in the total K input to the RS and CDC treatment was the reason for non-significant difference in the K concentration in both plow layer water and leaching water.

The Si concentration in plow layer water in both treatments increased until 6 WAT and decreased sharply until 10 WAT, and then kept constant until 16 WAT (Fig. 6.5). This trend is comparable with the other researches (Imaizumi and Yoshida 1958; Sumida and Ohyama 1991). The Si concentration in the plow layer water and leaching water were similar during cropping season, which means that Si in plow layer water leached to sublayer. The Si concentration in the plow layer water also significantly correlated to that in leaching water (data not shown). The exponential increase of Si uptake by rice plant (Imaizumi and Yoshida 1958) and high amount of Si leaching resulted in sharply decreasing in Si concentration in plow layer water after 6WAT. Compare to other nutrients, leaching amount of Si to sublayer was high. Therefore, Si application to paddy fields is more important than the other nutrients to maintain Si fertility in plow layer soil. The application of RS resulted in higher Si concentration in the plow layer and leaching water than CDC application.

The changing of Ca and Mg concentration in the plow layer water and leaching water were similar to that of K concentration (Fig. 6.6 & 6.7). A part of Ca and Mg in the plow layer water leaching out from plow layer. During the first weeks, rice plant was still small and could not uptake much Ca and Mg, which resulted in the increasing of Ca and Mg in the plow player water even the leaching amount was also increased. And then, however, since rice plant grows and uptakes more Ca and Mg, the Ca and Mg concentration in the plow layer water was decreased sharply. The trend of changing Ca and Mg concentration in plow layer water is comparable with the result of permeability testing reported by Kobo and Konno (1970). The application of RS resulted in higher Ca and Mg concentration in the plow layer water and leaching water than CDC application.

The changing of total C concentration in the plow layer water and leaching water was similar to that of total N (Fig. 6.8). The total C leached out from plow layer was constant and not affected by the total C concentration in the plow layer. The decreasing of total C concentration after 4 WAT in plow layer water can be explained by the loss by emission or absorption of total C by subsoil. The higher total C input from RS did not resulted in the higher total C concentration in the plow layer water and leaching water. The higher loss of C through emission in RS application treatment (Naser *et al.* 2007; Bhattacharyya *et al*. 2012; Liu *et al.* 2015; Zhang *et al.* 2017) may be the reason for this result.

6.5. Conclusion

All of nutrients and C excepted for P increased after transplanting reached to the peak and decreased after that. The plenty of input before and/or at transplanting and poor rice plant uptake resulted in the higher concentration in the plow layer water at early growth stage. In case of K, Si, Mg, and Ca, plant uptake, soil adsorption, and leaching to subsoil can be explained to the decreasing in the concentration in the plow layer water. In case of N and C, the concentration in the plow layer water did not affected to the leaching amount. P is a special nutrient, fixed firmly in soil, so there was few P existing in the solution and leaching.

The application of RS resulted in the same concentration of N, P, K, and C in the plow layer water and leaching water, but higher in the concentration of Si, Ca, and Mg than CDC application.

VII. GENERAL DISCUSSION

Soil fertility refers to the ability of the soil to supply essential plant nutrients and soil water in adequate amounts and proportions for plant growth. The fertility of soil can be evaluated through soil chemical (soil organic matter, pH, available nutrients, forms of N, and salinity or conductivity), physical (infiltration, aggregation, bulk density, and topsoil depth), and biological (microbial biomass) properties. The application of RS has been proven to increase the fertility of paddy soil (Nie *et al*. 2007; Liao *et al*. 2013; Cheng *et al*. 2016; Takakai *et al.* 2019). However, RS application also increases GHG emissions during the cropping season (Naser *et al*. 2007; Bhattacharyya *et al*. 2012; Liu *et al*. 2015; Zhang *et al*. 2017), especially in cold areas where RS cannot decompose during winter (Naser *et al*. 2007; Nakajima *et al*. 2016). The CDC application in mixed crop–livestock system, however, can reduces the GHG emission in compare to RS application (Yagi and Minami 1990; Kumagai *et al*. 2010; Das and Adhya 2014), because CDC is decomposed before applied. Besides, in the CDC treatment, RS was used to feed cow, which economically reduce the cost for cow husbandry. Thus, from the view of environmentally friendly and economically, CDC is better to use in paddy field than RS. In the general discussion, we will consider the relationship between the soil fertility and nutrients balance in the paddy fields under mixed crop–livestock system (CDC treatment) in comparing to the one under conventional RS application (RS treatment) to propose the optimizing fertilizer management to maintain soil fertility economically with environmental conservation.

In term of nutrients content and input, CDC is better than RS. In the present study, we found that the nutrients (N, P, and K) content of CDC was much higher than that of RS (Table 2.1), and it led to higher amount of nutrient input from CDC than RS (Table 2.2). The application of CDC usually results in better soil fertility than RS application (Shiga *et al*. 1985b; Izuoka *et al*.

1996; Sakai *et al.* 1999; Maeda and Harai 2002). In the present study, however, soil fertility under CDC treatment was not significant difference from that of the RS treatment, even the soil fertility in both treatments reached to adequate level (Table 2.3). To explain for the result of non-significant difference in soil total N, available N, available P, and exchangeable K despite the higher inputs of N, P, and K from CDC in this study, the N, P, and K balance were investigated.

The non-significant difference in soil total N and available N between the RS and CDC treatments (Table 3.1) was explained by non-significant difference in total N input, total N output, and N balance (Table 3.3). The N input from CDC was higher than that from RS (Table 3.2), but farmers applied the same level of fertilizer N. The N fixation was also the same level between treatments. The total N input, therefore, was higher in the CDC treatment than RS treatment, even the difference was not significant. The higher N input from CDC was not large enough to make the significantly higher in total N input in the CDC treatment than RS treatment. The output of N from the field through plant uptake were higher in the CDC treatment than in the RS treatment and through leaching were similar between treatments, which lead to non-significant difference of total N output. The application of RS or CDC in combine with fertilizer in long-term was reported to increase the soil total N and available N (Yan *et al*. 2007; Huang *et al*. 2009; Takakai *et al.* 2010; Yanai *et al.* 2011; Miura and Kusaba 2013; Shahid *et al*. 2013; Cheng *et al.* 2016), which means that the N balance is positive when RS or CDC applied in combined with fertilizer N. In this study, N balance in both treatments was also positive with the higher values seen in the CDC treatment, even the difference was not significant. The total N and available N in soil, however, did not increase during the two years (Table 3.1). This can be explained by the relatively small input into the large soil volume: the N input accounted for about 1% of soil total N. And, the duration of one year is not enough to see the change of soil N. The absence of RS or CDC application resulted in negative balance in some fields, which means that RS and CDC are important input to keep positive N balance in paddy field. The positive N balance in both treatments suggests reducing the amount of fertilizer N applied in this area, especially in the CDC treatment.

Non-significant difference in soil total P and available P (Table 4.1) was also explained by the non-significant difference in total P input, total P output, and P balance (Table 4.3). The higher P input from CDC than RS let farmer to apply higher fertilizer P in the RS treatment. The higher P input from CDC was offset by the higher fertilizer P applied in the RS treatment. This management resulted in the same level and non-significant difference of total P input in both treatments. Based on the data of 11 long-term experiments in Asian countries, Dobermann *et al*. (1996b) recommended to apply 20–25 kg P ha^{-1} to maintain rice yields of 5–6 t ha^{-1}. In Japan, however, the average rate of current commercial fertilizer P consumption in paddy rice fields was higher at 40–47 kg ha^{-1} yr^{-1} as P (Nishio 2002, 2003; Mishima *et al.* 2003). All the study fields were applied higher amount of fertilizer P than Dobermann *et al*. (1996b) recommended. Thus, we can recommend farmers in this area to reduce the amount of fertilizer P if no yield reduction observed. Plant P uptake was the main P output from the paddy field (Hasegawa 1992; Nanzyo 1996; Maruyama *et al.* 2008). In this study, rice plant P uptake was also the main output, accounting for 99% of total P output. The amount of P uptake was 52% and 47% of the total P input in the RS and CDC treatment, respectively. It means that almost half of P input accumulates in the soil. P leaching loss is usually small and negligible in paddy field, but it increases if the availability of P in soil is in high concentration (Zhang *et al.* 2003; Shan *et al*. 2005; Ooya *et al.* 2007). In this study, even the soil contains high level of available

P, the P leaching loss was still small and negligible. The distribution of Andosols in this study, which has higher P absorption co-efficiency, may be the reason for small leaching loss. The application of CDC resulted in the similar amount of leaching in compare with RS application. Overall, the total P output from the paddy fields in the CDC treatment was non-significant difference from that of the RS treatment. The application of RS or CDC with fertilizer increases soil available P (Beaton *et al*. 1992; Wang *et al.* 2005; Lee *et al*. 2004; Bhattacharyya *et al*. 2015), which means that application of RS or CDC combined with fertilizer P resulted in the positive P balance to the field. In this study, the P balance was also positive in both treatments at almost same level. From the result of the P balance, it is possible to reduce fertilizer P in the RS and CDC treatments with keeping the P balance in paddy fields in this area.

The non-significant difference in soil exchangeable K between treatments (Table 5.1) can be explained by non-significant difference in total K input, total K output, and K balance (Table 5.3). Input from RS and CDC were the main contribution to K balance, accounting for 59% and 45% of total K input in the RS and CDC treatments, respectively. K content in CDC was almost similar with that of RS and it resulted in the same level of K input from RS and CDC (Table 5.2, in 2017 and 2018). In 2016, however, K content in CDC was higher than that in RS, and it resulted in higher K input from CDC (Table 2.1, 2.2). The lower K content in RS collected in 2016 than that in 2017 and 2018 come from the difference in timing of RS sampling. In 2016, RS was collected on the field after harvest. The RS sample was supplied and let on the fields somedays before the collection. But, in 2017 and 2018, the RS sample was collected from the alive plant sample at harvest. It has been reported that K in the RS or organic matter is easy to leach by rain (Hasegawa *et al.* 2005; Rosolem *et al.* 2005; Jin *et al.* 2015), so in 2016, the K in RS was lost by leaching during the period from harvest to the collection. The fertilizer K was applied at the same level in both treatments. Therefore, the total K input in the RS treatment was non-significant difference with that of the CDC treatment. Plant K uptake was the main output of K from the field, accounting for 93% of total output. The leaching loss contributed 7% of total output. Thus, K leaching loss should be considered in K balance in paddy fields. In both plant K uptake and leaching, non-significant difference between treatments was seen. This leads to non-significant difference in total K output. Many researchers reported the negative K balance in paddy fields (Mohanty *et al.* 1989; Abedin *et al.* 1991; Dobermann *et al.* 1996a; Kumar *et al.* 1999; Mohammad 1999; Zhang *et al*. 2010). In this study, 40% of fields in CDC treatment have negative K balance. Thus, in the CDC treatment, farmers should concern on the amount of K inputs by increasing amount of fertilizer K or improving CDC nutrient content. In RS treatment, however, all of fields have positive K balance, which means that RS application is important to keep K balance in paddy field. The amount of plant K uptake was higher than K input from organic matter or fertilizer K. If there was no K input from RS or CDC, all fields will have negative balance, and at level of -41 and -47 kg ha^{-1} in the RS and CDC treatment, respectively. This result showed that RS and CDC are important source of K to keep K balance in paddy field.

VIII. CONCLUSION

This research had been conducted to evaluate the soil fertility, nutrients balance, and nutrients behavior of paddy fields under CDC application in a mixed crop-livestock system (CDC treatment) comparing to the paddy fields under conventional RS application (RS treatment). The soil fertility was evaluated in Chapter 1 using (1) 79 farmers' paddy fields (41 RS treatment and 38 CDC treatment) to assess the general soil fertility in all paddy fields in this area and (2) 14 neighboring field pairs of RS and CDC treatments to exclude the effect of various soil environmental conditions. The nutrients balance was evaluated in Chapter 2 (about N), Chapter 3 (about P), and Chapter 4 (about K) using 10 neighboring field pairs of RS and CDC treatments. The nutrients behavior was evaluated in Chapter 5 using 14 neighboring field pairs of RS and CDC treatments. From the result of all chapters, we concluded as following:

(1) The application of CDC to paddy fields in mixed crop–livestock system resulted in non–significant difference of soil fertility–as measured by SOC, total N and P, available N, P, and Si, CEC, exchangeable K, Ca, and Mg, base saturation percentage, pH, and bulk density–with that of RS application. The soil fertility of most fields was adequate by RS or CDC application in combine with fertilizer.

(2) The total N input, total N output, and N balance of paddy fields in mixed crop–livestock system was non-significant difference from those in conventional RS application, which is the reason for non-significant difference of soil total N and available N between treatments. The contribution of higher N input from CDC was not large enough to make the significantly higher total N input to the field in the mixed crop–livestock system. The leaching loss was small and negligible in N balance. Both RS and CDC application in combine with fertilizer N resulted in positive N balance.

(3) The total P input, total P output, and P balance of paddy fields in mixed crop–livestock system was non-significant difference from those in conventional RS application, which is the reason for non-significant difference of soil total P and available P between treatments. The higher P input from CDC was offset by higher fertilizer P input in the RS applied fields. P balance was positive in both systems. The amount of P fertilizer can be reduced with keeping P balance in the RS and CDC applied fields.

(4) The total K input, K output, and K balance of paddy fields in mixed crop–livestock system was non-significant difference from those in conventional RS application, which is the reason for non-significant difference of soil exchangeable K between treatments. All sources of K inputs were the same level between treatments. K in RS is easy to leach by rainfall, so the timing of RS sample affected to the K content in RS. In mixed crop–livestock system, farmer should apply more fertilizer K or improve K content of CDC to balance K for the field. The application of RS and CDC are important to keep K balance.

(5) In plow layer water, the concentration of all of nutrients and C excepted for P increased after transplanting, reached to the peak, and decreased after that. The plenty of input before and/or at transplanting and poor rice plant uptake resulted in high concentration in the plow layer at early growth stage. In case of K, Si, Mg, and Ca, plant nutrients uptake, soil adsorption, and the increasing of their leaching resulted in the sharply decreased in the concentration of plow layer water. In case of N and C, the concentration in the plow layer water have no relationship with that in the leaching water. P is a special nutrient, fixed firmly in soil, so there was few P existing in the solution and leaching.

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