Effects of Different Appllicaton Methods of Fertilizer and Manure on Soil Chemical Properties, Yield, and NPK Balances in Whole Crop Rice Cultivation

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Abstract

Whole crop rice (WCR) is expected to establish a recycling system exchanging animal feed with manure from livestock farming. In WCR cultivation, the above-ground parts are harvested as animal feed unlike food rice. WCR is also known to absorb more nutrients compared with food rice. Therefore, the application of manure in the paddy fields is beneficial to replenish the removed nutrients and maintain soil fertility. However, due to different availability of manure, field drainage, and available time for its application, some farmers applied manure excessively whereas other farmers have to rely only on chemical fertilizer, which might lead to deterioration in soil fertility, yield reduction, or environmental pollution. In addition, there have been limited studies on how different application methods of fertilizer and manure in actual farming situations affected soil chemical properties, yield, and nutrient balances in WCR cultivation.

Therefore, the objectives of this study were (1) to investigate the effects of different application methods of fertilizer and manure on soil chemical properties and yield in WCR cultivation, and (2) to assess NPK balances in actual paddy fields where WCR was cultivated under different manure and chemical fertilizer applications.

This study was conducted in 2013 and 2014 in Itoshima region, Fukuoka Prefecture, Japan. Eight fields were surveyed in both 2013 and 2014 with an additional two fields added in 2014 (18 fields in total). The surveyed fields included two application methods—manure (M) alone, and chemical fertilizer (CF) alone.

For the first objective, the total 18 fields were investigated. The results showed that soil texture (clay plus silt) partly contributed to the increases of total nitrogen (TN), total phosphorus (TP), and exchangeable potassium (Ex. K). Meanwhile, clear gaps of TN, TP,

Ex. K, K saturation degree and available N between CF and M at around 40% of clay plus silt content strongly suggested that manure application contributed to increases in the soil chemical properties. The relatively large negative values of yearly difference of available N in CF fields may suggest the decrease of mineralizable part of soil TN even though long-term study is needed to verify. In addition, potential N supply in soil was significantly correlated with straw weight ($r = 0.698$, $p < 0.05$ for 2013; $r = 0.873$, $p < 0.01$ for 2014) or yield of whole crop ($r = 0.852$, $p < 0.01$ for 2014) indicated that N mineralized from soil, which was enhanced by manure application, increased straw weight, resulting in an increase in yield of whole crop.

For the second objective, same surveyed fields were investigated. Residual N, P and K, which were calculated as NPK input-output balances, were markedly large in M fields: 390–1174 kg N ha^{-1}, 100–489 kg P ha^{-1}, and 168–968 kg K ha^{-1}, respectively. Contrarily, residual N, P and K were small in CF fields: 40–74 kg N ha^{-1}, 1–8 kg P ha^{-1}, and −18 to 24 kg K ha^{-1}, respectively. Excessive application of manure beyond crop requirement resulted in large residual N, P and K, which can cause water pollution through leaching and surface runoff. Positive trends of soil N and P balances in M fields implied that large amount of manure application accumulated N and P in the paddy fields. Applying manure to meet crop requirement on available P basis, which considers residual effects of continuous application and compensates for shortage of N using fertilizer, is a possible measure to produce yields comparable to N-based manure application with low environmental impact.

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List of Abbreviations and Acronyms

CEC: Cation exchange capacity

CF: Chemical fertilizer alone

EC: Electrical conductivity

Ex. K: Exchangeable potassium

M: Manure alone

TN: Total nitrogen

TK: Total potassium

TP: Total phosphorus

Chapter 1

Introduction

1.1 Background

The use of redundant paddy fields has been an important subject in Japan’s paddy farming since a continuous decline in rice consumption started in the 1960s (MAFF 2006). The government has been tackling this subject by encouraging the cultivation of soybean, wheat, and feed crops as substitutes for rice. The cultivation of those crops boosted the food self-sufficiency ratio on a calorie basis by 4.31% according to the estimation by Arahata (2014). However, substitutive upland crops were not always able to be cultivated in paddy fields because of unsuitable drainage conditions (Kato, 2008). Arahata (2014) estimated that the area of fallow paddy fields was currently approximately 293,000 ha. This situation has raised concerns about the loss of multiple functions of paddy fields such as food production, flood prevention, groundwater retention, and formation of rural landscapes.

Improving the low self-sufficiency ratio of livestock feed—27% in 2014 (MAFF, 2016)—is also important in relation to paddy farming in Japan. This low self-sufficiency ratio has occurred because the Agricultural Basic Law issued in 1961 promoted intensive livestock industry that was dependent on foreign feed (Nishio, 2005). Meanwhile, the demand for domestic feed has increased in recent years because of the unstable prices of foreign feed. For bulky feed, such as hay and rice straw, the self-sufficiency ratio was 78% in 2014 (MAFF, 2016); the potential to further boost the ratio is beneficial from the safety and economic aspects. Kato (2008) and Sakai *et al*. (2008) noted the infection risk of foot and mouth disease through imported bulky feed. Kato (2008) also mentioned the high transportation costs of some bulky feed imported from America, Canada and China.

Because of the concerns noted above, whole crop rice (WCR), which is cultivated in paddy fields with similar cultural practices as food rice, has been promoted by the government since 2000 (Kato 2008; Taniguchi *et al.,* 2010). The cultivation area of WCR has rapidly increased to reach 38,226 ha in 2015 (MAFF 2016). WCR cultivation is expected to establish a system that recycles local organic resources by exchanging feed with manure produced from animal wastes. The recycling system can lower the production cost of WCR and simultaneously solve problems related to the disposal of animal waste, which has always been a concern in livestock farming. The recycling system is also important to maintain soil fertility in WCR cultivation, because the entire above-ground biomass is harvested as animal feed unlike food rice where straw is normally incorporated into the soil. Ooya and Watanabe (2013) and Oya *et al.* (2015) demonstrated that a 2–4 year successive application of cow manure in WCR cultivation maintained or increased humus and total nitrogen (TN) in soil, and soil available N.

Meanwhile, manure application in actual farming situations is restricted by factors such as availability of manure, field drainage, and available time for its application, which is especially short in a dual-crop system. Moreover, farmers might rely more heavily on subsidies to cover their production costs rather than increasing yield because of low market price of WCR at about 40 JPY kg^{-1} (Taniguchi *et al.,* 2010). Thus, farmers can save fertilizer costs, and also apply excessive amounts of manure supplied from livestock farmers for free. These situations can cause excessive application of manure and insufficient application of fertilizer, which might lead to deterioration in soil fertility, yield reduction, or environmental pollution.

1.2 Previous studies on WCR

Due to decreasing trend of rice consumption, rice production in Japan has been restricted in order to balance the supply and demand of rice since 1970s (Sakai *et al.*, 2003). As a consequence, a large area of paddy fields was left without rice cultivation. In addition, to improve the low self-sufficiency ratio of animal feed, there is a strong need for domestic feed production. The experiment on the use of rice for feed has been conducted since 1970s; however, the cost of using food rice for animal feed was too high (Sakai *et al.,* 2003). Thus, in 1999, the Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan initiated a research project, which mainly focused on developing whole crop rice cultivar with high productivity and suitable for low-cost production (Sakai *et al.,* 2003; Sakai *et al.,* 2008). Consequently, this project has developed high yielding cultivars including Bekoaoba, Yumeaoba, and Kusayutaka for cool regions, Hoshiaoba, Kusahonami, Kusanohoshi, and Leafstar for moderate regions, and Mohretsu, Nishiaoba, and Tachiaoba for warm regions like Kyushu (Sakai *et al.,* 2008).

A few studies have focused on different aspects of WCR cultivation. Cheng *et al.* (2018) investigated differences in methane (CH_4) emission among food rice, feed rice, and WCR cultivation. Their research showed that methane emission from WCR (Tachisuzuka cultivar) and feed rice (Fukuhibiki cultivar) were 87% and 40% higher than that from food rice (Haenuki cultivar). Islam *et al.* (2004) estimated the nutritive value of WCR (Hamasari cultivar) at yellow mature stage. Their results showed that the head parts were more nutritious than leaf and stem.

Limited studies investigated the effects of different application methods of fertilizer and manure on soil chemical properties and yield of WCR in actual farming situations. Oya *et al.* (2014) and Oya *et al.* (2015) conducted surveys on 70 farmers' fields in western Japan and reported that 80% of the fields were below the standard for potassium (K) saturation degree and that the average yield (12.8 ton ha^{-1}) was about 2 ton ha^{-1} lower than the yield target (15 ton ha^{-1}).

N balance in WCR cultivation has been extensively studied due to environmental concerns, and possible use of WCR for reducing N loads in the environment. Kyaw *et al.* (2005) estimated N balance in a paddy field planted with WCR (Kusahonami cultivar) under unfertilized and fertilized (160 kg N ha^{-1}) conditions. They aimed to establish an appropriate fertilizer application method suitable for reducing N loads in the environment, and increase productivity. Their results showed that N uptake by WCR was a main output in both treatments and N losses by leaching were relatively small, 4.8–7.3 kg N ha^{-1}. Zhou and Hosomi (2008) investigated N balance in a constructed wetland for nutrient-polluted river water treatment. They found that WCR absorbed large amount of N from the wetland suggesting that harvesting aboveground biomass could recycle large amount of removed N. Gusmini *et al.* (2015) estimated N balance by pot experiment when WCR was cultivated with 140 and 280 kg N ha^{-1} applied from combined cow and poultry manure.

1.3 Research objectives and thesis outline

There have been limited studies focusing on the effects of different application methods of fertilizer and manure on soil chemical properties and yield of WCR in actual farming situations. From the aspects of environmental impact, some studies investigated N balances in WCR cultivation, while they did not compare N balances under different application methods of fertilizer and manure. In addition, phosphorus (P) and potassium (K) balances have not been investigated in WCR cultivation. Therefore, the objectives of this study were (1) to investigate the effects of different application methods of fertilizer and manure on soil chemical properties and yield in WCR cultivation, and (2) to assess NPK balances in a paddy field where WCR is cultivated under different application methods of fertilizer and manure.

Chapter 2 presents the study on the first objective. To complete this objective, field surveys were conducted in 2013 and 2014 in Itoshima region, Fukuoka Prefecture, Japan. The surveyed fields included two application methods of fertilizer and manure—manure (M) alone, and chemical fertilizer (CF) alone. Soil chemical properties including TN, TP, exchangeable potassium (Ex. K), K saturation degree, and available N were compared between M and CF fields. The relationships between soil chemical properties, soil potential N supply and yield were also investigated.

Chapter 3 shows the study on the second objective. To complete this objective, we assessed NPK input-output balances, which is expressed as residual values, calculated by nutrient input in minus nutrient output from a paddy field during the estimation period. In addition, we assessed soil NPK balances in a paddy field by subtracting NPK in soil after harvest in 2013 from soil after harvest in 2013. Then, we investigated trends of NPK input-output balances (residual) and soil NPK balances in M and CF fields and considered its environment impact.

Chapter 2

Effects of Different Application Methods of Fertilizer and Manure on Soil Chemical Properties and Yield in Whole Crop Rice Cultivation

2.1 Introduction

WCR is expected to establish a cultivation method using manure produced from animal wastes. Meanwhile, application methods of fertilizer and manure in the WCR cultivation are affected by manure availability, available time for manure application, and field drainage, and low market price of WCR. Moreover, farmers might rely more heavily on subsidies to cover their production costs rather than increasing yield. These situations can cause excessive application of manure and insufficient application of fertilizer which might lead to deterioration in soil fertilizer and yield reduction.

This chapter focuses on the effects of different application methods of fertilizer and manure on soil chemical properties and yield in WCR cultivation. Section 2.2 shows the materials and methods used in this study. This section includes information on field surveys, application methods, soil and manure sampling, chemical analysis methods and statistical analysis. Section 2.3 presents physicochemical properties of manures, soil chemical properties, yield, relationships between soil texture and soil chemical properties, relationships between soil total nitrogen and available nitrogen, and relationships between yield and nitrogen supply sources. Section 2.4 discusses the yearly differences of soil chemical properties in M and CF fields. The section also discusses the relationships between soil texture and soil chemical properties, effects of fertilizer and manure application on soil chemical properties, and yield. Section 2.5 concludes the main findings presented in this chapter.

2.2 Materials and methods

2.2.1 Surveyed fields

Field surveys were conducted in the Itoshima region, Fukuoka Prefecture, Japan (33°30'N–33°34'N, 130°08'E–130°15'E). Eight fields were surveyed in both 2013 and 2014, and two more fields were added in 2014 (i.e., 18 fields in total). The surveyed fields were cultivated by five different farmers. The Tachiaoba cultivar (*Oryza sativa* L.) was grown in all surveyed fields. Transplanting dates were from 14–25 June in 2013 and 11–26 June in 2014. Heading dates were from 6–18 September in 2013 and 12–18 September in 2014. Harvesting dates were 17 October in 2013, and 8 and 11 October in 2014.

Table 2.1 shows soil properties and cultivation period in surveyed fields. The surveyed fields included two application methods of manure (M) alone (5 fields: Field Nos. 1–5) and chemical fertilizer (CF) alone (5 fields: Field Nos. 6–10). Soil types included and the ranges of CEC in the surveyed fields were as follows: light clay (LiC), sandy clay loam (SCL) and clay loam (CL), and 10.58–18.74 cmol kg^{-1} in M fields; SCL and sandy loam (SL), and 5.81–9.68 cmol kg^{-1} in CF fields. The cropping system was single WCR in all the surveyed fields. The periods of WCR cultivation were 4–13 years, and manure was applied yearly in M fields.

Table 2.2 shows application methods of manure and chemical fertilizer. In M fields, estimated amounts of TN, TP, and total K (TK) applied from manure varied widely from 418–1211 kg ha^{-1} (average: 763 kg ha^{-1}), 124–505 kg ha^{-1} (average: 275 kg ha^{-1}), and 243–1073 kg ha^{-1} (average: 804 kg ha^{-1}), respectively. The application timings of manure extended from February to April. In CF fields, TN, TP, and TK applied from chemical fertilizer amounted to 50–82 kg ha^{-1} (average: 75 kg ha^{-1}), 18–24 kg ha^{-1} (average: 23 kg ha^{-1}), and 35–69 kg ha^{-1} (average: 60 kg ha^{-1}), respectively.

Table 2.1 Soil properties, cropping system, and cultivation period in surveyed fields

Field No.	Application methods[a]	Soil classification[b]	Clay (%)	Silt (%)	Sand (%)	Soil type[c]	CEC (cmol kg^{-1})	Cropping system	WCR cultivation period (year)[d]	Manure application history (year)[d]
1	M	GrL-bf	28	25	47	LiC	15.85	Single WCR	4	4
2	M	GrL-bf	29	24	47	LiC	17.30	Single WCR	4	4
3	M	G-sf	30	34	36	LiC	18.74	Single WCR	8	8
4	M	G-f	18	19	63	SCL	11.43	Single WCR	6	6
5	M	G-smc	18	24	58	CL	10.58	Single WCR	6	6
6	CF	G-smc	20	11	69	SCL	8.48	Single WCR	13	N.A
7	CF	G-smc	23	18	59	SCL	9.68	Single WCR	13	N.A
8	CF	G-f	12	11	77	SL	5.81	Single WCR	13	N.A
9	CF	G-f	21	10	69	SCL	7.50	Single WCR	13	N.A
10	CF	G-f	16	20	64	SCL	9.10	Single WCR	13	N.A

[a] M = manure alone; CF = chemical fertilizer alone. [b] Based on the Classification of Cultivated Soils in Japan - 2nd Approximation (Third Division of Soils, National Institute for Agro-Environmental Sciences, 1983). G-f = Fine-textured Gley soils; G-smc = Medium and Coarse-textured Strong-gley soils; GrL-bf = Fine-textured Gray Lowland soils (grayish brown type); G-sf = Fine-textured Strong-gley soils. [c] CL = clay loam; SCL = sandy clay loam; SL = sandy loam; LiC = light clay. [d] Approximation based on interviews with farmers (as of October in 2014). N.A = Not applied.

Table 2.2 Application methods of manure and chemical fertilizer

Year	Field No.	Application method[a]	Manure application[b]					Chemical fertilizer[b]				
								Basal application		Topdressing		Total[f]
			Total weight[c] (ton ha^{-1})	TN-TP-TK (kg ha^{-1})	Manure[d]	Timing	Application history (years)[e]	TN-TP-TK (kg ha^{-1})	Date	TN-TP-TK (kg ha^{-1})	Date	TN-TP-TK (kg ha^{-1})
2013	1	M	200	809-209-1058	1	Feb.–Mar.	4	-	-	-	-	-
	2	M	200	809-209-1058	1	Feb.–Mar.	4	-	-	-	-	-
	3	M	40	510-250-522	2	Feb.–Mar.	8	-	-	-	-	-
	4	M	100	1211-505-1023	3	Mar.	6	-	-	-	-	-
	6	CF	-	-	-	-	-	56-24-46	2 June	18-0-13	16 Aug.	74-24-60
	7	CF	-	-	-	-	-	56-24-46	2 June	18-0-13	10 Aug.	74-24-60
	8	CF	-	-	-	-	-	56-24-46	2 June	18-0-13	9 Aug.	74-24-60
	9	CF	-	-	-	-	-	56-24-46	2 June	18-0-13	16 Aug.	74-24-60
2014	1	M	200	740-287-1073	1	mid-Apr.	4	-	-	-	-	-
	2	M	200	740-287-1073	1	mid-Mar.	4	-	-	-	-	-
	3	M	40	585-294-577	2	Mar.	8	-	-	-	-	-
	4	M	100	1045-310-608	3	late Mar.–mid-Apr.	6	-	-	-	-	-
	5	M	40	418-124-243	3	late Mar.	6	-	-	-	-	-
	6	CF	-	-	-	-	-	56-24-46	2 June	26-0-19	20 Aug.	82-24-66
	7	CF	-	-	-	-	-	56-24-46	2 June	26-0-19	20 Aug.	82-24-66
	8	CF	-	-	-	-	-	56-24-46	2 June	26-0-19	20 Aug.	82-24-66
	9	CF	-	-	-	-	-	56-24-46	2 June	26-0-19	20 Aug.	82-24-66
	10	CF	-	-	-	-	-	50-18-35	5 June	-	-	50-18-35

[a] M = manure alone; CF = chemical fertilizer alone. [b] Information on application amount and timing of manure and chemical fertilizer is approximation based on interviews with farmers. [c] Wet basis. [d] Refer to Table 3. [e] Based on interviews with farmers (as of October 2014). [f] The total values are not always equal to the summation of basal application and topdressing in the table due to rounding.

2.2.2 Measurements of physicochemical properties of manure

Samples of the manures were collected in May in both 2013 and 2014 from three locations in piles of manure at each of three different cow sheds. The maturity of collected manures was nearly same with those applied in the surveyed fields. Manure samples were preserved in Ziploc® bags. Three samples of manure from the same shed were mixed; half of the amount of each mixed sample was air-dried and passed through a 1-mm sieve, while the remaining raw sample was stored at 4 °C. The air-dried sample was then ground using a standard Wiley Cutting Mill (No.1029, YOSHIDA SEISAKUSHO CO., Ltd, Tokyo, Japan).

First, moisture content of raw manure was measured by oven-drying at 105 °C for 24 h. Then, raw manure, which was equivalent to 15 g on a dry weight basis, was placed in a beaker. The beaker was left for 1 h after adding hot water at approximately 70 °C. The reason for using hot water was to sterilize manure before chemical analysis. Here, hot water was used following the method of a germination test to evaluate the quality of animal waste compost (Kumagai and Yamaguchi, 2004). The solution of raw manure was adjusted to be 150 mL for total water volume. Then, manure extract was collected by filtering the solution through a No. 5B filter paper (Advantec, Tokyo, Japan). Electrical conductivity (EC), pH, ammonium (NH_4–N), and nitrate (NO_3–N) were measured using the manure extract. The EC and pH were measured using an EC meter (B-173; HORIBA, Ltd., Kyoto, Japan) and a pH meter (B-212; HORIBA, Ltd.), respectively. NH_4–N and NO_3–N were measured by the indophenol method (Cataldo *et al.,* 1974) and Cataldo method (Cataldo *et al.,* 1975), respectively.

TN, TP, and TK were measured using dry ground samples. Each of the samples was digested by the H_2SO_4-H_2O_2 Kjeldahl digestion method (Ohyama *et al*., 1991) with three replications. TN and TP were measured by the indophenol method and ascorbic acid method (Murphy and Riley, 1962), respectively. Absorbance at 625 nm and 710 nm were determined for TN and TP, respectively, using a spectrophotometer (V-630; JASCO, Tokyo, Japan) with a rapid sampler (NQF-720; JASCO). TK was measured using atomic absorption spectrophotometry (Z-5300; Hitachi High-Technologies Co., Tokyo, Japan). Total carbon (TC) was measured for dry ground samples using a total organic carbon analyzer (TOC-5000A; Shimadzu, Kyoto, Japan) equipped with solid sample module (SSM-5000A; Shimadzu) in 2013 and a CHN coder (MT-5, Yanaco) in 2014.

2.2.3 Measurements of soil chemical properties

Soil samples were collected at five locations with a crisscross pattern in each surveyed field. The soil from 0–10 cm depth was sampled using a 5-cm diameter soil core sampler. Soil was sampled before transplanting (late May to early June) and after harvest (early December in 2013, early to mid- October in 2014).

Soil samples were air-dried, and were then passed through a 2-mm sieve by a Soil Sample Crusher (SSM-1; Fujihara, Tokyo, Japan), while five soil samples from each surveyed field were mixed into one composite. The composite samples were ground into fine particle using a sample mill (Cyclotec TC 1093, Fisher Scientific, Atlanta, Georgia).

The soil samples that had been collected after harvest were analyzed for TN and TP following the same procedures as described in Section 2.2 for manure. Ex. K was extracted with 1 M ammonium acetate (pH 7) by a shaking extraction method (Muramoto *et al.*, 1992) and measured by atomic absorption spectrometry (Z-2300, Hitachi, Tokyo, Japan). The soil samples that had been collected before transplanting were analyzed for available N under 4-week incubation. First, 20 g of dry soil was added to a 500-mL glass bottle, then 50 mL of distilled water was added. Next, the headspace in the bottle was replaced with N gas and the bottle capped with a rubber stopper. The flooded soil in the bottle was incubated at 30 °C for 4 weeks. After incubation, NH_4–N was extracted with 100 mL of 0.5 M K_2SO_4 by shaking the bottle for 20 min. The extract was filtered through a No. 5B filter paper and NH_4–N in the extract was measured by the indophenol method. Finally, available N was evaluated as values per 1 kg of dry soil.

2.2.4 Measurement of yield of whole crop

Yield of whole crop was estimated by quadrat sampling of 60 hills. Of these, 30 hills were manually harvested in each of the two plots located in a diagonal direction across the field on October 17, 2013 (yellow ripening stage) and on October 8 and 11, 2014 (one week before yellow ripening stage). Straw and grain heads were separately weighed and measured for moisture content by oven-drying at 70 °C for 48 h. Then, yield of whole crop including straw and grain heads were calculated on a dry weight basis.

2.2.5 Statistical analysis

Correlation analysis was conducted on the relationships between clay plus silt content and soil TN, TP, Ex. K, K saturation degree, and available N. These relationships were analyzed by pooling the data from the two-year survey where data from two application methods (M, CF) were analyzed as a pool, and analyzed separately by application methods. The correlation analysis was conducted to evaluate the effects of application methods of fertilizer and manure on soil chemical properties considering the effects of soil texture simultaneously. Correlation analysis was also conducted on the relationship between soil TN and available N. In addition, correlation analysis was conducted to evaluate the effects of N supply sources (soil, basal application, topdressing) on straw weight, grain head weight, and yield of whole crop. Yearly difference was calculated in fields surveyed for two, by subtracting values in 2013 from those in 2014. For all statistical analysis, Microsoft Excel 2016 was used.

2.3 Results

2.3.1 Physicochemical properties of manures

Table 2.3 shows physicochemical properties of manures applied in the surveyed fields. Three different manures were applied in surveyed fields each year: manure 1, Field Nos. 1 and 2; manure 2, Field No. 3; and manure 3, Field Nos. 4 and 5 (Table 2.2). The materials of manures were dairy cow waste, sawdust, and rice husk in manure 1 and beef cow waste and sawdust in manures 2 and 3. Manure 1 had a high moisture content of around 70%, whereas manure 3 tended to be dry with a moisture content around 40%. For all three manures, pH and EC were in the range of 6.1–8.8, and 3.8–10.1 dS m^{-1}. NH_4–N content in manure 1 was consistently low in both years, while it fluctuated from 5.6 g kg^{-1} in 2013 to 1.1 g kg^{-1} in 2014 in manure 2. The NO_3–N was detected at low levels in all manures in 2013, while it was 0.61 g kg^{-1} in manure 1 and 0.71 g kg^{-1} in manure 3 in 2014. TN was low in manure 1 and high in manure 2, whereas that of all manures, it ranged from 12.0–29.5 g kg^{-1}. TP and TK were high in manure 2 in both years. High TC and low TN in manure 1 resulted in a high C/N ratio of 29–30. C/N ratio was 11 in manure 2 and 11–14 in manure 3.

2.3.2 Soil chemical properties

Table 2.4 shows TN, TP, Ex. K, and K saturation degree for soil after harvest and available N measured for soil before transplanting. Differences in mean values between CF and M fields showed a similar trend for all the chemical properties in both years. The mean values of the two years were higher in M (TN: 2.5 g kg^{-1}, TP: 1.6 g kg^{-1}, Ex. K: 0.5 g kg^{-1}, K saturation degree: 3.4%, available N: 164 mg kg^{-1}) than those in CF (TN: 1.3 g kg^{-1}, TP: 0.7 g kg^{-1}, Ex. K: 0.1 g kg^{-1}, K saturation degree: 1.4%, available N: 85 mg kg^{-1}). Yearly differences of TN tended to be higher in M fields than those is CF fields, while the differences of TP and Ex. K were around 0 in both CF and M fields. For K saturation degree, relatively high yearly differences were observed in M fields (Field No. 1: 0.5%, Field No. 3: 0.6%) and in one CF field (Field No. 7: 1.7%). Yearly differences of available N in CF showed relatively large negative values consistently (−17 to −32 mg kg^{-1}). Moreover, the values of yearly differences in M (−10 to 27 mg kg^{-1}) were larger than those in CF.

2.3.3 Yield

Table 2.5 shows straw weight, grain head weight, and yield of whole crop in each surveyed field. For straw weight and yield of whole crop, the mean values in 2013 were higher in M (straw weight: 9.1 ton ha^{-1}; yield of whole crop: 14.1 ton ha^{-1}) than in CF (straw weight: 7.2 ton ha^{-1}; yield of whole crop: 11.8 Ton ha^{-1}). The trend was same in 2014; the mean values were higher in M (straw weight: 9.6 ton ha^{-1}; yield of whole crop: 13.4 ton ha^{-1}) than in CF (straw weight: 7.2 ton ha^{-1}; yield of whole crop: 10.9 ton ha^{-1}). For grain head weight, the mean value in 2013 was higher in M (5.1 ton ha^{-1}) than CF (4.6 ton ha^{-1}), whereas the mean values in 2014 were similar between M (3.8 ton ha^{-1}) and CF (3.7 ton ha^{-1}).

Table 2.3 Physicochemical properties of applied manures

Manure	Material		Moisture content (%)	pH	EC (dS m^{-1})	NH_4–N (g kg^{-1})	NO_3–N (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	TK (g kg^{-1})	TC (g kg^{-1})	C/N ratio
	Waste	Bulking material										
2013												
1	Dairy cow	Sawdust, Rice husk	66	7.9	5.0	0.7	0.02	12.0	3.1	15.7	354.0	30
2	Beef cow	Sawdust	52	6.1	10.1	5.6	0.01	26.3	12.9	26.9	295.2	11
3	Beef cow	Sawdust	38	7.7	4.4	1.3	0.05	19.4	8.1	16.4	265.6	14
2014												
1	Dairy cow	Sawdust, Rice husk	71	8.8	3.8	0.3	0.61	12.9	5.0	18.7	376.5	29
2	Beef cow	Sawdust	50	7.9	6.0	1.1	N.D	29.5	14.8	29.1	313.4	11
3	Beef cow	Sawdust	45	8.0	5.2	2.5	0.71	18.9	5.6	11.0	211.4	11

N.D = Not detected.

Table 2.4 Soil TN, TP, Ex. K, K saturation degree, and available N

Year	Field No.	Application methods[a]	TN[b] (g kg^{-1})	TP[b] (g kg^{-1})	Ex. K[b] (g kg^{-1})	K saturation degree[b] (%)	Available N[c] (mg kg^{-1})
2013	1	M	2.2	1.6	0.5	3.3	158
	2	M	2.6	1.5	0.7	4.1	184
	3	M	2.6	1.8	0.4	2.1	170
	4	M	2.6	1.6	0.5	4.0	175
	6	CF	1.5	0.7	0.1	1.1	102
	7	CF	1.4	0.8	0.1	1.4	108
	8	CF	1.0	0.5	0.1	1.6	109
	9	CF	1.0	0.8	0.1	1.2	76
2014	1	M	2.5	1.7	0.6	3.8	148
	2	M	2.9	1.5	0.7	3.8	211
	3	M	2.8	1.9	0.5	2.7	168
	4	M	2.4	1.5	0.5	4.1	173
	5	M	2.0	1.2	0.3	2.9	85
	6	CF	1.4	0.8	0.1	1.1	79
	7	CF	1.5	0.8	0.3	3.1	90
	8	CF	1.1	0.5	0.1	1.3	77
	9	CF	1.0	0.7	0.1	1.4	59
	10	CF	1.6	0.8	0.1	0.8	66
Mean of two years		M	2.5	1.6	0.5	3.4	164
		CF	1.3	0.7	0.1	1.4	85
Yearly difference[d]							
	1	M	0.3	0.1	0.1	0.5	–10
	2	M	0.3	0.0	0.0	–0.3	27
	3	M	0.2	0.1	0.1	0.6	–2
	4	M	–0.2	–0.1	0.0	0.1	–2
	6	CF	–0.1	0.1	0.0	0.0	–23
	7	CF	0.1	0.0	0.2	1.7	–18
	8	CF	0.1	0.0	0.0	–0.3	–32
	9	CF	0.0	–0.1	0.0	0.2	–17
	Mean of yearly difference						
		M	0.2	0.0	0.1	0.2	3
		CF	0.0	0.0	0.1	0.4	–23

[a] M = manure alone; CF = chemical fertilizer alone. [b] Soil TN, TP, Ex. K, and K saturation degree were measured for soil samples collected after harvest. [c] Available N was measured for soil samples collected before transplanting. [d] Yearly difference was calculated by subtracting values in 2013 from those in 2014. Yearly difference was only calculated for fields where soil chemical properties were measured in both 2013 and 2014 (fields 1–4 and 6–9).

Table 2.5 Straw weight, grain head weight, and yield of whole crop

Year	Field No.	Application methods[a]	Straw weight[b] (ton ha^{-1})	Grain head weight[b] (ton ha^{-1})	Yield of whole crop[b] (ton ha^{-1})
2013	1	M	10.1	5.5	15.6
	2	M	9.5	5.2	14.7
	3	M	9.2	4.9	14.1
	4	M	7.4	4.6	12.0
	6	CF	7.3	4.8	12.1
	7	CF	7.6	4.5	12.2
	8	CF	6.7	4.1	10.9
	9	CF	7.2	4.8	11.9
	Mean				
		M	9.1	5.1	14.1
		CF	7.2	4.6	11.8
2014	1	M	9.9	3.6	13.6
	2	M	10.4	3.5	13.9
	3	M	8.7	4.2	12.9
	4	M	10.2	4.0	14.2
	5	M	8.6	3.6	12.2
	6	CF	6.4	3.5	9.9
	7	CF	7.9	4.0	11.9
	8	CF	7.4	3.9	11.3
	9	CF	7.6	3.9	11.6
	10	CF	6.9	3.1	10.0
	Mean				
		M	9.6	3.8	13.4
		CF	7.2	3.7	10.9

[a] M = manure alone; CF = chemical fertilizer alone. [b] Dry basis.

2.3.4 Relationships between clay plus silt content and soil chemical properties

Figures 2.1–2.5 show the relationships between clay plus silt content and soil TN, TP, Ex. K, K saturation degree, and available N. The relationships showed positive correlations for TN ($r = 0.831$, $p < 0.001$, Fig. 2.1) and TP ($r = 0.876$, $p < 0.001$, Fig. 2.2) with the data pooled for the two application methods. Positive correlations lowered with the data separated for the application methods both for TN and TP. Soil TN and TP involved a large gap between CF and M at around 40% of clay plus silt content.

Ex. K ($r = 0.776$, $p < 0.001$, Fig. 2.3) and K saturation degree ($r = 0.543$, $p < 0.01$, Fig. 2.4) showed a positive correlation with clay plus silt content for the pooled data. Ex. K and K saturation degree also involved a large gap between CF and M at around 40% of clay plus silt content except for one field in CF (Field No. 7 in 2014; Table 2.4), which had higher values than other fields in CF. Unlike TN, TP and Ex. K, K saturation degree in M fields tended to decrease as clay plus silt content increased.

For available N, a positive correlation was significant with the pooled data ($r = 0.701$, $p < 0.001$, Fig. 2.5), whereas correlations were not significant with the separated data. The available N also involved a gap between CF and M at around 40% of clay plus silt content except for one field in M (Field No. 5 in 2014; Table 2.4), which had a lower value than other fields in M.

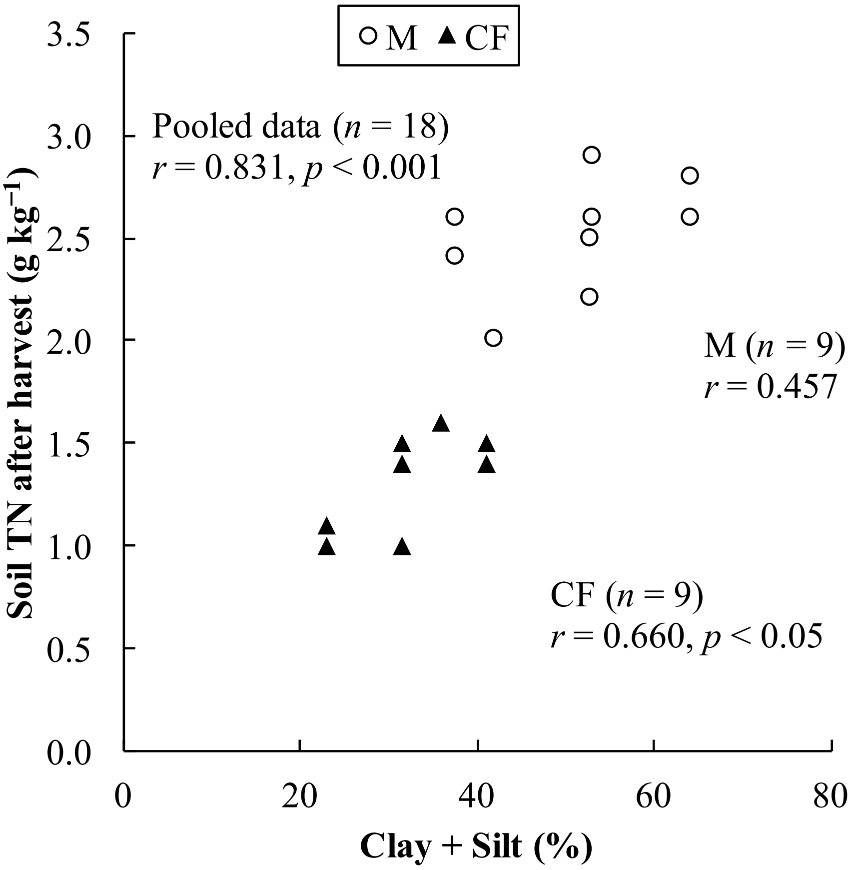

Figure 2.1 Relationships between clay plus silt percentage and soil TN after harvest. M = manure alone; CF = chemical fertilizer alone. Pooled data means correlation was analyzed by pooling the data from M and CF.

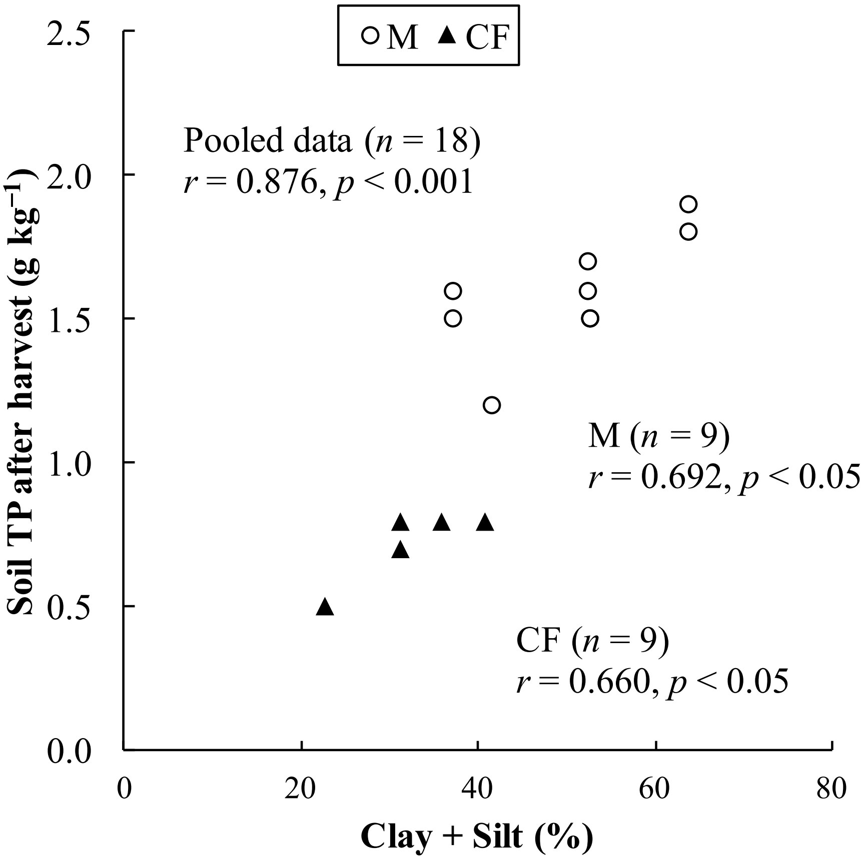

Figure 2.2 Relationships between clay plus silt percentage and soil TP after harvest. M = manure alone; CF = chemical fertilizer alone. Pooled data means correlation was analyzed by pooling the data from M and CF.

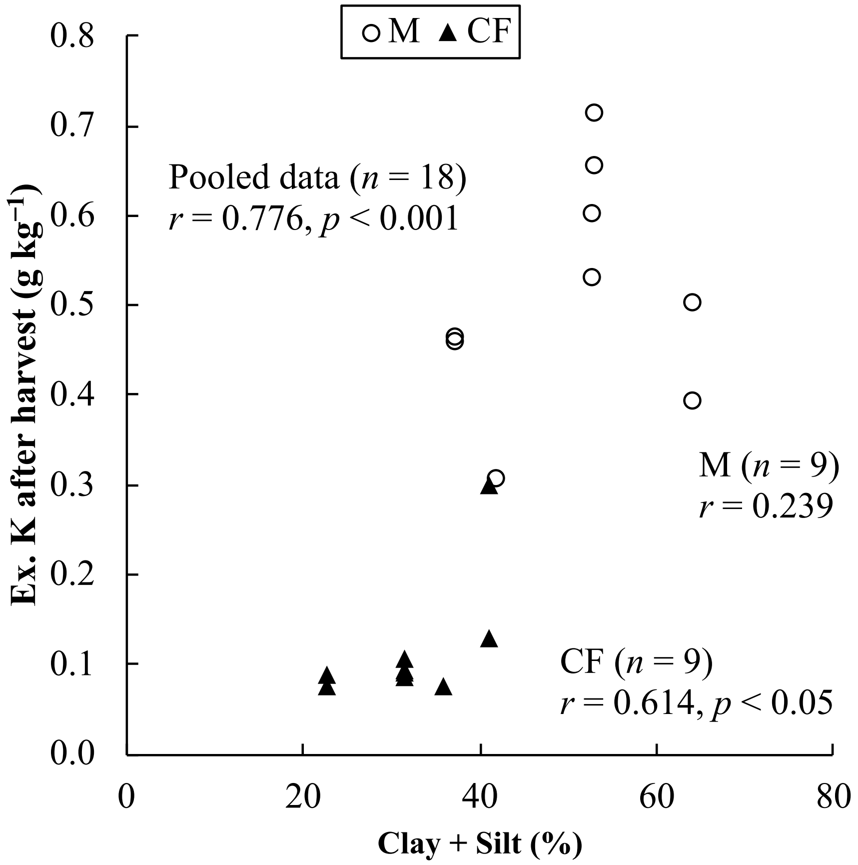

Figure 2.3 Relationships between clay plus silt percentage and Ex. K after harvest. M = manure alone; CF = chemical fertilizer alone. Pooled data means correlation was analyzed by pooling the data from M and CF.

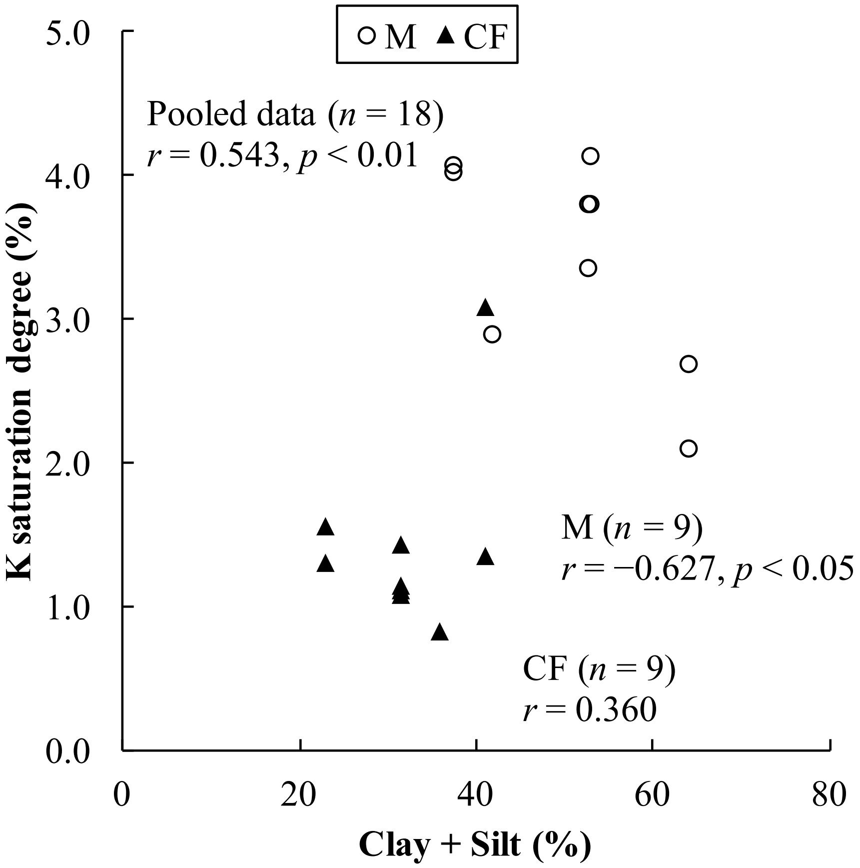

Figure 2.4 Relationships between clay plus silt percentage and K saturation degree. M = manure alone; CF = chemical fertilizer alone. Pooled data means correlation was analyzed by pooling the data from M and CF.

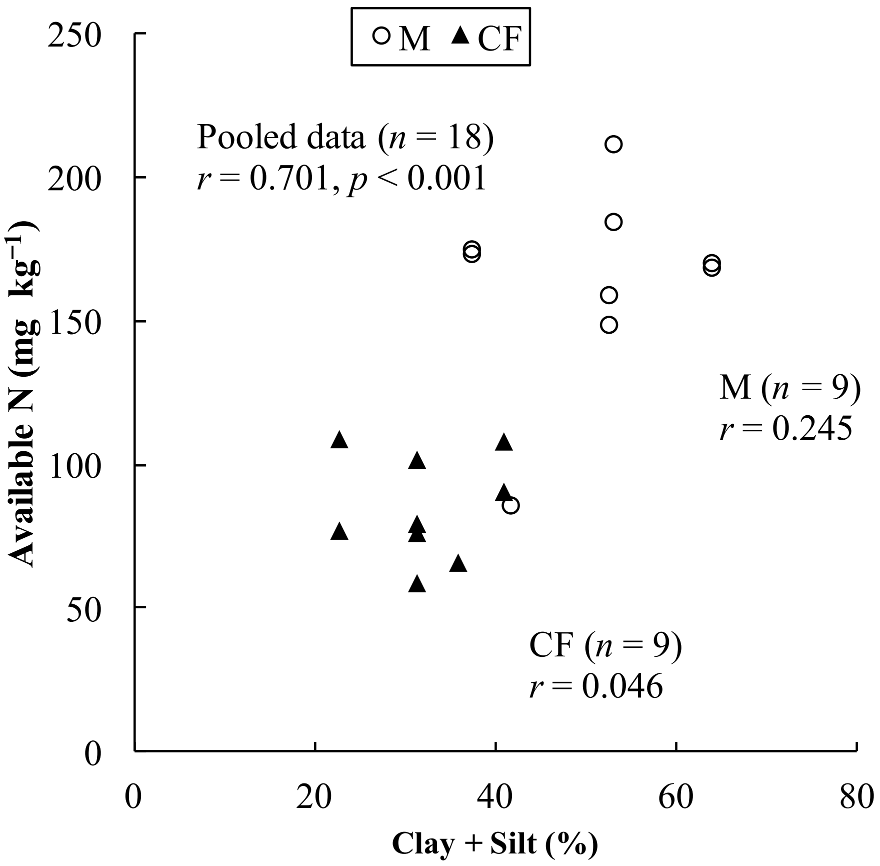

Figure 2.5 Relationships between clay plus silt percentage and available N. The available N was measured for soil samples collected before transplanting. M = manure alone; CF = chemical fertilizer alone. Pooled data means correlation was analyzed by pooling the data from M and CF.

2.3.5 Relationships between soil TN and available N

The relationship between soil TN and available N showed a strong positive correlation with the pooled data ($r = 0.897$, $p < 0.001$, Fig. 2.6). A positive correlation was significant only for M with the separated data ($r = 0.835$, $p < 0.01$).

2.3.6 Relationships between straw weight, grain head weight, yield of whole crop, and N supply sources

Table 2.6 shows results of correlation analysis between straw weight, grain head weight, yield of whole crop and N supply sources including potential N supply and N input from basal application and topdressing. Here, potential N supply was calculated by the product of available N, soil depth (10 cm), and bulk density (1 g cm^{-3}). Straw weight was significantly correlated with potential N supply in both 2013 ($r = 0.698$, $p < 0.05$) and 2014 ($r = 0.873$, $p < 0.01$). Yield of whole crop showed a significant correlation with potential N supply only in 2014 ($r = 0.852$, $p < 0.01$). Correlations were not significant between straw weight, grain head weight or yield of whole crop, and N supply sources including basal application and topdressing.

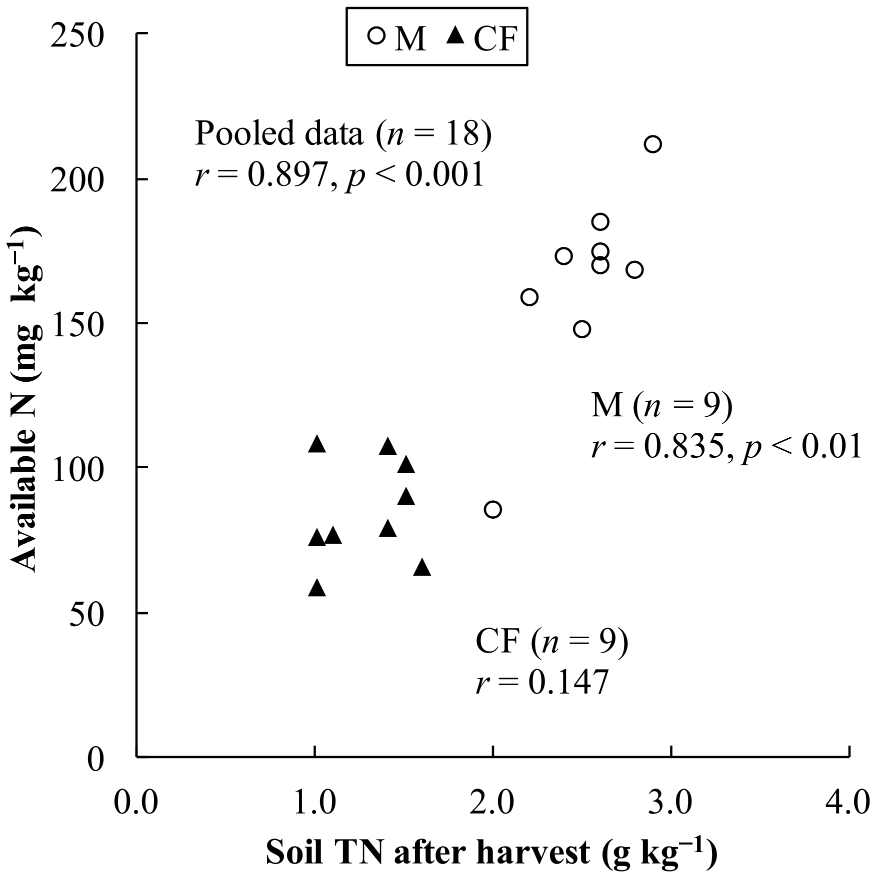

Figure 2.6 Relationships between soil TN after harvest and available N. The available N was measured for soil samples collected before transplanting. M = manure alone; CF = chemical fertilizer alone. Pooled data means correlation was analyzed by pooling the data from M and CF.

Table 2.6 Correlation analysis between straw weight, grain head weight, yield of whole crop, and N supply sources

	Year	Potential N supply[a]	Potential N supply + basal application	Potential N supply + basal application + topdressing
Straw weight	2013	0.698*	0.346	–0.176
	2014	0.873**	0.629	0.389
Grain head weight	2013	0.469	0.033	–0.445
	2014	0.217	0.234	0.338
Yield of whole crop	2013	0.664	0.295	–0.222
	2014	0.852**	0.628	0.430

[a] Potential N supply was calculated by the product of available N, soil depth (10 cm), and bulk density (1 g cm^{-3}). * = significant at $p < 0.05$. ** = significant at $p < 0.01$. Numbers of observation were 8 in 2013 and 10 in 2014.

2.4 Discussion

2.4.1 Yearly differences of soil chemical properties

Yearly differences of TN were higher in M fields (Table 2.4). However, it was not clear that manure application contributed to increases of TN because TN input from manure was not significantly correlated with increase of TN. Yearly differences of TP and Ex. K were similar in M and CF. The reason for relatively large yearly differences of K saturation degree in Field Nos. 1, 3, and 7 was not clear from data collected in this study. For available N, it was consistent that CF fields had relatively large negative values and the values of yearly differences were larger in M fields. These results might suggest that WCR cultivation without organic matter applications for 13 years (Table 2.1) in CF fields has been decreasing mineralizable part of TN in soil. Therefore, long-term study is needed to verify the possible decrease of available N in the WCR cultivation with CF alone.

2.4.2 Relationships between clay plus silt content and soil chemical properties

Close correlations between clay plus silt content and soil TN and TP (Figs. 2.1, and 2.2) were partly because fine-textured soils have a higher retention of organic matter than coarse-textured soils (Van Veen and Kuikman, 1990). A possible reason of significant correlation between clay plus silt content and Ex. K (Fig. 2.3) is a close correlation between clay plus silt content and CEC ($r = 0.970$, $p < 0.01$). Meanwhile, correlation coefficients calculated using pooled data were always higher than those calculated each for CF and M (Figs. 2.1–2.3). Tokutsu (2002) points out that correlation coefficients can be overestimated when samples from different populations are mixed in correlation analysis. In Figs. 2.1–2.3, samples from CF are located at the lower left, while samples from M are located at the upper right. The relative positions of data points are likely to emphasize correlations between clay plus silt content and soil TN, TP, and Ex. K.

A positive correlation between clay plus silt content and K saturation degree for the pooled data (Figs. 2.4) seemed to be mistakenly determined by relative positions of data points from CF and M. A negative correlation shown in M fields was considered more reasonable because CEC linearly increased with clay plus silt content ($r = 0.970$, $p < 0.01$). A positive correlation shown in CF fields was because of high K saturation degree of 3.1% at Field No. 7 in 2014 (Table 2.4).

A positive correlation between clay plus silt content and available N for the pooled data (Fig. 2.5) also seemed to be mistakenly determined by relative positions of data points from CF and M. The correlation analysis using separated data indicated that clay plus silt content was not correlated with available N.

2.4.3 Effects of fertilizer and manure application on soil chemical properties

Clear gaps of TN, TP, Ex. K, and K saturation degree between CF and M at around 40% of clay plus silt content (Figs.2.1–2.4), strongly suggested that TN, TP, Ex. K, and K saturation degree were increased by manure application. In addition, significant correlations between TN, TP, and TK input from manure and chemical fertilizer (Table 2.2) and soil TN ($r = 0.852$, $p < 0.01$), TP ($r = 0875$, $p < 0.01$), and Ex. K ($r = 0.941$, $p < 0.01$) can verify that large amounts of manure application increased the soil chemical properties, although the input was approximation based on interviews with farmers.

A gap of available N values between CF and M at around 40% of clay plus silt content also suggested that available N was increased by manure application. A significant correlation between TN input from manure and chemical fertilizer (Table 2.2) and soil available N ($r = 0.852$, $p < 0.01$) can also verify that manure application increased the available N. Meanwhile, available N in M fields had a strong positive correlation ($r = 0.835$, $p < 0.01$) with soil TN (Fig. 2.6) unlike its relationship with clay plus silt content (Fig. 2.5). These results implied that TN increased by manure application, which was suggested by a clear gap, contributed more to the increases in available N than TN increased by soil texture did (Fig. 2.1). A correlation between TN and available N is likely to be overestimated in the regression analysis using pooled data (Fig. 2.6).

From overall discussion, manure application increased TN, TP, Ex. K, K saturation degree and available N. However, these effects on soil chemical properties were possibly achieved by abundant amounts of manure application, which ranged from 40 to 200 ton ha^{-1} (Table 2.2). Excessive application of manure can cause groundwater and surface water pollution (Brandjes *et al.,* 1996). Thus, nutrient balances in a paddy field need to be further analyzed to determine an appropriate application amount of manure.

2.4.4 Effects of fertilizer and manure application on yield

The yield of whole crop varied in the lower range of values of 9.9–12.2 ton ha^{-1} (mean in 2013: 11.8 ton ha^{-1}; mean in 2014: 10.9 ton ha^{-1}) in CF (Table 2.5). The yield range was similar to the range of 9.85–12.07 ton ha^{-1} (mean: 11.31 ton ha^{-1}) obtained for Tachiaoba cultivar by Oya *et al.* (2014), whereas it was markedly lower than the 17.5 ton ha^{-1} reported by Sakai *et al.* (2008). Sakai *et al.* (2008) cultivated Tachiaoba under heavy fertilizer application of 160 kg N ha^{-1} in total, with 120 kg N ha^{-1} from basal application and 40 kg N ha^{-1} from topdressing. The total amount of N fertilizer application in CF—50–82 kg N ha^{-1}, including 50–56 kg N ha^{-1} from basal application and 18–26 kg N ha^{-1} from topdressing (Table 2.2) was substantially lower than that in Sakai *et al.* (2008). The low N application amounts in this study were because farmers determined the amounts following the application standard of food rice or because topdressing was omitted. Oya *et al*. (2014) and Oya *et al*. (2015) also reported that the average yield of whole crop in 70 surveyed fields, which was 12.8 ton ha^{-1}, was about 2 ton ha^{-1} lower than the target yield of 15 ton ha^{-1}, and the amounts of fertilizer application were lower than the standard for WCR cultivation in many surveyed fields. The difference in mean values of grain head weight between years (M: 5.1 ton ha^{-1} in 2013, 3.8 ton ha^{-1} in 2014; CF: 4.6 ton ha^{-1} in 2013, 3.7 ton ha^{-1} in 2014) was maybe because the harvest was one week earlier in 2014 than in 2013.

Straw weight and yield of whole crop were significantly correlated with potential N supply (Table 2.6). This result suggested that N mineralized from soil, which we interpreted was enhanced by manure application (Figs. 2.1, 2.5, and 2.6), increased straw weight, resulting in an increase in yield of whole crop. Oya *et al*. (2014) similarly reported that yield of whole crop (Tachisuzuka cultivar) was significantly correlated with N mineralized from soil at 4 weeks ($r = 0.2602, p < 0.05$) and N mineralized from manure ($r = 0.5405, p < 0.001$). The summation of N mineralized from soil and manure approximately corresponded to potential N supply in this study, because potential N supply was calculated by using available N which was measured using soil samples in which manure had been already incorporated. Meanwhile, N supply sources including basal application and topdressing were not significantly correlated with straw weight and yield probably because the effect of N supply from soil (potential N supply) was dominant. Rice growth heavily depends on N supplied from soil, which accounts for close to 70% of total N uptake (Koyama, 1975). The correlations between N supply sources and grain head weight were not determined because data collected in this study didn’t allow us to estimate N supply sources, which mainly contributed to grain head weight.

2.5 Conclusions

The objective of this chapter was to show the effects of different application method of fertilizer and manure on soil chemical properties, and yield in WCR cultivation. The conclusions are as follows:

1) Application of manure contributed to increases of TN, TP, Ex. K, K saturation degree, and available N.
2) Yearly differences of available N had relatively large negative values in CF fields, suggesting a possible decrease in mineralizable part of soil TN in the WCR cultivation with CF alone.
3) Significant relationships between potential N supply and straw weight ($r = 0.698$, $p < 0.05$ for 2013; $r = 0.873$, $p < 0.01$ for 2014) or yield of whole crop ($r = 0.852$, $p < 0.01$ for 2014) indicated that N mineralized from soil, which was enhanced by manure application, increased straw weight, resulting in an increase in yield of whole crop. However, the results above were caused probably by abundant amounts of manure application ranging from 40 to 200 ton ha^{-1}. In future research, nutrient balances in a paddy field need to be analyzed to determine an appropriate application amounts of manure considering environmental impacts.

Chapter 3

NPK Balances in Whole Crop Rice Cultivation under Different Application Methods of Fertilizer and Manure

3.1 Introduction

In WCR cultivation, the entire above-ground biomass is harvested as animal feed unlike food rice where straw is normally incorporated into the soil. In addition, WCR has a larger N absorption capacity than food rice (Kyaw *et al.,* 2005). Thus, soil fertility is likely to deteriorate unless organic matter is applied in paddy fields.

To maintain soil fertility in paddy fields, WCR cultivation is expected to establish a recycling system that exchanges feed with manure produced from animal wastes in local regions. The recycling system is also beneficial for solving problems related to the disposal of animal waste (Ogino *et al.,* 2008), which has always been a concern in livestock farming.

WCR cultivation focuses on yield of above-ground biomass rather than grain quality; thus, cow manures, which are readily supplied from livestock farmers, tend to be applied excessively as a substitute for chemical fertilizer (Hara *et al.,* 2009). Excessive application of manure can pollute surface water and groundwater (Abe *et al.,* 2016; Moore *et al.,* 1995), cause water eutrophication (Daniel *et al.,* 1994), and endanger human health (Nishikawa *et al.,* 2012). Thus, it is necessary to assess environmental impacts for an appropriate application of manure in WCR cultivation.

This chapter aims to assess the NPK balances in actual paddy fields where WCR was cultivated under different manure and chemical fertilizer application. The assessment clarified differences of NPK balances between different methods of manure and chemical application. Section 3.2 shows nutrient flow associated with rice production. Section 3.3 presents fields information, application methods of manure and chemical fertilizer, measurement of soil chemical properties, estimation of NPK uptake by WCR, and nutrient balance estimation. Section 3.4 shows the estimated N balance, P balance, and K balance. Section 3.5 discusses the three balances and the environmental impacts caused by the estimated balances. Finally, Section 3.6 concludes the main findings in this chapter.

3.2 Nutrient flow associated with rice production

There are two parts in nutrient flow associated with rice production—inputs and outputs. Fig. 3.1 shows N flow associated with rice production which is the main concept of input-output balance or residual in this study. The inputs include manure, chemical fertilizer, rain, irrigation, N_2 fixation whereas the outputs include uptake by crop. Mishima (2001) included non-utilized livestock wastes in the input part, and denitrification and the removed crop by-products in the output. Parameters are the same for P and K flows except for N_2 fixation in the inputs. The difference between inputs and outputs is expressed as residual values, which have potential to cause environmental pollution.

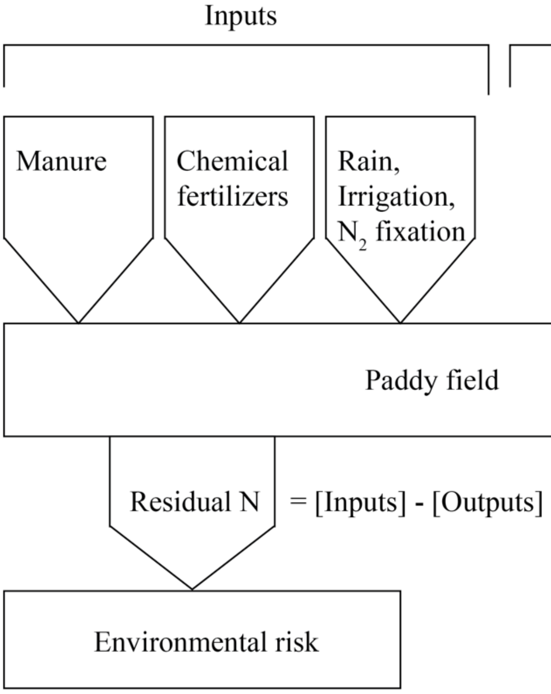

Figure 3.1 N flow associated with rice production.

3.3 Materials and methods

3.3.1 Fields information

Field surveys were conducted in the Itoshima region, Fukuoka Prefecture, Japan (33°30'N–33°34'N, 130°08'E–130°15'E). Eight fields were surveyed in both 2013 and 2014 and additional two fields were surveyed only in 2014 (i.e. 10 different fields and 18 observations in total). The surveyed fields were cultivated by five different farmers. The Tachiaoba cultivar (*Oryza sativa* L.) was planted in all surveyed fields. The transplanting period was from mid to late- June followed by heading from early to mid- September and harvest from early to mid- October.

Table 3.1 shows soil properties in the surveyed fields. The surveyed fields included two application methods of manure (M) alone (5 fields: field Nos. 1–5) and chemical fertilizer (CF) alone (5 fields: field Nos. 6–10). Soil types included light clay, sandy clay loam, and clay loam in M fields and sandy clay loam and sandy loam in CF fields. The ranges of CEC were 10.58–18.74 cmol kg^{-1} in M fields and 5.81–9.68 cmol kg^{-1} in CF fields. The cropping system was single WCR in all the surveyed fields.

3.3.2 Application methods of manure and chemical fertilizer

Table 3.2 shows the application methods of manure and chemical fertilizer. The amount of manure applied in M fields varied from 40 to 200 ton ha^{-1}. The applied manures were produced from different wastes — dairy cow waste for manure 1, and beef cow waste for manures 2 and 3 (Table 3.3). The moisture content varied from 37.6–71.3%. NH_4–N and NO_3–N were in the range of 0.3–5.6 g kg^{-1}, and 0 (not detected)–0.71 g kg^{-1}, respectively. TN, TP, and TK ranged from 12.0–29.5 g kg^{-1}, 3.1–14.8 g kg^{-1}, and 11.0–29.1 g kg^{-1}, respectively; they were highest in manure 2. C/N ratios were 29–30 in manure 1, 11 in manure 2, and 11–14 in manure 3. The estimated input amount of total nitrogen (TN), total phosphorus (TP) and total potassium (TK) from manure varied from 418–1211 kg ha^{-1}, 124–505 kg ha^{-1}, and 243–1073 kg ha^{-1}, respectively (Table 2). The application timings of manure were from February to April, and manure has been applied continuously for 4–8 years. Most farmers incorporated manure into soil with the depth between 0–15 cm using a rotary tiller, while one farmer incorporated manure into soil deeper than 20 cm by using a chisel plow before a rotary tiller. The input from chemical fertilizer were 50–82 kg ha^{-1}, 18–24 kg ha^{-1}, and 35–66 kg ha^{-1} for TN, TP, and TK, respectively. The application of chemical fertilizer was separated into basal application and topdressing except for field No. 10 where only basal application was carried out.

Table 3.1 Soil properties in the surveyed fields

Field No.	Application methods [a]	Clay (%)	Silt (%)	Sand (%)	Soil type [b]	CEC (cmol kg^{-1})
1	M	28	25	47	LiC	15.85
2	M	29	24	47	LiC	17.30
3	M	30	34	36	LiC	18.74
4	M	18	19	63	SCL	11.43
5	M	18	24	58	CL	10.58
6	CF	20	11	69	SCL	8.48
7	CF	23	18	59	SCL	9.68
8	CF	12	11	77	SL	5.81
9	CF	21	10	69	SCL	7.50
10	CF	16	20	64	SCL	9.10

[a] M = manure alone; CF = chemical fertilizer alone.

[b] LiC = light clay; SCL = sandy clay loam; SL = sandy loam.

3.3.3 Measurement of soil chemical properties

Soil samples were collected at five locations with a crisscross pattern in each surveyed field. The soil from 0–10 cm depth was sampled using a 5-cm diameter soil core sampler. Soil was sampled after harvest (8 December in 2013, 8 and 11 October in 2014). Soil samples were air-dried, and passed through a 2-mm sieve by a Soil Sample Crusher (SSM-1; Fujihira, Tokyo, Japan), then the five soil samples from each surveyed field were mixed into one composite. The composite samples were ground into fine particle using a sample mill (Cyclotec TC 1093, Fisher Scientific, Atlanta, Georgia). The samples were digested by the H_2SO_4-H_2O_2 Kjeldahl digestion method (Ohyama et al. 1991). TN and TP were measured by the indophenol method (Cataldo et al. 1974) and ascorbic acid method (Murphy and Riley 1962), respectively. Absorbance at 625 nm and 710 nm were determined for TN and TP, respectively, using a spectrophotometer (V-630; JASCO, Tokyo, Japan) with a rapid sampler (NQF-720; JASCO). TK was measured using atomic absorption spectrophotometry (Z-5300; Hitachi High-Technologies Co., Tokyo, Japan).

3.3.4 Estimation of NPK uptake by WCR

NPK uptake (kg ha^{-1}) was estimated by the product of TN, TP, or TK contents and dry matter weight of WCR. Straw weight and grain head weight in each surveyed field were estimated by quadrat sampling of 60 hills. Of these, 30 hills were manually harvested in each of the two plots located in a diagonal direction across the field on 17 October in 2013 and on 8 and 11 October in 2014. Straw and grain heads were separately weighed and measured for moisture content by oven-drying at 70 ºC for 48 h. During the above harvest, 10 continuous hills from two plots (20 hills in total) per field were harvested for the measurements of TN, TP, and TK contents of WCR. Samples were left to dry in the room and then were cut to separate straw and grain heads. Samples were milled using a cyclone sample mill (UDY Corporation, Colorado, USA). NPK contents in straw and grain heads were determined following the same procedure described in Section 3.3.3 for soil.

Table 3.2 Application methods of manure and chemical fertilizer

Year	Field No.	Application method [a]	Manure application [b]					Chemical fertilizer [b]				
								Basal application		Topdressing		Total [f]
			Total weight (ton ha^{-1}) [c]	TN-TP-TK (kg ha^{-1})	Manure [d]	Timing	Application history (years) [e]	TN-TP-TK (kg ha^{-1})	Date	TN-TP-TK (kg ha^{-1})	Date	TN-TP-TK (kg ha^{-1})
2013	1	M	200	809-209-1058	1	Feb.–Mar.	4	-	-	-	-	-
	2	M	200	809-209-1058	1	Feb.–Mar.	4	-	-	-	-	-
	3	M	40	510-250-522	2	Feb.–Mar.	8	-	-	-	-	-
	4	M	100	1211-505-1023	3	Mar.	6	-	-	-	-	-
	6	CF	-	-	-	-	-	56-24-46	2 June	18-0-13	16 Aug.	74-24-60
	7	CF	-	-	-	-	-	56-24-46	2 June	18-0-13	10 Aug.	74-24-60
	8	CF	-	-	-	-	-	56-24-46	2 June	18-0-13	9 Aug.	74-24-60
	9	CF	-	-	-	-	-	56-24-46	2 June	18-0-13	16 Aug.	74-24-60
2014	1	M	200	740-287-1073	1	mid-Apr.	4	-	-	-	-	-
	2	M	200	740-287-1073	1	mid-Mar.	4	-	-	-	-	-
	3	M	40	585-294-577	2	Mar.	8	-	-	-	-	-
	4	M	100	1045-310-608	3	late Mar.–mid-Apr.	6	-	-	-	-	-
	5	M	40	418-124-243	3	late Mar.	6	-	-	-	-	-
	6	CF	-	-	-	-	-	56-24-46	2 June	26-0-19	20 Aug.	82-24-66
	7	CF	-	-	-	-	-	56-24-46	2 June	26-0-19	20 Aug.	82-24-66
	8	CF	-	-	-	-	-	56-24-46	2 June	26-0-19	20 Aug.	82-24-66
	9	CF	-	-	-	-	-	56-24-46	2 June	26-0-19	20 Aug.	82-24-66
	10	CF	-	-	-	-	-	50-18-35	5 June	-	-	50-18-35

[a] M = manure alone; CF = chemical fertilizer alone. [b] Information on application amount and timing of manure and chemical fertilizer is approximation based on interviews with farmers. [c] Wet basis. [d] Refer to Table 3. [e] Based on interviews with farmers (as of October 2014). [f] The total values are not always equal to the summation of basal application and topdressing in the table due to rounding.

Table 3.3 Physicochemical properties of applied manures

Manure	Material		Moisture content (%)	NH_4–N (g kg^{-1}) [a]	NO_3–N (g kg^{-1}) [b]	TN (g kg^{-1}) [c]	TP (g kg^{-1}) [d]	TK (g kg^{-1}) [e]	TC (g kg^{-1}) [f]	C/N ratio
	Waste	Bulking material								
2013										
1	Dairy cow	Sawdust, Rice husk	66.3	0.7	0.02	12.0	3.1	15.7	354	30
2	Beef cow	Sawdust	51.5	5.6	0.01	26.3	12.9	26.9	295	11
3	Beef cow	Sawdust	37.6	1.3	0.05	19.4	8.1	16.4	266	14
2014										
1	Dairy cow	Sawdust, Rice husk	71.3	0.3	0.61	12.9	5.0	18.7	377	29
2	Beef cow	Sawdust	50.4	1.1	N.D [g]	29.5	14.8	29.1	313	11
3	Beef cow	Sawdust	44.7	2.5	0.71	18.9	5.6	11.0	211	11

[a] NH_4–N, [b] NO_3–N were measured for raw manure, hot water extracted, by indophenol method (Cataldo et al. 1974) and Cataldo method (Cataldo et al. 1975), respectively. [c] TN, [d] TP, and [e] TK were measured for dry manure, passed through a 1-mm sieve, following the same methods used on soil samples described in section 2.3. [f] TC was measured for dry ground samples using a total organic carbon analyzer (TOC-5000A; Shimadzu, Kyoto, Japan) and solid sample module (SSM-5000A; Shimadzu) in 2013 and a CHN coder (MT-5, Yanaco) in 2014. [g] N.D = Not detected.

3.3.5 Estimation of NPK balances

NPK balances in a paddy field were estimated for two periods: one-year period from 8 December in 2012 to 7 December in 2013 (estimation period 1) and the period between the soil sampling dates after harvest in 2013 (8 December) and after harvest in 2014 (8 and 11 October) (estimation period 2). NPK input-output balances were estimated for the estimation periods 1 and 2 using Eq. (1). On the other hand, soil NPK balances were estimated only for the estimation period 2 using Eq. (2) for field Nos. 1–4 and 6–9, where soil TN, TP, and TK after harvest were available both in 2013 and 2014.

$$\text{NPK input-output balances} = (N_f + N_m + N_{irr} + N_{pr} + N_{fix}) - (N_{up}) \quad (1)$$

Where N_f, N_m, N_{irr}, and N_{pr} represent N, P or K input from chemical fertilizer, manure, irrigation water, and precipitation, respectively; N_{fix} represents biological N_2 fixation; and N_{up} represents N, P or K uptake by WCR. NPK input-output balances estimate residual N, P or K which are the potential source to cause water pollution through leaching and surface runoff. Mishima (2001) defined the residual N, which included denitrification in the estimation, as the potential to cause environmental pollution.

N or P input from irrigation water was estimated by the product of water requirement at each growth stage of rice and TN or TP concentration in irrigation water at the corresponding period (Table 3.4). The water requirement used in the calculation was measured in agricultural research center in Fukuoka Prefecture (Jinnouchi and Iwabuchi 2000). The water requirement for puddling used in the calculation was 1,250 ton ha^{-1} (Mizuta 2001). The concentrations of TN and TP in irrigation water were measured in 2010 at Ikedagawa-bashi in Zuibaiji River (Iseri et al. 2013), which was one of the water sources for irrigation in the surveyed area. K input from irrigation water used in the calculation was 39.9 kg ha^{-1}

estimated by Mizuta (2001) using water requirement (Jinnouchi and Iwabuchi 2000) and K concentration in irrigation water surveyed in Fukuoka Prefecture.

N, P or K input from precipitation was estimated by the product of accumulated precipitation during the estimation period and TN, TP, or K ion concentration in precipitation. The precipitation used in the calculation were measured by AMeDAS at Maebaru, Fukuoka Prefecture, which was near the surveyed area. The concentrations of TN (1.11 mg L^{-1}) and TP (0.046 mg L^{-1}) in precipitation were measured between December in 1991 and January in 1992 in Dazaifu city, Fukuoka Prefecture (Matsuo et al. 1995). The season of the measurement didn't cover the estimation period of NPK balances, but we judged that the values were applicable because similar values were observed by 10-year measurement at Kusatsu city in Shiga Prefecture (TN: 1.05 mg L^{-1}, TP: 0.035 mg L^{-1}) (Kunimatsu and Sudo 1994). The concentrations of K ion used in the calculation were monthly average values (Table 3.5) measured in Fukuoka Prefecture, which were released as 5th survey dataset on Global Environmental database (http://db.cger.nies.go.jp/dataset/acidrain/ja/05/) by Center for Global Environmental Research (Environmental Laboratories Association 2011).

The value of N_2 fixation in paddy soil throughout the year, which included the fallow period, was not available. On the other hand, Hamada (1987) reported that N_2 fixation in paddy soil throughout the year was 15.5–27.9 kg ha^{-1} in the transplanted rice-tilled barely cropping system, which changed the application levels of N fertilizer and rice/barely straw. Hamada (1987) also reported that the N_2 was largely fixed during the rice growth period; N_2 fixation during the cultivation period of barely was as small as 1–3.4 kg ha^{-1}. Thus, we judged that using the value of N_2 fixation during the rice growth period is not likely to affect the estimation of N balance significantly. Then, we used 25.8 kg ha^{-1} as the input from N_2 fixation, which measured during the rice growing period under the condition that N supply was restricted (Ono and Koga 1984). The value of 25.8 kg ha^{-1} was in the range of 20–30 kg ha^{-1} reported by Smil (1999) and was close to 25 kg ha^{-1} used by Kirk et al. (2015). The data cited from other source and used in the calculation of NPK input are summarized in Table 3.6.

On the other hand, soil NPK balances were estimated by using the following Eq. (2).

$$\text{Soil NPK balances} = \text{Soil}_{2014} - \text{Soil}_{2013} \quad (2)$$

Where Soil NPK balances represent soil N, P or K balances in a paddy field during the estimation period; Soil_{2014} and Soil_{2013} represent the amount of soil TN, TP or TK after harvest in 2014 and after harvest in 2013, respectively. The amount of soil TN, TP or TK was calculated by the product of TN, TP or TK contents in soil, bulk density (1 g cm^{-3}), and soil depth (10 cm). All balances were calculated by using kg ha^{-1} unit. Positive and negative balances represent NPK accumulation in and NPK loss from a paddy field, respectively.

Table 3.4 Water requirement, and N and P concentration in irrigation water.

Irrigation timing	Water requirement (ton ha^{-1}) [a]	N concentration (mg L^{-1}) [b]	P concentration (mg L^{-1}) [b]
Puddling	1250 [c]	1.15	0.20
Tillering	3600	1.08	0.13
Midsummer drainage	60	0.50	0.04
Panicle development	4360	1.10	0.17
Booting	2220	1.07	0.08
Ripening	2920	1.30	0.06

[a] All water requirement data, except for booting stage, were cited from Junnouchi and Iwabuchi, 2000. [b] Source: Iseri et al. (2013). [c] Source: Mizuta, 2001.

Table 3.5 K concentration used in the calculation of K input from precipitation

Year	Month	K concentration (mg L^{-1})
2012	12	0.216
2013	1	0.150
	2	0.052
	3	0.159
	4	0.157
	5	0.031
	6	0.034
	7	0.032
	8	0.026
	9	0.040
	10	0.085
	11	0.252
	12	0.279
2014	1	0.248
	2	0.099
	3	0.148
	4	0.053
	5	0.033
	6	0.076
	7	0.037
	8	0.035
	9	0.066
	10	0.154

Source: Environmental Laboratories Association, 2011 (http://db.cger.nies.go.jp/dataset/acidrain/ja/05/)

Table 3.6 Cited data used in the calculation of NPK input-output balances.

Parameters	Values	References
Biological N_2 fixation (kg ha^{-1})	25.8	Ono and Koga 1984
Precipitation		
TN concentration (mg L^{-1})	1.11	Matsuo et al. 1995
TP concentration (mg L^{-1})	0.046	Matsuo et al. 1995
K concentration (mg L^{-1})	0.026–0.279	Environmental Laboratories Association 2011) (see Table 3.5)
Irrigation		
TN (kg ha^{-1})	16.3	See Table 3.4
TP (kg ha^{-1})	1.8	
TK (kg ha^{-1})	39.9	Mizuta (2001)

3.4 Results

3.4.1 N balance

Fig. 3.2(a) shows N input and output in the surveyed fields, where positive and negative values represent input in and output from a paddy field, respectively. The largest input was from manure (418–1211 kg N ha^{-1}), followed by fertilizer (50–82 kg N ha^{-1}) and biological N_2 fixation (25.8 kg N ha^{-1}). The input from precipitation was 19.7 kg N ha^{-1} in 2013 and 16.7 kg N ha^{-1} in 2014. The input from irrigation was 16.3 kg N ha^{-1}. The uptake by WCR, output from a paddy field, was larger in M (87–145 kg N ha^{-1}) than in CF (67–95 kg N ha^{-1}) (Table 3.7). Fig. 3.2(b) shows residual N, which was calculated as input-output balances using Eq. (1). M fields showed markedly large values ranging from 390–1174 kg N ha^{-1}, whereas CF fields showed small values ranging from 40–74 kg N ha^{-1}.

Table 3.8 shows soil TN after harvest in 2013 and 2014 used to estimate soil N balances by Eq. (2). In M fields, soil TN after harvest ranged from 2210–2610 kg N ha^{-1} in 2013 and 2448–2919 kg N ha^{-1} in 2014. The soil N balances were positive in three out of four fields (221–409 kg N ha^{-1}), whereas one field showed negative balance of –152 kg N ha^{-1}. In CF fields, soil TN after harvest were smaller than those in M fields, ranging from 980–1460 kg N ha^{-1} in 2013 and 1019–1492 kg N ha^{-1} in 2014. The soil N balances were positive in three fields (39–89 kg N ha^{-1}), whereas one field showed negative balance of –84 kg N ha^{-1}.

Table 3.7 NPK uptake by WCR

Fields No.	Application method [a]	NPK uptake by WCR (kg ha^{-1}) N	P	K
2013				
1	M	121	25	194
2	M	120	23	166
3	M	143	27	209
4	M	99	19	124
6	CF	95	24	108
7	CF	83	23	104
8	CF	73	19	99
9	CF	72	23	92
2014				
1	M	89	20	146
2	M	122	24	220
3	M	145	24	187
4	M	123	31	171
5	M	87	26	116
6	CF	67	19	83
7	CF	81	24	103
8	CF	81	22	103
9	CF	70	25	103
10	CF	69	19	94

[a] M = manure alone; CF = chemical fertilizer alone.

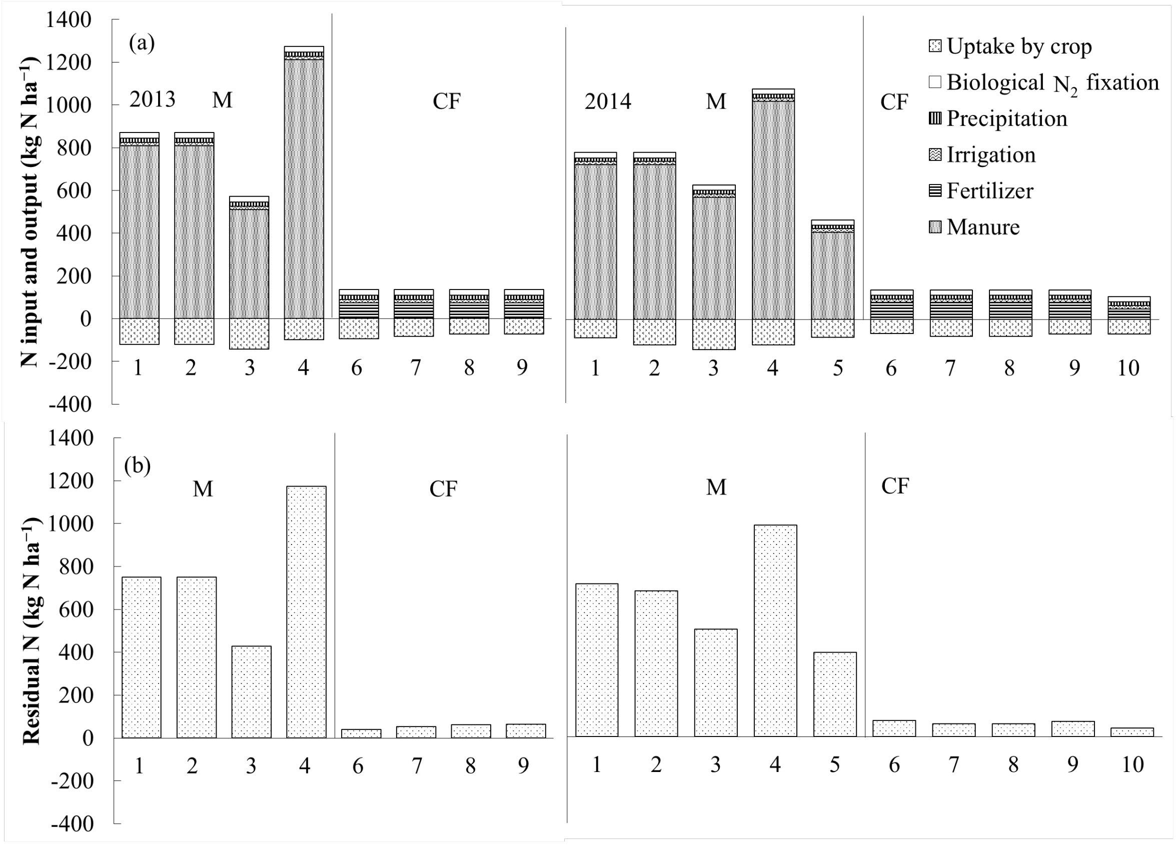

Figure 3.2 N input-output (a) and residual N (b). The values of input from manure, fertilizer, irrigation, precipitation, and biological N_2 fixation were taken positive, and the values of uptake by WCR were taken negative. Residual N was calculated as input-output balances using Eq. (1).

Table 3.8 TN, TP and TK in soil after harvest and soil NPK balances

Fields No.	Application method [a]	Soil after harvest in 2013 (kg ha^{-1})			Soil after harvest in 2014 (kg ha^{-1})			Soil NPK balances (kg ha^{-1}) [b]		
		TN	TP	TK	TN	TP	TK	N	P	K
1	M	2210	1583	3963	2495	1690	3841	285	107	−122
2	M	2510	1510	3895	2919	1541	3803	409	31	−92
3	M	2610	1841	2964	2831	1893	3345	221	52	381
4	M	2600	1600	3060	2448	1522	3140	−152	−78	80
6	CF	1460	740	2238	1376	805	2321	−84	65	83
7	CF	1403	809	2851	1492	794	3126	89	–15	275
8	CF	1000	545	1737	1076	535	1724	76	–10	−13
9	CF	980	786	2204	1019	725	2360	39	–61	156

[a] M = manure alone; CF = chemical fertilizer alone.

[b] Soil NPK balances = $Soil_{2014}$ – $Soil_{2013}$ (Eq. (2)).

3.4.2 P balance

Fig. 3.3(a) shows P input and output in the surveyed fields. The largest input was from manure (124–505 kg P ha^{-1}), followed by fertilizer (18–24 kg P ha^{-1}) and irrigation (1.8 kg P ha^{-1}). The input from precipitation was 0.8 kg P ha^{-1} in 2013 and0.7 kg P ha^{-1} in 2014. The uptake by WCR was similar between M (19–31 kg P ha^{-1}) and CF fields (19–25 kg P ha^{-1}) (Table 3.7). M fields showed markedly large residual P ranging from 100–489 kg P ha^{-1}, whereas CF fields showed small values ranging from 1–8 kg P ha^{-1} (Fig. 3.3(b)).

Table 3.8 shows soil TP after harvest in 2013 and 2014 used to estimate soil P balances by Eq. (2). In M fields, soil TP after harvest ranged from 1510–1841 kg P ha^{-1} in 2013 and 1522–1893 kg P ha^{-1} in 2014. The soil P balances were positive in three out of four fields (31–107 kg P ha^{-1}), whereas one field showed negative balance of –78 kg P ha^{-1}. In CF fields, soil TP after harvest were smaller than those in M fields, ranging from 545–809 kg P ha^{-1} in 2013 and 535–805 kg P ha^{-1} in 2014. The soil P balances were negative in three out of four fields (−61 to −10 kg P ha^{-1}) whereas one field showed positive balance of 65 kg P ha^{-1}.

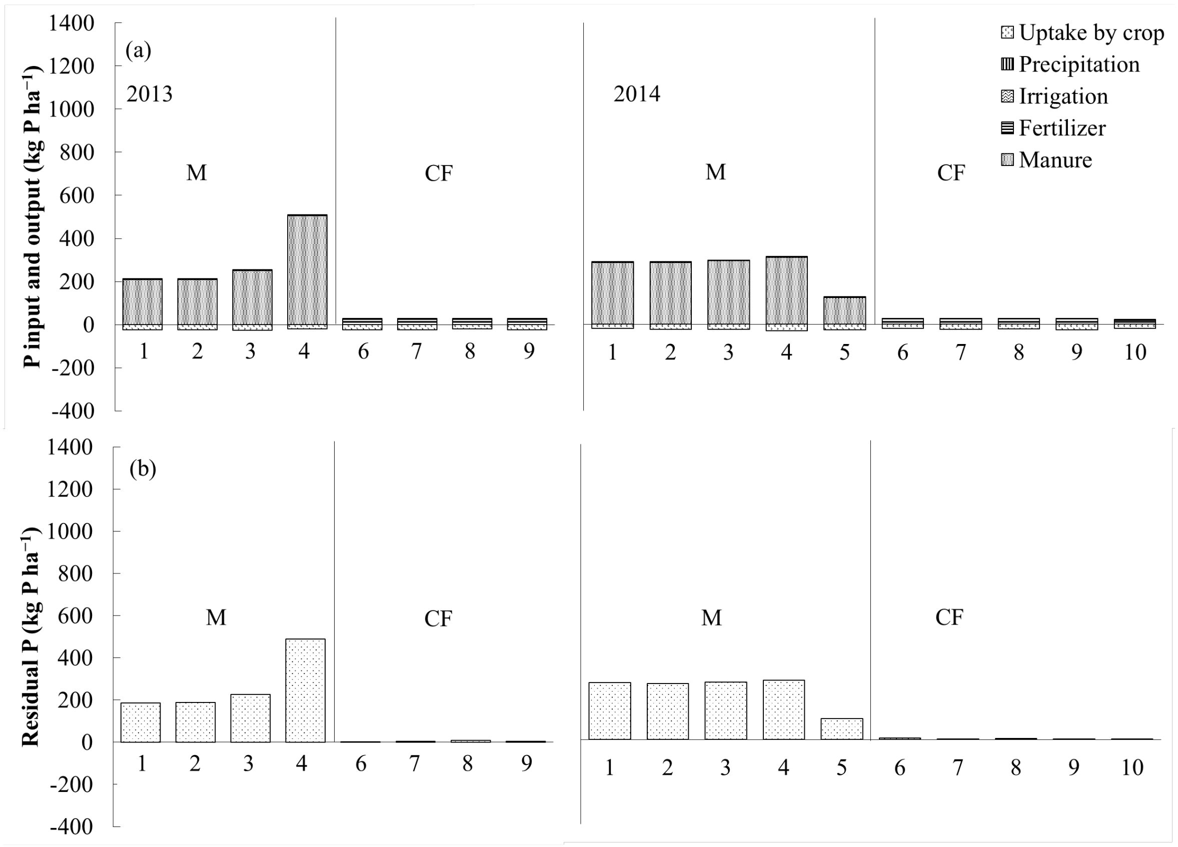

Figure 3.3 P input-output (a) and residual P (b). The values of input from manure, fertilizer, irrigation, and precipitation were taken positive, and the values of uptake by WCR were taken negative. Residual P was calculated as input-output balances using Eq. (1).

3.4.3 K balance

Fig. 3.4(a) shows K input and output in the surveyed fields. The largest K input was from manure (243–1073 kg K ha^{-1}), followed by fertilizer (35–66 kg K ha^{-1}), and irrigation (39.9 kg K ha^{-1}). The input from precipitation was 1.4 kg K ha^{-1} in 2013 and 1.1 kg K ha^{-1} in 2014. The uptake by WCR was larger in M (116–220 kg K ha^{-1}) than CF fields (83–108 kg K ha^{-1}) (Table 3.7). M fields showed markedly large residual K ranging from 168–968 kg K ha^{-1}, whereas CF fields showed small values ranging from −18 to 24 kg K ha^{-1} (Fig. 3.4(b)).

Table 3.8 shows soil TK after harvest in 2013 and 2014 used to estimate soil K balances by Eq. (2). In M fields, soil TK after harvest ranged from 2964–3963 kg K ha^{-1} in 2013 and 3140–3841 kg K ha^{-1} in 2014. The soil K balances were positive in two fields (80 and 381 kg K ha^{-1}), whereas they were negative in the other two fields (−122 and −92 kg K ha^{-1}). In CF fields, soil TK after harvest had smaller values than those in M fields, ranging from 1737–2851 kg K ha^{-1} in 2013 and 1724–3126 kg K ha^{-1} in 2014. The soil K balances were positive in three out of four fields (83–275 kg K ha^{-1}), whereas one field showed a negative balance of −13 kg K ha^{-1}.

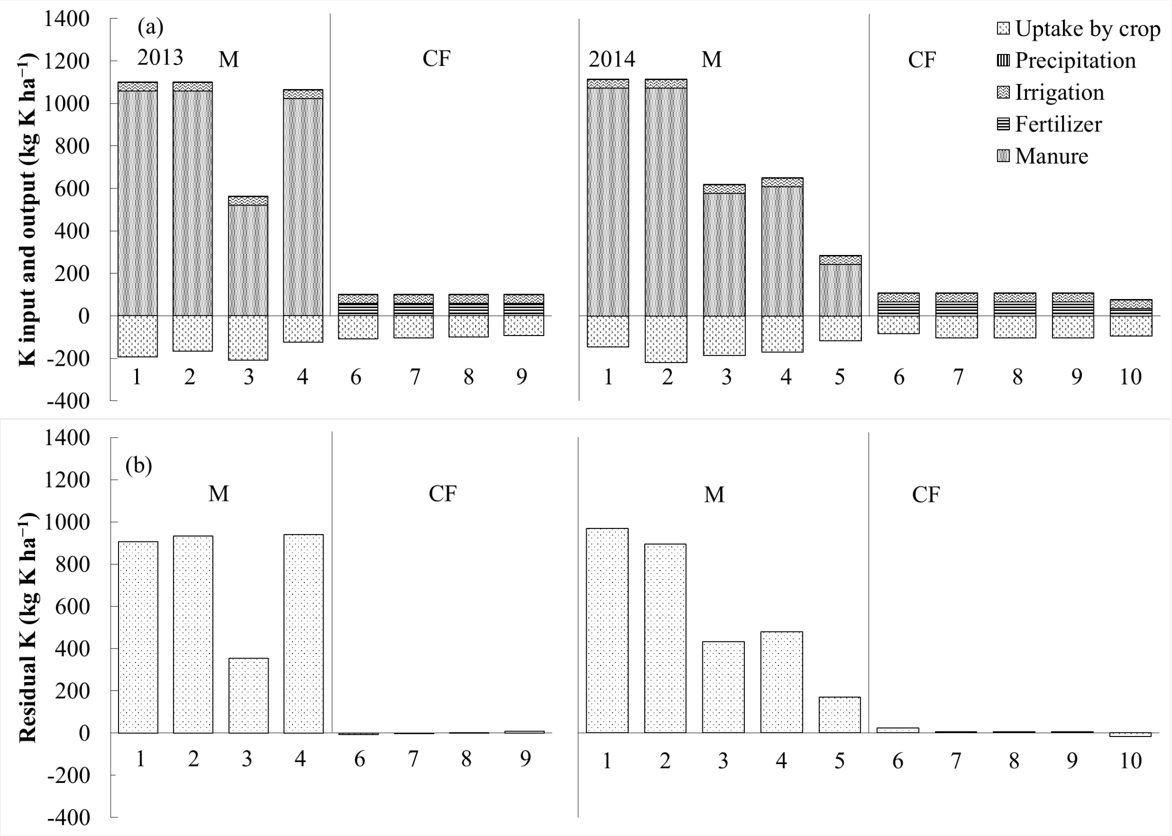

Figure 3.4 K input-output (a) and residual K (b). The values of input from manure, fertilizer, irrigation, and precipitation were taken positive, and the values of uptake by WCR were taken negative. Residual K was calculated as input-output balances using Eq. (1).

3.5 Discussion

3.5.1 N balance

Excessive TN input from manure (418–1211 kg N ha^{-1}) (Table 3.2) was 3.6 to 12.2 times TN uptake by WCR (87–145 kg N ha^{-1}) (Table 3.7) and corresponded to 20–47% of soil TN amount (2448–2919 kg N ha^{-1}) (Table 3.8). The excessive input contributed large residual N ranging from 390–1174 kg N ha^{-1} (Fig. 3.2(b)). In M fields, these excessive amounts of manure have been applied continuously for 4–8 years. Continuous application of manure increases the amount of N mineralized for one year because of the fractions mineralized from manure applied in the previous years. Shiga et al. (1985) estimated that the amount of N mineralized for one year was about one-third of TN input from manure applied in the year when fermented cow manure (TN: 27.2 g kg^{-1}, C/N ratio: 9.5) has been applied continuously for five years. One-third of TN input from manure corresponded to 139–404 kg N ha^{-1} in this study, which was 27–305 kg N ha^{-1} more than N uptake by WCR. This excessive inorganic N can cause environmental pollution through leaching and surface runoff. The rest of two-third of TN input from manure (279–807 kg N ha^{-1}) can be potential amount of TN accumulated in a paddy field. The accumulated N in a paddy field can cause environmental pollution through surface runoff. Abe et al. (2016) revealed through a long-term field experiment (1976–2006) that continuous application of excessive manure (110 kg N ha^{-1} year^{-1}, 180 kg P_2O_5 ha^{-1} year^{-1}, 320 kg K_2O ha^{-1} year^{-1}) substantially increased soil TC and TN, resulting in increased chemical oxygen demand concentration in paddy surface water compared to the inorganic fertilizer treatment.

Residual N in CF fields was 40–74 kg N ha^{-1} (Fig. 3.2(b)), which was markedly smaller than those in M fields. Estimated loss of N from fertilizer (50–82 kg N ha^{-1}) was 32–52 kg

N ha^{-1} when using 36% as N recovery rate of chemical fertilizer by rice crop (Cassman et al. 1993). Thus, the estimated residual N probably represented typical loss caused by the application of chemical fertilizer.

Positive and negative soil N balances shown in Table 3.8 represent N accumulation in and N reduction from a paddy field, respectively. Although larger residual N (input-output balances) (Fig. 3.2(b)) was expected to have more N accumulation, a correlation between residual N and soil N balances was not significant (r= 0.208, P = 0.621). Possible reasons for the correlation being not significant were because soil N balances estimated using Eq. (2) can include errors generated by estimation error of soil TN and the same soil bulk density (1 g cm^{-3}) assumed in all the surveyed fields. Soil TN estimated in this study from five samples collected in a paddy field can involve estimation error of 16% at the probability level of 95% (Yanai et al. 2008). It is possible that soil bulk densities were initially different among the surveyed fields and changed after large amount of manure was applied continuously. Abe et al. (2016) have showed through a long-term field experiment (1976–2006) that bulk densities became 0.74, 1.06, and 1.18 g cm^{-3} in 2016 under farmyard manure, inorganic fertilizer, and unfertilized control treatments, respectively. On the other hand, the trend that positive soil N balances were markedly larger in M fields (Nos. 1–3: 221–409 kg N ha^{-1}) than CF fields (Nos. 7–9: 39–89 kg N ha^{-1}) implied that large amount of manure application accumulated N in M fields.

3.5.2 P balance

Excessive TP input from manure (124–505 kg P ha^{-1}) (Table 2) was 4.8 to 26.6 times TP uptake by WCR (19–31 kg P ha^{-1}) (Table 3.7) and corresponded to about 13–32% of soil TP amount (1510–1893 kg P ha^{-1}) (Table 3.8). The excessive input contributed large residual P ranging from 100–489 kg P ha^{-1} (Fig. 3.3(b)). Eghball and Power (1999) reported through four-year experiment that manure application based on N removal of corn, in which available P input from the manure was beyond corn requirement, increased the soil P level. Ito et al. (2005) showed that available phosphate in soil after rice cultivation significantly increased compared with that before cultivation, when poultry manure was applied based on N requirement of rice. P is prone to accumulating in the soil surface due to low mobility in the soil (Abe et al. 2016). Thus, we judged that residual P estimated in this study contributed to accumulation of TP in soil. The accumulated P in a paddy field pollutes surface water and increases effluent loads from a paddy field (Abe et al. 2016). In CF fields, small residual P ranging from 1–8 kg P ha^{-1} (Fig. 3.3(b)) indicated that P input-output was almost balanced.

Soil P balances were not significantly correlated with residual P (r= 0.266, P = 0.524) probably because of the estimation error of soil TP and the assumption of the same bulk density as mentioned in the estimation of soil TN balances. On the other hand, the trend that soil P balances were positive more in M fields (Nos. 1–3: 31–107 kg P ha^{-1}) than in CF fields (No. 5: 65 kg P ha^{-1}) implied that large amount of manure application accumulated P in M fields.

3.5.3 K balance

Excessive TK input from manure (243–1073 kg K ha^{-1}) (Table 2) was 2.1 to 8.3 times TK uptake by WCR (116–220 kg K ha^{-1}) (Table 3.7) and corresponded to 17–33% of soil TK amount (2964–3963 kg K ha^{-1}) (Table 3.8). The excessive input contributed large residual K ranging from 168–968 kg K ha^{-1} (Fig. 3.4(b)). Excessive K input from manure increases soluble K in paddy surface water and becomes effluent loads from a paddy field (Abe et al. 2016). In addition, K is prone to leaching because of its high mobility in the soil (Abe et al. 2016). Thus, we judged that residual K estimated can cause K loss which could be released to the environment through surface runoff and leaching. In CF fields, small residual K ranging from −18 to 24 kg K ha^{-1} (Fig. 3.4(b)) indicated that K input-output was approximately balanced.

Soil K balances were not significantly correlated with residual K (r= −0.516, P = 0.191) probably because the estimation error of soil TK and the assumption of the same bulk density as mentioned in the estimation of soil TN balances. M fields didn't show a trend of TK accumulation, unlike the cases of TN and TP.

Surveyed fields in this study included sandy clay loam and sandy loam and had small CEC mainly in CF fields (Table 3.1). This soil condition was assumed to involve more leaching loss, while soil N, P, and K balances didn't show consistent positive correlations with CEC.

3.5.4 Measures to reduce environmental impacts

Residual N, P, and K estimated in this study ranged from 390–1174 kg N ha^{-1}, 100–489 kg P ha^{-1}, and 168–968 kg K ha^{-1} in M fields, respectively, which were markedly larger than those in CF fields: 40–74 kg N ha^{-1}, 1–8 kg P ha^{-1}, and −18 to 24 kg K ha^{-1}. This large amount of residual NPK can cause water pollution through leaching and surface runoff.

One of the measures to reduce environmental impacts is to adjust the application amount of manure to meet nutrient requirement of crop. The form of N in cow manure was largely organic (Table 3.3). Thus, the fraction of N mineralized from manure applied in the previous years (residual effects of manure) needs to be taken into consideration when manure was applied continuously. The mathematical model to predict N mineralized from organic materials, which was employed by Shiga et al. (1985) under yearly application of organic matters for 50 years, can be used for estimating available N including the residual effects of manure.

On the other hand, because N/P ratio of manure is smaller than that of crop uptake (Tables 3.2 and 3.7), P input becomes excessive when manure is applied to meet crop N requirement (Ito et al. 2005). In this study, residual N in M fields was on average 3 times larger than residual P. However, the environmental standard of TP for lakes and marshes is less than 0.005 mg/L, which is one-twentieth of the standard of TN (0.1 mg/L) according to environmental standards on the conservation of the living environment (Takeda 2001). Thus, environmental impacts caused by excessive TP input seems to be more serious.

Ito et al. (2005) showed that when poultry manure was applied to meet standard application amount of phosphate on available phosphate basis, with additional N as fertilizer, rice yields were comparable to those for N-based application and the accumulation of available P in soil was restrained. Eghball and Power (1999) found that available soil P level was kept the original level after beef cattle manure was applied for four years to meet P requirement of corn on available P basis. Low level of available soil P reduces the risk of P runoff. The P-based application (Eghball and Power 1999) also considered residual available P from manure applied in the previous years. Moreover, the P-based manure application, with additional N as fertilizer, produced grain yields similar to those for N-based manure application.

Thus, applying manure to meet crop requirement on available P basis, which considers residual effects of continuous application and compensates for shortage of N using fertilizer, is a possible measure to produce yields comparable to N-based manure application with low environmental impacts.

K is not listed in environmental standards on the conservation of the living environment (Takeda 2001), and thus K losses seem to be not serious in terms of environmental pollution. However, determining the application amount of manure to meet crop K requirement can also become important since natural resources of potash is limited (Maene 1995).

3.6 Conclusions

We assessed NPK balances in actual paddy fields where WCR was cultivated under different manure and chemical fertilizer applications, and concluded:

1) Large residual N, P and K were estimated in M (manure) fields: 390–1174 kg N ha^{-1}, 100–489 kg P ha^{-1}, and 168–968 kg K ha^{-1}, respectively.
2) Residual N, P and K in CF (chemical fertilizer) fields were 40–74 kg N ha^{-1}, 1–8 kg P ha^{-1}, and −18 to 24 kg K ha^{-1}, respectively.
3) Excessive application of manure beyond crop requirement resulted in large residual N, P and K, which can cause water pollution through leaching and surface runoff.
4) Positive trends of soil N and P balances in M fields implied that large amount of manure application accumulated N and P in the paddy fields.
5) Applying manure to meet crop requirement on available P basis, which considers residual effects of continuous application and compensates for shortage of N using fertilizer, is a possible measure to produce yields comparable to N-based manure application with low environmental impacts.

Chapter 4

Summary and Conclusions

This study was conducted to investigate the effects of different application methods of fertilizer and manure on soil chemical properties, yield, and NPK balances in WCR cultivation. The main findings in this study are mentioned below.

In Chapter 2, we investigated the effects of different application methods of fertilizer and manure on soil chemical properties and yield in WCR cultivation. Eight fields were surveyed in 2013 and 2014 with additional two fields added in 2014. The surveyed fields included two application methods of manure (M) alone, and chemical fertilizer (CF) alone. Soil samplings were conducted two times—before transplanting, and after harvest. The soil samples collected before transplanting were analyzed for available N at 4-week while those collected after harvest were analyzed for TN, TP, Ex. K, and K saturation degree. The results showed that the soil texture (clay plus silt percentage) partly affected the levels of TN, TP, Ex. K, and K saturation degree in M and CF fields. The results also suggested that manure application contributed to increases in TN, TP, Ex. K, K saturation degree, and available N. Relatively large negative values of yearly differences of available N in CF fields suggested a possible decrease in mineralizable part of soil TN in the WCR cultivation with CF alone, which needs to be clarified through long-term study. Significant relationships between potential N supply in soil and straw weight or yield of whole crop indicated that N mineralized from soil, which was enhanced by manure application, increased straw weight, resulting in an increase in yield of whole crop. However, the results above were caused probably by abundant amounts of manure application. In future research, nutrient balances in a paddy field need to be analyzed to determine an appropriate application amounts of manure considering the environmental impacts.

In Chapter 3, we assessed NPK balances in actual paddy fields where WCR is cultivated under different manure and chemical fertilizer applications. In this assessment, same surveyed fields as Chapter 2 were investigated. NPK balances were assessed by differences of NPK input in a paddy field minus NPK output from a paddy field (i.e., NPK input-output balances or residual NPK) and by differences in the amount of soil TN, TP and TK between after harvest in 2014 and after harvest in 2013 (i.e., soil NPK balances). Nutrient input included input from chemical fertilizer, manure, irrigation water, precipitation, and biological N_2 fixation (only for N balance). Nutrient output included nutrient uptake by WCR. Residual N, P and K, which were calculated as NPK input-output balances, were markedly large in M fields: 390–1174 kg N ha^{-1}, 100–489 kg P ha^{-1}, and 168–968 kg K ha^{-1}, respectively. Contrarily, residual N, P and K were small in CF fields: 40–74 kg N ha^{-1}, 1–8 kg P ha^{-1}, and −18 to 24 kg K ha^{-1}, respectively. Excessive application of manure beyond crop requirement resulted in large residual N, P and K, which can cause water pollution through leaching and surface runoff. Positive trends of soil N and P balances in M fields implied that large amount of manure application accumulated N and P in the paddy fields. Applying manure to meet crop requirement on available P basis, which considers residual effects of continuous application and compensates for shortage of N using fertilizer, is a possible measure to produce yields comparable to N-based manure application with low environmental impact.

Overall, the application of manure in the fields in the long term increased the level of soil chemical properties. The decline of TN level in fields where fertilizer was applied alone may suggest the possible decrease of mineralizable part of soil TN. However, long-term study is needed to verify this phenomenon. The excessive application of manure commonly raises concern over its effects on environment. The current study showed consistently large residual NPK in fields where manure was applied alone. This suggested that P-based manure application, which considers residual effects of continuous application and compensates for shortage of N using fertilizer, is a possible measure to produce equivalent yield, and reduce risks of environmental impacts.

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