

Effects of the Continuous Application of Rice Straw Compost and Chemical Fertilizer on Soil Carbon and Available Silicon under a Double Rice Cropping System in the Mekong Delta, Vietnam

Takeshi WATANABE^{1*}, Hong Man LUU² and Kazuyuki INUBUSHI^{1*}

¹ Crop, Livestock and Environment Division, Japan International Research Center for Agricultural Sciences (Tsukuba, Ibaraki 305-8686, Japan)

² Cuu Long Delta Rice Research Institute (Thoilai district, Can Tho city, Vietnam)

³ Graduate School of Horticulture, Chiba University (Matsudo, Chiba 271-8510, Japan)

Abstract

We conducted a series of field experiments to study the effects of rice straw compost (RSC) and chemical fertilizer application on soil carbon and silicon under a double rice cropping system for 25 crops successive in the Mekong Delta, Vietnam. The results showed that the continuous application of RSC (6 Mg ha⁻¹ as fresh weight for each crop) caused a higher yield and more available silicon than treatment without RSC. Available silicon in the surface (0 - 10 cm from the ground surface) soil was 36.3 to 38.7 mg Si kg⁻¹ in treatment with RSC, while it was 24.2 to 30.0 mg Si kg⁻¹ for treatment without RSC. Regardless the amount of chemical fertilizer applied, the rice yields for treatment without RSC were lower than those for treatment with RSC and entailed less chemical fertilizer. Moreover, RSC application used in combination with moderate doses of chemical fertilizer increased total carbon in the soil at a rate of 356 to 401 kg C ha⁻¹ year⁻¹. Our results suggested that Si availability in paddy soil must be maintained or increased in order to maintain rice yield, for which the application of rice straw compost offers an option. Our results also showed that the application of RSC increased total-C in the soil, suggesting that paddy fields can be used effectively for carbon sequestration.

Discipline: Soils, fertilizers and plant nutrition

Additional key words: carbon sequestration, soil fertility, sustainable land use

Introduction

The Mekong Delta is the largest rice-producing region in Vietnam, contributing more than 20 million tonnes of rice annually (General Statistical Office, Vietnam 2010). The soil of the Mekong Delta contains a relatively high amount of organic matter in tropical Asia (Kyuma 1985, National Institute for Soils and Fertilizers & Department of Science, Technology and Product Quality 2002). Rice straw can be used for many purposes such as roughage and litter for animal husbandry and horticulture. However, only part of the rice straw is now being used for such purposes in the Mekong Delta. At present, many farmers in the Mekong Delta simply burn rice straw in the field or incorporate it into the field after harvest, while some rice straw is shipped for mushroom cultivation (Tran et al. 2014). Annual rice straw production

in the Mekong Delta is estimated to be nearly 20 million tonnes based on a harvest index of about 0.5 for modern high yielding rice varieties (General Statistical Office, Vietnam 2010). This resource is huge, even if some rice straw must be returned to paddy fields for sustainable rice production. When rice straw becomes a practical source for bio-fuel production, the Mekong Delta could supply huge amounts of this biomass resource for industry in the future. Thus, the best usage of rice straw should be explored.

The continuous burning or removing of rice straw from the field may reduce the content of soil organic matter. Moreover, intensified land use combined with a reduced supply of nutrient-laden sediments caused by the improved control of floodwater from the Mekong River may exacerbate the decrease in soil fertility. Hence, there is a need to develop management practices that maintain

*Corresponding author: e-mail watatake@affrc.go.jp
Received 21 January 2016; accepted 20 October 2016.

or enhance soil fertility for a longer term. For this reason, we have studied the effects of the continuous application of rice straw compost (RSC) on rice yield in alluvial soil in Vietnam's Mekong Delta (Watanabe et al. 2009, 2013), and our results showed that RSC application with reduced rates of chemical fertilizer application can maintain rice productivity for a longer term than under conventional fertilization practices. Furthermore, our results suggested that the continuous removal of rice straw may reduce silicon (Si) availability in the soil, and that the deficiency of Si appears faster than that of other nutrients (N, P, K, Ca, Mg, Fe, Zn, Mn, Cu) in the field, thereby decreasing rice productivity.

The objective of this study was to evaluate the effects of the continuous application of RSC on total carbon and available Si in the soil under the double rice cropping system in the Mekong Delta, Vietnam.

Materials and methods

1. Experimental design

This experiment was conducted in an experimental field at the Cuu Long Delta Rice Research Institute (CLRRI), Thoilai district, Can Tho city, Vietnam (10°08'N, 105°35'E). The soil of the experimental field is Typic Humaquept (U.S. Department of Agriculture and National Resources Conservation Service 2014). Table 1 lists certain soil properties for a comparison with other Asian paddy soils (Watanabe et al. 2009, 2013). Long-term studies on the effects of rice straw compost application were initiated in the wet season of 2000. Rice crop has traditionally been cultivated twice a year in the wet and dry seasons. The wet season crop was planted in April or May, followed by the dry season crop in November or December.

This experiment was conducted with the seven

treatments described below arranged in a randomized block design with three replications from the 2009/2010 dry season to the 2012/2013 dry season, as shown in Table 2. Through the experimental period, the variety OM4900 was directly seeded at the rate of 100 kg ha⁻¹ by using a row seeder. Each plot covered an area of 30 m² (5 × 6 m). The F100C- treatment was based on conventional farming practices in the Mekong Delta region. RSC prepared solely from rice straw harvested from the experimental field and phosphorus (P) fertilizer (single superphosphate) were applied on the surface of soil, and then mixed into the soil down to a depth of about 10 cm by using spades before sowing. N fertilizer (urea) was split into three applications, with equivalent thirds broadcasted at 10, 20 and 30 days after sowing (DAS), respectively. The potassium (K) fertilizer (potassium chloride) was split into two applications: half of which was broadcasted at 10 DAS and the remainder at 30 DAS. F0C-, F0C+, F40C+, F60C+, and F100C- treatments were initiated in the wet season 2000. Before the 2009/2010 dry season, the F40C- and F60C- treatment plots were fertilized with RSC (6 Mg ha⁻¹) + NPK (16:6:6 for the wet season, 20:6:6 for the dry season N:P₂O₅:K₂O kg ha⁻¹) and RSC (6 Mg ha⁻¹) + NPK (64:24:24 for the wet season, 80:24:24 for the dry season N:P₂O₅:K₂O kg ha⁻¹), respectively. At harvest, the rice straw was cut at about 5 cm above ground level in all plots, removed from the field, heaped up and then treated with water. Every three to five days, the heap was turned over and watered. The heap became RSC after two months. The average dry matter content of RSC was 197 g kg⁻¹ (and ranged from 170 to 210, the same hereinafter). The average C, N, P, K and Si concentrations in dry matter were 315 g kg⁻¹ (304 to 332), 19.8 g kg⁻¹ (17.2 to 23.0), 2.4 g kg⁻¹ (2.3 to 2.6), 10.1 g kg⁻¹ (5.3 to 14.9) and 97.0 g kg⁻¹ (96.9 to 97.0), respectively. Hence, 6 Mg ha⁻¹ (wet weight basis) of RSC

Table 1 Properties of surface soil (0 - 10 cm) of the experimental field¹ and paddy soils in tropical Asia²

	Soil of the experimental field ¹	Paddy soils in the tropical Asia
pH (H ₂ O)	5.3	6.0
Bulk density	0.96 ³	no-data
Total-C (g kg ⁻¹)	35.1	14.1
Total-N (g kg ⁻¹)	3.3	1.3
Available-P (mg kg ⁻¹)	240 ⁴	38 ⁵

¹ : Measured in August 2000 except for bulk density. Watanabe et al. 2009, 2013

² : Kyuma, 1985 (n=410)

³ : Measured in March 2007.

⁴ : Measured by the Truog method.

⁵ : Measured by the Bray No. 2 method.

per season was equivalent to 372 kg ha⁻¹ as C, 23.5 kg ha⁻¹ as N, 6.6 kg ha⁻¹ as P₂O₅ (2.9 kg ha⁻¹ as P), 21.2 as K₂O (17.6 kg ha⁻¹ as K) and 120 kg ha⁻¹ as Si, respectively.

2. Measurement of grain yield, rice straw production, total carbon and available Si in the soil

We determined the grain yields and rice straw production at harvest for four crops from the 2012 wet season to the 2013/2014 dry season. Grain yield was based on a harvested area of 2.5 × 2 m in each replication. The rice straw was sampled from four sampling areas (each 0.5 × 0.5 m) within each plot (n = 3).

Available Si was determined for soil collected at 0 - 10 cm and 10 - 20 cm from the ground surface after harvest of the 2012/2013 dry season crop. The soil samples were air dried, passed through a sieve with a 2-mm mesh, then incubated under a flooded condition at 40°C for one week. Water-soluble Si was determined using a colorimetric method (Takahashi 1986).

Surface soil (0 - 10 cm) samples from the experimental plots were periodically collected following initiation of the experiment in 2000. Total carbon (total-C) was determined by a NC analyzer (Sumigraph NC-220F; Sumika Chemical Analysis Service, Osaka, Japan). As the treatment was changed to F40C⁻ and F60C⁻ from the 2009/2010 dry season, both treatments were excluded from the analysis of total-C.

Statistical analysis of the data was conducted using software (JMP 9.0.2, SAS Institute Inc.). Differences in rice yields and available Si in the soil among the treatments were assessed with Tukey's test. Significance

of the change in total carbon in the surface soil (0 - 10 cm) was assessed by the t-test regarding whether the slopes of regression lines for total carbon concentrations during the years since the start of the experiment differed significantly from zero.

Results

The rice yields for the F40C⁺ and F60C⁺ treatments were significantly higher than those for the other treatments in the four cropping seasons, except for F60C⁻ in the 2012/2013 dry season, as shown in Fig. 1. The average yields for the F40C⁺ treatment were 7.63, 7.36, 4.60 and 4.65 Mg ha⁻¹ for the 2011/2012 dry season, 2012/2013 dry season, 2012 wet season, and 2013 wet season, respectively. The average yields for the F60C⁺ treatment were 7.48, 7.18, 4.74 and 4.76 Mg ha⁻¹ for the 2011/2012 dry season, 2012/2013 dry season, 2012 wet season, and 2013 wet season, respectively. The yields of the four crops under F0C⁺ treatment were significantly higher than under F0C⁻ treatment. The average yields for the F0C⁺ treatment were 6.17, 5.83, 3.63 and 3.61 Mg ha⁻¹ for the 2011/2012 dry season, 2012/2013 dry season, 2012 wet season, and 2013 wet season, respectively. The average yields for the F0C⁻ treatment were 5.36, 5.12, 2.36 and 2.32 Mg ha⁻¹ for the 2011/2012 dry season, 2012/2013 dry season, 2012 wet season, and 2013 wet season, respectively. In addition, the yields for F0C⁺ were not significantly different from those for F40C⁻, F60C⁻ and F100C⁻ for the two wet seasons.

The average available Si concentrations in the

Table 2 Rice straw compost and chemical fertilizer application rates (kg ha⁻¹) since the wet season in 2000

Season	Rice straw compost (RSC)		Chemical fertilizer ¹					
			N		P ₂ O ₅		K ₂ O	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
F0C ⁻	0	0	0	0	0	0	0	0
F0C ⁺	6000	6000	0	0	0	0	0	0
F40C ⁻²	0	0	32	40	12	12	12	12
F40C ⁺	6000	6000	32	40	12	12	12	12
F60C ⁻²	0	0	48	60	18	18	18	18
F60C ⁺	6000	6000	48	60	18	18	18	18
F100C ⁻	0	0	80	100	30	30	30	30

¹: Chemical fertilizer application rate for each crop. N, P₂O₅ and K₂O were applied as urea, single superphosphate, and potassium chloride, respectively. RSC and single superphosphate were applied before sowing. Urea was split into three applications and equivalent thirds broadcasted at 10, 20 and 30 days after sowing (DAS). Potassium chloride was split into two applications and half was broadcasted 10 and 30 DAS.

²: Before the 2009/2010 dry season, the F40C⁻ and F60C⁻ treatment plots were fertilized with RSC (6 Mg ha⁻¹) + NPK (16:6:6 for the wet season, 20:6:6 for the dry season N:P₂O₅:K₂O kg ha⁻¹) and RSC (6 Mg ha⁻¹) + NPK (64:24:24 for the wet season, 80:24:24 for the dry season N:P₂O₅:K₂O kg ha⁻¹), respectively.

surface (0 - 10 cm) layer of the plots with RSC (37.8, 40.4 and 38.2 mg Si kg⁻¹ for F0C+, F40CL and F60C+, respectively) were higher than those without RSC (25.2, 28.5, 31.3 and 28.4 mg Si kg⁻¹ for F0C-, F40C-, F60C- and F100C-, respectively), as shown in Fig. 2. The lowest and second lowest concentrations were observed in the F0C- and F100C- treatments, respectively, where RSC had not been applied since the wet season in 2000. No significant difference was found in available Si concentrations (25.0 to 28.2 mg Si kg⁻¹ in dry soil on average) among the treatments for sub-surface (10 - 20 cm) soil samples.

Fig. 3 shows changes in total-C in the surface (0 - 10 cm) soil. Based on the slopes of regression lines, total-C in the surface layer was found to be significantly increased in the F40C+ and F60C+ treatments (0.42 g kg⁻¹ year⁻¹ and 0.37 g kg⁻¹ year⁻¹, respectively), but significantly decreased in the F0C- treatment (0.17 g kg⁻¹ year⁻¹). No annual significant change in total-C was detected in the F0C+ and F100C- treatments.

Discussion

Regardless the amount of chemical fertilizer application, the yield data indicated that as compared to conventional fertilization practices, the application of RSC along with a reduced amount of chemical fertilizer maintained higher rice yields (Fig. 1). This result is in agreement with that reported earlier (Watanabe et al. 2013). Our previous report (Watanabe et al. 2013) showed that the Si concentration of rice straw in the F100C- treatment was significantly lower than that in the F0C+, F40C+ and F60C+ treatments; and that the Si concentrations of rice straw in all the treatments averaged 42.9 g kg⁻¹, lower than the proposed critical Si concentration of 50 g kg⁻¹ (Dobermann and Fairhurst 2000, Barbosa-Filho et al. 2001) or the typical concentrations in rice straw collected in Japan (Fujii 2002). Although there is room for discussion regarding whether a rice Si concentration of less than 50 g kg⁻¹ was really critical, rice plants in the experimental field might suffer from Si deficiency. Our previous report (Watanabe et al. 2013) suggested that the deficiency of Si appears

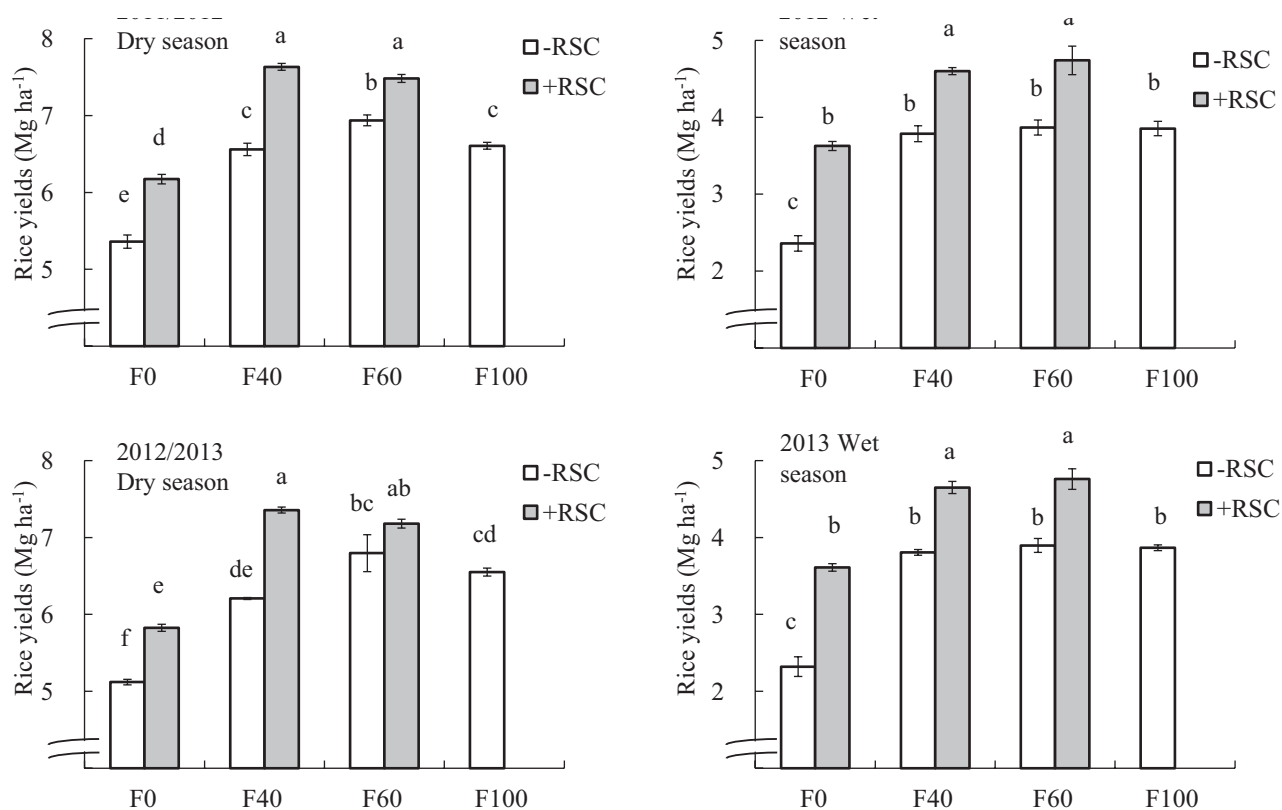


Fig. 1. Yields of four rice crops under different fertilizer management treatments.

Error bars are standard errors (n=3). Data with the same letter is not significantly different (Tukey $p < 0.05$). +RSC and -RSC indicate the application and non-application of rice straw compost, respectively.

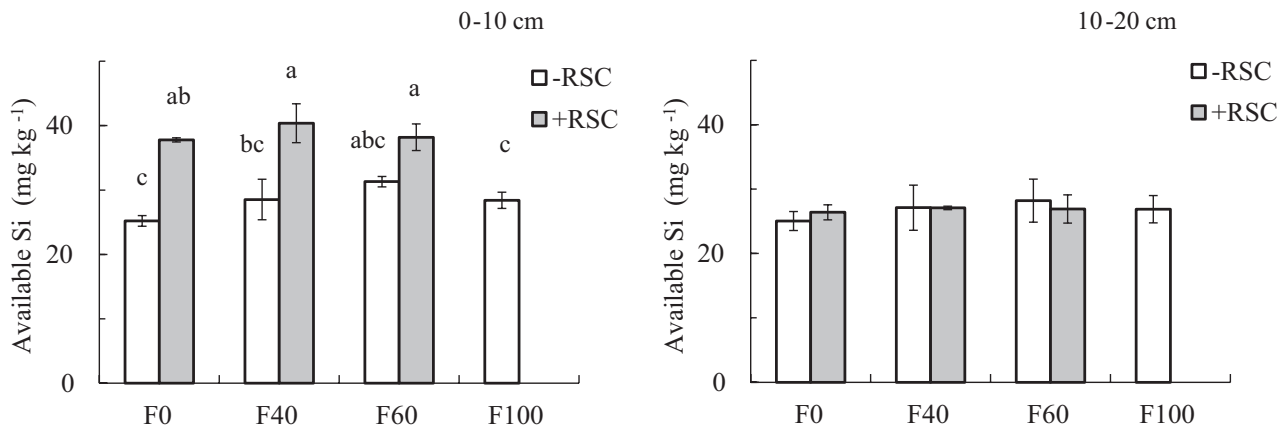


Fig. 2. Available silicon in the experimental paddy field following 25 seasons of rice cropping.

Error bars are standard errors (n=3). Vertical axis indicates available Si (mg) in air-dry soil (kg). Data with the same letter does not differ significantly (Tukey $p < 0.05$) (0-10 cm). There was no significant difference in available Si in the treatments of sub-surface (10-20 cm) soil samples. +RSC and -RSC indicate the application and non-application of rice straw compost, respectively.

faster than that of other nutrients (N, P, K, Ca, Mg, Fe, Zn, Mn, Cu) when rice straw is continuously removed from paddy fields in the Mekong Delta. Our data on available Si concentrations in the surface (0 - 10 cm) layer (Fig. 2) showed that the continuous application of RSC increased available Si in the paddy field. Therefore, we concluded that the continuous application of RSC maintained

available Si in the paddy soil, which contributed to higher yields than those from plots that did not receive RSC. This conclusion does not exclude the possibility that other unidentified mechanisms are involved in increasing rice yields when using RSC.

Phytoliths have been proposed as a major source of Si available to plants (Ma & Takahashi 1989, Wickramasinghe & Rowell 2006). A long-term trial conducted at Rothamsted Experimental Station revealed that annual straw exports from wheat fields reduce the amount of phytolith input to the soil, which decreases the bio-available Si in the soil (Guntzer et al. 2012). Moreover, plant-available Si in the surface soil with continuous rice straw application was found to be 1.25 times higher than that without application in a long-term trial with rice conducted at four experimental stations located in northern Japan (Kobayashi 2006). Our results agree with those of the previous reports. However, whether RSC has any difference as a source of Si for paddy rice compared to fresh rice straw or rice straw ash remains unclear. The amount of Si removed as rice straw from our field was 236 to 337 kg ha⁻¹ for the dry seasons and 203 to 320 kg ha⁻¹ for the wet seasons, as shown in Table 3. These amounts were calculated from the Si concentrations of rice straw in our previous report (Watanabe et al. 2013) and in biomass (rice straw) production. Furthermore, some Si must be removed as grain, although we could not calculate the amount due to a lack of data regarding Si concentrations in the grain. However, only 120 kg ha⁻¹ of Si were returned to our experimental field as RSC. Phutela and Sahni (2013) showed that fungi promote the solubilization of Si components in rice straw, which

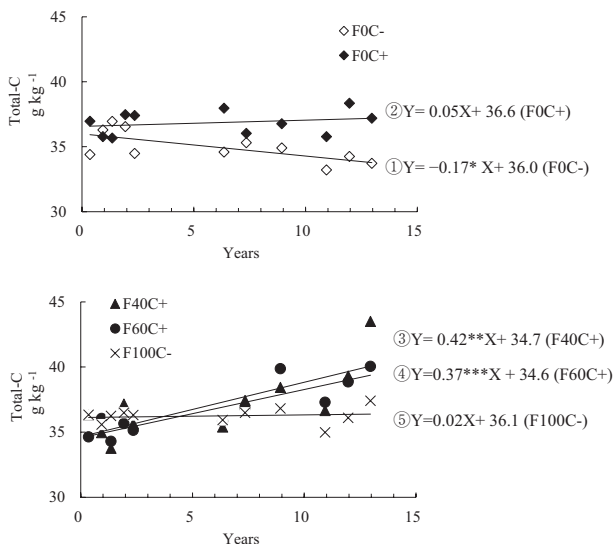


Fig. 3. Changes in total carbon (g kg⁻¹) in the soil (0-10 cm) in the experimental paddy.

X-axis indicates the year after March 1, 2000 when the field experiment started.

① to ⑤ indicate regression lines for F0C-, F0C+, F40C+, F60C+ and F100C-, respectively (see Table 2). *, ** and *** indicate that the slope was significantly different from 0 ($p < 0.05$, 0.01 and 0.001, respectively).

suggests that RSC may contain more plant-available Si. Conversely, making RSC entails considerable labour cost. It is necessary to clarify whether RSC application is better than the application of fresh straw or ash of rice straw to maintain plant-available Si in paddy fields.

Total-C in the surface (0 - 10 cm) soil was found to decrease by continuously cultivating rice without RSC or chemical fertilizer, and removing the rice straw. In the F0C- treatment, total-C concentration in the surface soil decreased by 0.17 g kg⁻¹ annually (Fig. 3). Based on the bulk density of the soil (0.96), the rate of decrease was calculated as 164 kg C ha⁻¹ year⁻¹ in the F0C- treatment. Both RSC application (F0C+) and chemical fertilizer application (F100C-) apparently worked to maintain total-C in the soil. Total-C increased in the F40C+ and F60C+ treatments where RSC and chemical fertilizer were applied together (Fig. 3). The rates of increase for the F40C+ and F60C+ treatments were calculated as 401 kg C ha⁻¹ per year⁻¹ and 356 kg C ha⁻¹ per year⁻¹, respectively. In studying what caused the difference in total-C in the F0C- and F100C- treatments, rice straw production in plots with the F100C- treatment was higher than that in the F0C- treatment by 2.24 Mg ha⁻¹ and 2.74 Mg ha⁻¹ for dry and wet seasons, respectively (Table 3). It is reasonable to consider that stubbles (i.e., plant residue about 5 cm from the ground surface), roots and root exudates in the F100C- plots were more extensive than those in the F0C- treatment in proportion to their rice straw biomass. This would explain the difference in total-C between the F0C- and F100C- treatments, despite removal of the rice straw. We can explain the difference in total-C between the F0C+, F40C+ and F60C+ treatments in a similar way. As shown in the F40C+ and F60C+ treatments, the application of RSC

with reduced chemical fertilizer increased total-C in the soil. This suggests that paddy fields in the Mekong Delta could be used effectively for carbon sequestration. Cassman et al. (1998) reported that soil organic carbon increased in a tropical paddy soil despite the complete removal of all aboveground crop residues. Pampolino et al. (2008) reported that total organic C in the topsoil (0 - 20 cm) increased after 17 to 21 years of continuous rice cultivation in four paddy fields in the Philippines, along with the removal of all aboveground plant biomass after every cropping.

As reported previously, we found that RSC application also decreased bulk density and soil penetration resistance (Watanabe et al. 2009). However, these results do not necessarily indicate the indispensability of RSC or the application of other organic matter for sustainable rice production. It may be possible to increase Si availability by using the ash of rice straw or rice husks, or siliceous fertilizer. Increasing organic C in the soil may not increase rice yield in the Mekong Delta, given its generally high concentration (Kyuma 1985, National Institute for Soils and Fertilizers & Department of Science, Technology and Product Quality 2002). The high organic C content suggests that soil physical properties in the region are favorable for rice production. As a next step, we should determine how much rice straw must be applied to maintain rice productivity.

In conclusion, our study showed that we need to maintain or increase Si availability in paddy soil to maintain rice yield, for which RSC application offers an option. Our results also showed that the application of RSC with reduced chemical fertilizer increased total-C in the soil, suggesting that we can effectively use paddy fields in the Mekong Delta for carbon sequestration.

Acknowledgments

We wish to thank Ms. Nguyen Ngoc Han for her devoted support of field management and the collection of data. We are grateful to Dr. Osamu Ito for his invaluable advice and support for continuing this study. We also appreciate Dr. Kazunobu Toriyama and Dr. Kanwar Sahrawat for their most useful advice regarding this document.

References

- Barbarosa-Filho, M. P. et al. (2001) Evaluation of soil test procedures for determining rice-available silicon. *Commun. Soil Sci. Plant Anal.* **21**, 1779-1892.
- Cassman, K. G. et al. (1998) Opportunities for increased nitrogen-use efficiency from improved resource management in irrigated rice systems. *Field Crops Res.* **56**,

Table 3 Rice straw production and amount of Si in rice straw

	Rice straw (Mg ha ⁻¹)		Si (kg ha ⁻¹)	
	DS§	WS¶	DS†	WS‡
F0C-	5.07	4.38	236	203
F0C+	5.46	4.88	283	245
F40C-	6.73	6.35	332	276
F40C+	6.83	6.81	349	320
F60C-	7.09	6.99	355	307
F60C+	7.25	6.97	377	315
F100C-	7.31	7.12	308	272

WS, wet season; DS, dry season. § Average of four crops from 2009/2010 DS to 2012/2013 DS. ¶ Average of four crops from 2010 WS to 2013 WS. † Average of two crops of 2009/2010 and 2010/2011 DS. ‡ Average of two crops of 2010 and 2011 WS. Si concentrations used for this calculation were quoted from Watanabe et al. 2013.

7-39.

- Dobermann, A. and Fairhurst, T. (2000) Nutrient disorders and nutrient management, International Rice Research Institute, Potash & Phosphate Institute and Potash & Phosphate Institute of Canada, Makati City, Philippines (distributed in the form of CD-ROM).
- Fujii, H. (2002) Effect of silicate on growth, yield and taste of rice, in Japanese society of soil science and plant nutrition. (eds.), Silicon and crop production. Hakuyu-sha, Tokyo, pp.41 [In Japanese].
- General Statistics Office, Vietnam (2010) Statistical Yearbook 2009. Statistical publishing house, Hanoi, pp.159.
- Guntzer, F. et al. (2012) Long-term removal of wheat straw decreases soil amorphous silica at Broadbalk Rothamsted. *Plant Soil*, **352**, 173-184.
- Kobayashi, N. (2006) Effect of long-term application of rice straw on the plant available silicon of paddy soil. Proceedings of the 18th World Congress of Soil Science, July 9-15, Philadelphia, Pennsylvania, USA.
- Kyuma, K. (1985) Fundamental Characteristics of Wetland Soils. *Proc. of Wetland Soils Workshop*, IRRI, 191-206.
- Ma, J. F. and Takahashi, E. (1989) Release of silicon from rice straw under flooded conditions. *Soil Sci. Plant Nutr.* **35**, 663-667.
- National Institute for Soils and Fertilizers and Department of Science, Technology and Product Quality (2002) The basic information of main soil units of Vietnam. Thegioi publishers, Hanoi, 60-63.
- Pampolino, M. F. et al. (2008) Soil carbon and nitrogen changes in long-term continuous lowland rice cropping. *Soil Sci. Soc. Am. J.* **72**, 798-807.
- Phutela, U. G. and Sahni, N. (2013) Microscopic structural changes in paddy straw pretreated with *Trichoderma reesei* MTCC 164 and *Coriolus versicolor* MTCC 138. *Indian J. Microbiol.* **53**, 227-231.
- Takahashi, K. (1986) Standard methods of soil analysis. (eds.), Committee of standard methods of soil analysis. Hakuyu-sha, Tokyo 161-165 [In Japanese].
- Tran, S. N. et al. (2014) Estimated quantity of rice straw and its uses in some provinces in the Mekong Delta region. *Can Tho University's Journal of Science and Technology*, **52** (3A), 316-322.
- United States Department of Agriculture, Natural Resources Conservation Service (2014) Key to soil taxonomy, twelfth edition, 2014.
- Watanabe, T. et al. (2009) Effects of continuous rice straw compost application on rice yield and soil properties in the Mekong Delta. *Soil Sci. Plant Nutr.*, **55**, 754-763.
- Watanabe, T. et al. (2013) Combined effects of continual application of composted rice straw and chemical fertilizer on rice yield under double rice cropping system in the Mekong Delta, Vietnam, *JARQ*, **47**, 397-404.
- Wickramasinghe, D. B. and Rowell, D. L. (2006) The release of silicon from amorphous silica and rice straw in Sri Lankan soils, *Biol. Fertil. Soils*, **42**, 231-240.

