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Combined Effects of the Continual Application of Composted Rice Straw and Chemical Fertilizer on Rice Yield under a Double Rice Cropping System in the Mekong Delta, Vietnam

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Abstract

We conducted a 12-year field experiment to study the combined effects of rice straw compost and chemical fertilizer application on a double rice cropping system in the Mekong Delta, Vietnam and established 7 treatments using a randomized block design with 3 replications. We calculated the yields of treatments relative to those of conventionally fertilized plots (i.e. with no added rice straw compost), and analyzed their annual trends. In the plots with rice straw compost, we observed a positive trend over 12 continuous wet cropping seasons. In comparison with conventional fertilization, the application of rice straw compost with reduced chemical fertilizer can maintain rice productivity over a longer period. We analyzed the nutrient status of the rice straw at harvest over 4 cropping seasons and observed that the Si concentration of the rice straw in conventionally fertilized plots was significantly lower than that in the plots where rice straw compost was applied. The N, P and Mg concentrations of the rice straw increased with the fertilizer application rate, while the concentrations of K, Ca, Mn, Fe, Zn, and Cu did not differ significantly among treatments. Our results suggest that continuous removal of rice straw may reduce the Si availability in soil, thereby decreasing rice productivity. In addition, we verified that rice straw compost can be an effective source of silicon for paddy rice.

Discipline: Soils, fertilizers and plant nutrition
Additional key words: nutrient balance, silicon, soil fertility, sustainable land use

Introduction

The Mekong Delta is the largest rice-producing area in Vietnam. The region produces more than 18 million tons of rice annually[6], which constitutes approximately half the country's total rice production. The soil organic matter content of the Mekong Delta is generally high[11,13]. In contrast to the Red River Delta in northern Vietnam, most farmers in the Mekong Delta cultivate rice (*Oryza sativa*) without manure or compost; moreover, farmers generally burn the rice straw, or remove it for use in mushroom cultivation, vegetable mulching, or cattle feeding. The intensification of land use, combined with a reduced supply of nutrient-laden sediment because of improved control of floodwater from the Mekong River, may exacerbate the decrease in soil fertility, hence the increasing importance of soil fertility management. Limited data exist regarding the long-term trends in soil fertility of the Mekong Delta[14,19]. To develop practical soil fertility management options for the region's rice farmers, it is essential to clarify the sustainability of conventional farming practice. If the current practice is unsustain-

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able, the reasons must be identified.

In the present study, we investigated the long-term effects of the continuous application of rice straw compost on the overall soil fertility status of a Mekong Delta alluvial soil[20,21]. We also compared annual rice yield trends between plots fertilized with chemical fertilizer alone and those fertilized with a combination of rice straw compost (RSC) and chemical fertilizer. To evaluate the combined effects of RSC and chemical fertilizer application, we determined the nutrient content (N, P, K, Si, Ca, Mg, Mn, Fe, Zn, and Cu) of the rice straw. A nutrient imbalance has previously been shown to cause a reduction in yield[4,23], and we postulated that manure and compost could potentially supply the required nutrients.

Materials and methods

1. Experimental design

We conducted our experiment in an experimental field at the Cuu Long Delta Rice Research Institute (CLRRI, Thoi Lai District, Can Tho City, Vietnam, 10°08'N, 105°35'E). Long-term studies on the effects of rice straw compost application were initiated during the 2000 wet season[20]. The rice crop was cultivated twice per year, during 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. The crop variety used, sowing method and seed application rate are summarized in Table 1.

Throughout the experiment, the rice variety OM4900 (growth duration of 95−100 days) was directly sown using a row seeder planting machine.

We established the following 7 treatments using a randomized block design with 3 replications:

(1) F0C− (or control), 0:0:0 N:P_2O_5:K_2O
(2) F0C+, RSC (6 t ha^{-1})
(3) F40C−, 40% NPK (32:12:12 or 40:12:12 N:P_2O_5:K_2O kg ha^{-1})
(4) F40C+, RSC (6 t ha^{-1}) + 40% NPK (32:12:12 or 40:12:12 N:P_2O_5:K_2O kg ha^{-1})
(5) F60C−, 60% NPK (48:18:18 or 60:18:18 N:P_2O_5:K_2O kg ha^{-1})
(6) F60C+, RSC (6 t ha^{-1}) + 60% NPK (48:18:18 or 60:18:18 N:P_2O_5:K_2O kg ha^{-1})
(7) F100C−, 100% inorganic fertilizer (wet season, 80:30:30 N:P_2O_5:K_2O kg ha^{-1}; dry season, 100:30:30 N:P_2O_5:K_2O kg ha^{-1})

Each plot covered an area of 30 m^2 (5 × 6 m). Treatment F100C− was based on the conventional farming practice in the region. RSC (which was made only from the rice straw grown in the experimental field) and phosphorus (P) fertilizer (single superphosphate) were mixed into soil at the time of cultivation before sowing the rice seed. N fertilizer (urea) was split into three applications: equivalent thirds broadcast at 10, 20 and 30 days respectively after sowing (DAS). The potassium (K) fertilizer (potassium chloride) was split into two applications: half of which was broadcast at 10 DAS and the remainder at 30 DAS. Treatments F0C−, F0C+, F40C+, F60C+, and F100− were initiated during the 2000 wet season. Before the 2009/2010 dry season, the F40C− and F60C− treatment plots were fertilized with RSC (6 t ha^{-1}) + NPK (16:6:6 or 20:6:6 N:P_2O_5:K_2O kg ha^{-1}) and RSC (6 t ha^{-1}) + NPK (64:24:24 or 80:24:24 N:P_2O_5:K_2O kg ha^{-1}), respectively. The field layout and experimental details, including the soil site characteristics, were described previously[20]. Rice straw was cut and removed from the field after harvest, while pest management practices followed the standard CLRRI practices.

2. Yield measurement and statistical analysis of relative yield trends

We determined the yields from the sampling area for harvest (2.5 × 2 m) within each plot at harvest and counted the panicle number for four sampling areas (each 0.5 x 0.5 m) within each plot at harvest. The spikelet per panicle, filled grain (%) and 1000 grain weight was measured from 40 panicles randomly selected within each plot. The cultivars and sawing method changed during the experiment, meaning annual changes in yield could not be directly analyzed. To evaluate annual trends in rice yield, as affected by the crop varieties used and weather variables, we calculated the relative cropping yields using the following formula:

Table 1. Variety of the cultivated rice, the seeding rate and the sowing method

Duration†	Variety	Seeding rate (kg ha^{-1})	Method of sowing
2000WS ~ 2004/2005DS	IR64	200	Broadcasting
2005 WS	IR64	150	Broadcasting
2005/2006DS ~ 2008WS	OM2517	100	Row seeding
2008/2009DS ~ 2011WS‡	OM4900	100	Row seeding

† Rice was not cultivated in the dry season 2003/2004. ‡ Two treatments were changed from the dry season 2009/2010. WS, wet season; DS, dry season.

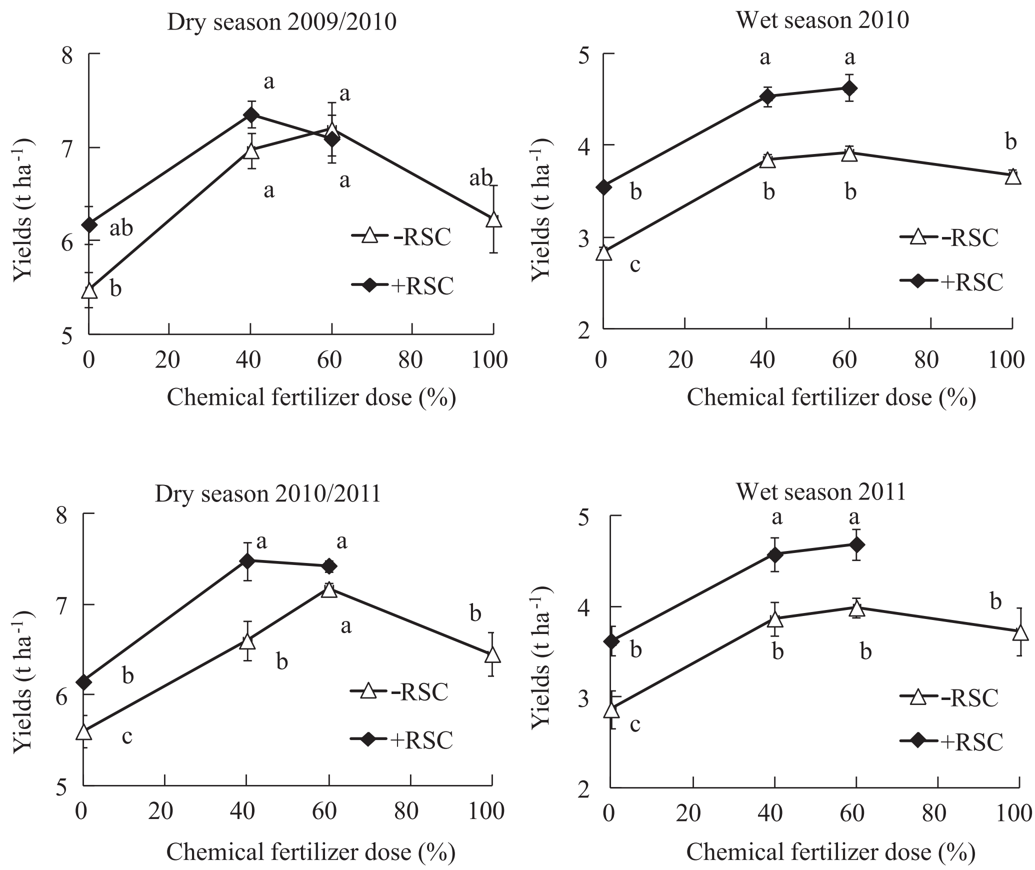

Fig. 1. Rice yields from different forms of fertilizer management

Data with the same alphabet do not differ significantly (Tukey $p<0.05$). +RSC and –RSC mean that the rice straw compost was applied and not applied, respectively.

Yield of each treatment in each crop/Yield of F100C−[§] × 100 (1)

[§]Average yield of the triplicate F100C− treatment plots for each crop

The annual trends of yields relative to that of the F100C− treatment, for the 4 treatments (F0C−, F0C+, F40C+, and F60C+) during the wet and dry seasons, were statistically analyzed using an Excell Tohkei 2008 (SSRI, Tokyo, Japan).

3. Nutrient measurement in plants

The rice straw at harvest was sampled from the 2009/2010 dry season to the 2011 wet season. The samples were dried at 70°C for 3 days, and ground. The N content was determined using an NC analyzer (Sumigraph NC-220F; Sumika Chemical Analysis Service, Osaka Japan). Si was solubilized using dilute hydrofluoric acid extraction, and determined using the molybdenum colorimetric method[16]. The concentrations of P, K, Ca, Mg, Mn, Fe, Zn, and Cu were determined using inductively coupled plasma (ICP) (ICPE-9000; Shimadzu, Kyoto, Japan), after digestion with a mixture of nitric acid and hydrogen peroxide using a microwave digester (MlS 1200 mega; Milestone, Sorisole, Italy).

Results

The rice yields from the 2009/2010 dry season to the 2011 wet season are shown in Fig. 1. During the two wet seasons, the yields for the F40C+ and F60C+ treatments (4.54 - 4.69 t ha^{-1}) significantly exceeded those for the other treatments. During the 2009/2010 dry season, there were no significant differences among treatments, except for the F0C− treatment. Conversely, during the 2010/2011 dry season, the yields for the F40C+ and F60C+ treatment (7.09 t ha^{-1} and 7.48 t ha^{-1}) significantly exceeded those for the F0C−, F0C+, F40C−, and F100C− treatments. Table 2 shows the yield components from the 2009/2010 dry season to the 2011 wet season. Compared with the F60C– and F100C– treatments, the filled grain (%) for the F40C+ and F60C+ treatments for the 2010/2011 DS, 2010WS and 2011WS was higher. The 1000 grain weight for F40C+ and F60C+ for the 2 wet seasons was also higher than the other treatments.

Table 2. Yield components

	2009/2010 DS	2010/2011 DS	2010 WS	2011 WS	2009/2010 DS	2010/2011 DS	2010 WS	2011 WS
Panicle number/m^2					Spikelets/Panicle			
F0C-	407a	386b	373b	369b	74.6c	78.4e	59.9d	62.5b
F0C+	427a	415ab	379b	380ab	84.4bc	84.1d	73.5cd	65.9b
F40C-	407a	319ab	418ab	413ab	97.0ab	94.1c	83.3bc	87.6a
F40C+	400a	420ab	448a	451a	97.9ab	103.3a	102.6a	96.3a
F60C-	421a	432a	414ab	435ab	100.3a	101.6a	100.7a	101.3a
F60C+	426a	429a	441a	446a	104.7a	102.4a	105.2a	104.7a
F100C-	429a	435a	428a	428ab	95.1b	98.4b	95.2ab	90.2a
Filled grain (%)					1000 grain weight (g)			
F0C-	71.2a	74.4a	67.7a	68.6a	29.2a	29.0d	27.4c	27.5b
F0C+	72.2a	74.4a	67.3a	68.5a	29.2a	29.1cd	27.6bc	27.6b
F40C-	70.5a	74.3a	67.1a	67.4b	29.6a	29.3ab	27.9b	27.9b
F40C+	71.6a	74.1a	67.2a	67.5b	29.1a	29.3a	28.9a	28.6a
F60C-	71.8a	72.2b	62.4a	64.6d	29.2a	29.3ab	27.6c	27.6b
F60C+	70.5a	74.0a	64.9a	65.8c	29.1a	29.3ab	28.9a	28.8a
F100C-	71.6a	71.2b	62.0a	64.3d	29.3a	29.2bc	27.5bc	27.5b

Values in a column followed by the same letter do not differ significantly using a Tukey's multiple comparison ($P<0.05$). DS, dry season; WS, wet season

The relative yields for the F0C+, F40C+, and F60C+ treatments during the wet season increased significantly over time (Fig. 2). The relative yields for all of the treatments during the dry season showed no significant changes over time, probably because of abnormal results during the 2002/2003 season, when rice blast disease heavily affected the rice growth and yield; this was especially true for in the F100C− treatment, which was used as the denominator to calculate the relative yield. When the data for the 2002/2003 season were excluded (as shown in different symbol from other years in Fig. 3), significant increases in the yield over time were recorded for the F0C−, F0C+, F40C+, and F60C+ treatments .

The N, P, and Mg concentrations of rice straw increased in response to the chemical fertilizer dosage (Fig. 4). Conversely, the Si concentration of rice straw from the F100C− treatment plots was significantly lower than those from the F0C+, F40C+, and F60C+ treatment plots (Fig. 4). The concentrations of K, Ca, Mn, Fe, Zn, and Cu did not differ significantly among treatments; therefore, only the averages and standard errors of these nutrients for each harvest are shown in Table 3.

Discussion

We observed significant increases in the relative yields over time for the F0C+, F40C+, and F60C+ treatments, in the wet and dry seasons. These results indicate a gradual decrease in soil fertility for the F100C− treatment or a gradual increase in soil fertility for the F0C+, F40C+, and F60C+ treatments. The significant increases in relative yields over time are most likely caused by repeated application of RSC.

The N and P concentrations in the rice straw increased with the fertilizer application rate (Fig. 4) but were not correlated with the yield increase. These results are in accordance with those of previous studies[20]. The concentrations of K, Ca, Mn, Fe, Zn, and Cu did not differ significantly among treatments (Table 3), suggesting that these elements may not be limiting factors for the rice yield.

In comparison with the optimum N concentration range of rice straw at maturity, which is proposed by IRRI[4] to be 6–8 g kg^{-1}, the N concentration for the F100C− treatment was much higher, while those for the F40C+ and F60C+ treatments were either within the optimum range, or slightly higher. The P concentration for the F100C− treatment was within the optimum range (1.0–1.5 g kg^{-1}), while those for the F40C+ and F60C+ treatments were lower. The K, Mg, and Ca concentrations for all treatments were close to the optimum ranges (15–20, 2–3, and 3–5 g kg^{-1}, respectively), while Cu concentrations for all treatments exceeded the critical level (6 mg kg^{-1}). No optimum or critical ranges for Mn, Fe, or Zn are defined by IRRI. Our results indicate that farmers in the Mekong Delta can reduce N and K fertilization rate below the conventional application rates. Dobermann and Fairhurst[4] showed that the critical level of Fe toxicity for young leaves, from the tillering to the panicle initiation stage, should be approximately 300–500 mg kg^{-1}. Our present data regarding Fe concentrations were derived from a different growth stage; nevertheless, it is reasonable to suspect potential Fe toxicity in the field, because the Fe concentration ranged from 318 to 630 mg kg^{-1}.

The Si concentration for the F100C− treatment, where the rice straw had been removed, was significantly lower than those for the F0C+, F40C+, and F60C+ treatments

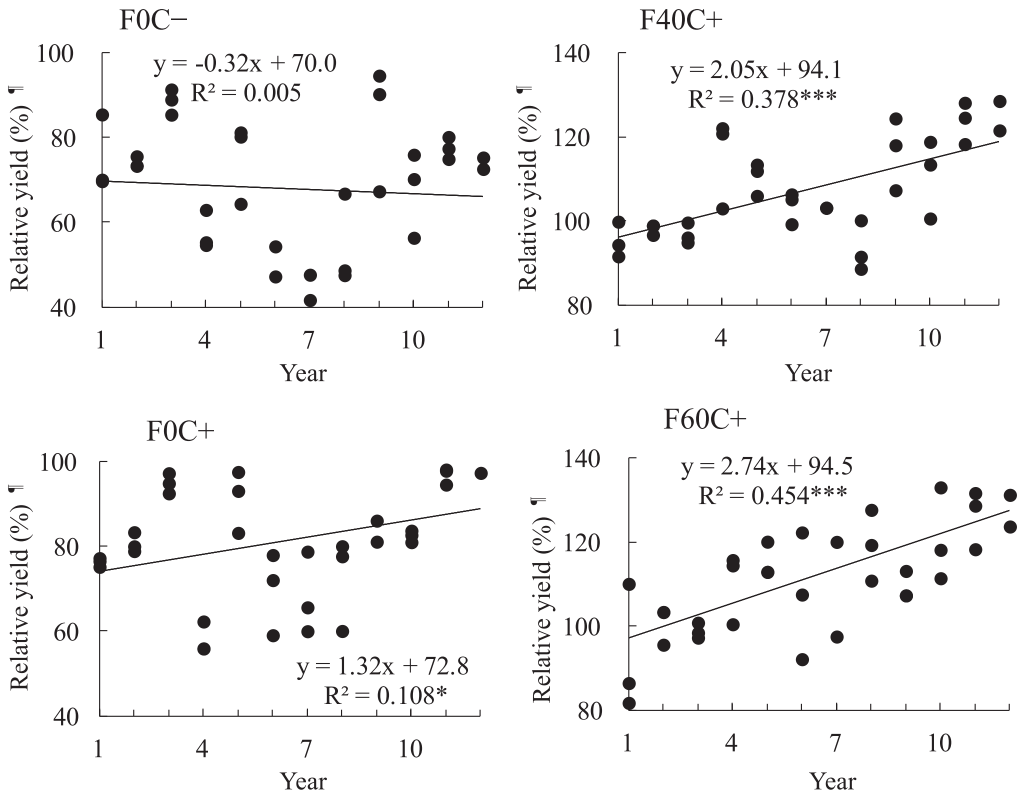

Fig. 2. Annual changes in relative yields in the wet season

¶: (Yield of each treatment) / (Yield of F100C−) ×100. *, ** and *** means the slopes of the regression lines differed significantly from zero ($p<0.05$, 0.01 and 0.001, respectively).

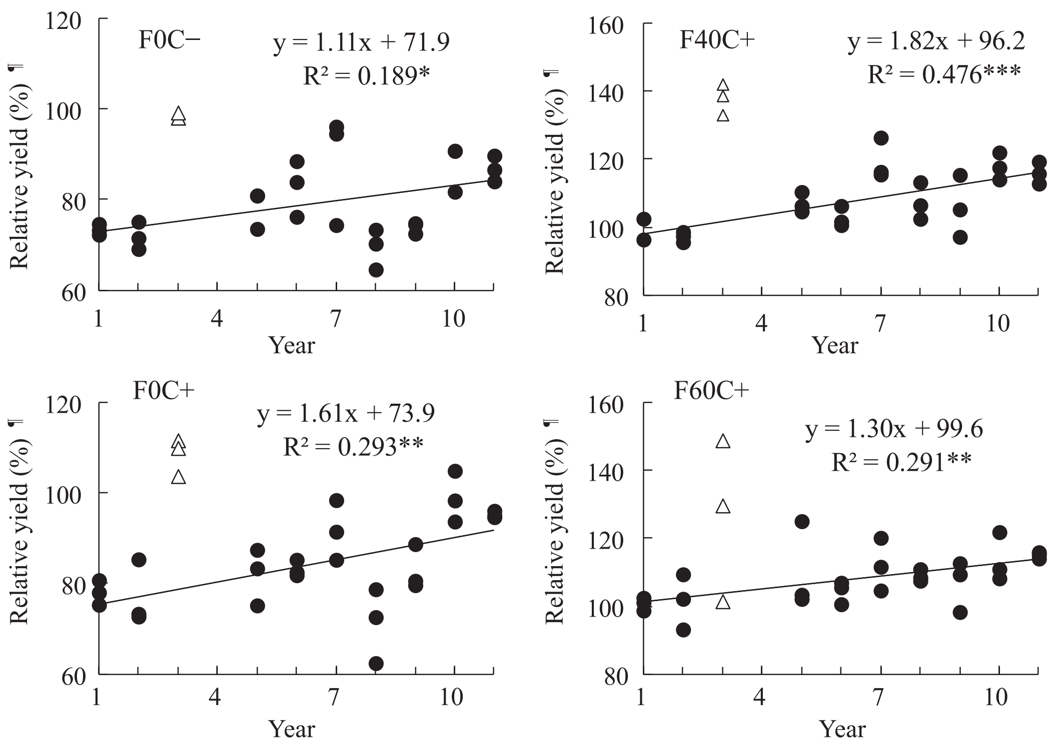

Fig. 3. Annual changes in relative yields in the dry season

¶: (Yield of each treatment) / (Yield of F100C−) ×100. *, ** and *** means the slopes of the regression lines differed significantly from zero ($p<0.05$, 0.01 and 0.001, respectively). Third year data (shown by △) was excluded from the calculation of the regression line and the statistical test.

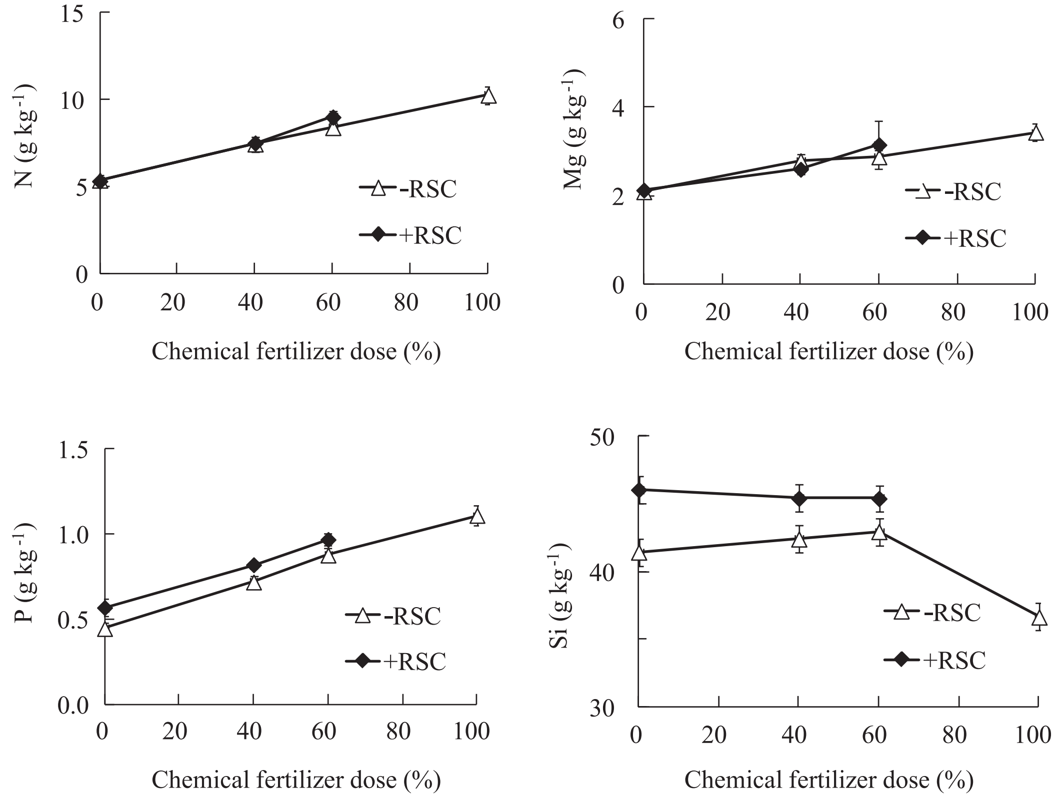

Fig. 4. Nitrogen, phosphorus, magnesium and silicon concentrations in rice straw at harvest* from the different fertilizer managements

Bars mean standard errors. +RSC and −RSC mean that the rice straw compost was applied and not applied, respectively.
*: Average of the 4 cropping seasons crops from the dry season 2009/2010 to the wet season 2011.

Table 3. Average concentrations of K, Ca, Mn, Fe, Zn and Cu in the rice straw

	2009/2010 DS	2010/2011 DS	2010 WS	2011 WS
K (g kg^{-1})	21 (0.39)	17 (0.32)	17 (0.38)	16 (0.22)
Ca (g kg^{-1})	4.9 (0.17)	4.0 (0.18)	3.3 (0.06)	3.6 (0.18)
Mn (mg kg^{-1})	600 (14)	718 (29)	769 (29)	611 (35)
Fe (mg kg^{-1})	377 (14)	630 (40)	488 (29)	318 (16)
Zn (mg kg^{-1})	32 (0.8)	32 (0.8)	37 (0.9)	31 (1.0)
Cu (mg kg^{-1})	22 (1.6)	17 (0.8)	16 (1.2)	11 (0.5)

Standard errors are shown in brackets. DS, dry season; WS, wet season.

(Fig. 4). As mentioned previously, the low yield for the F100C− treatment during the 2002/2003 dry season, which was caused by rice blast disease, increased the relative yields of the remaining treatments and distorted the annual yield trends. The higher N and lower Si concentrations of the rice straw for the F100C− treatment appear to have made the rice more susceptible to rice blast disease[8,24]. Sumida[18] reported that Si contents of rice leaf blades were negatively correlated with N contents. As a consequence of higher N application, and the continuous removal of rice straw without RSC application, an imbalance between N and Si for the F100C− treatment may have led to increases in relative yields over time for the F0C+, F40C+, and F60C+ treatments. The filled grain (%) and 1000 grain weight of the F100C− treatment tended to be lower than those of the F40C+ and F60C+ treatments (Table 2). The lower yields for the F40C− and F60C− treatments in comparison with the F40C+ and F60C+ treatments (Fig. 1) suggest that this imbalance cannot be corrected solely by adjusting the N fertilizer application rate.

Although not generally considered an essential element, Si is often beneficial for rice[1,9,12]. The Si concentrations of our rice straw (average 42.9 mg kg^{-1}) were lower than the critical concentration (<50 mg kg^{-1})[4] and also the typical concentrations reported in Japan[5]. Si has been reported as playing an important role in rice growth, but its physiological functions remain poorly understood. Si is known to be required to develop strong leaves, stems, and roots. The formation of a thick silicated epidermal cell layer reduces the susceptibility of rice plants to fungal and bacterial diseases[8], and also to insects (stem borers, plant hoppers) and mite pests. Rice plants with an adequate supply of Si have erect leaves, which boosts dry matter production through more efficient radiation and N use[1,4].

Recently, phytoliths have been considered a major source of Si available to plants. It is shown by a long-term trial conducted at Rothamsted Experimental Station that the annual straw exports from wheat fields reduce the amount of phytolith input to the soil, which decreases the bio-available Si in soils. A significant correlation between Si concentration in straw and yield is also shown[7]. In a long-term trial with rice conducted at four experimental stations located in northern Japan, it was shown that the plant-available Si in the surface soil with continuous rice straw application was 1.25 times higher than without the application[10]. Savant et al.[17] suggests that the depletion of plant-available Si in paddy soils could be a possible limiting factor contributing to the declining yields often observed in continuous rice cropping area worldwide.

Because phytoliths remain in soil long-term, it was thought that rice straw might not effectively supply Si for the following crops. Anzai[2] confirmed that rice straw ash supplied more Si than rice straw compost for paddy rice under field conditions. However, Wickramasinghe and Rowell[22] demonstrated that rice straw added to soil suspensions increased the silicon concentration during incubation. Phutela and Sahni[15] showed that fungi promotes the solubilization of silica components in rice straw.

Dawe et al.[3] analyzed yield trends in 7 long-term experiments in Asia, with the rice cultivated twice a year, and concluded that the application of manure or straw failed to improve yield trends. The results of our present study contradict this conclusion. Watanabe et al.[20] reported the significant effect of RSC application on soil physical properties. RSC application was shown to maintain soils in a softer state, i.e. with a lower bulk density, than that of soils without RSC. However, the increase in relative yields for the F0C+, F40C+, and F60C+ treatments in our present study may not have been caused exclusively by organic matter amendment. If the relative yield trend in our present study was caused by a decrease in available Si for the F100C− treatment, it may be possible to compensate for this by applying Si using a chemical fertilizer. Further studies to clarify the effect of Si application are required.

Collectively, our results suggest that continuous removal of rice straw may reduce the Si availability in soil, thereby decreasing rice productivity. Although this causal relationship remains to be confirmed, our results indicate that, in comparison with the conventional fertilization, application of RSC with reduced chemical fertilizer can maintain rice productivity over a longer period. In addition, we verified that rice straw compost could be an effective source of silicon for paddy rice.

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