RESEARCH

Controlled-Release Nitrogen Fertilizer Improved Lodging Resistance and Potassium and Silicon Uptake of Direct-Seeded Rice

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ABSTRACT

Lodging is a severe problem for rice (*Oryza sativa* L.) because it interferes with mechanical harvesting, and potentially results total crop loss. This study investigated whether a controlled-release urea (CRU) could reduce lodging, improve the uptake of K and Si, and yields of direct-seeded rice. The 2-yr field experiment included four rates of CRU (120, 180, 240, and 360 kg N ha^{-1}), each provided in one application; a conventional urea fertilizer provided in four applications (360 kg N ha^{-1} total); and a control with no N fertilizer. Results indicated that the N release rates from the CRUs were matched well to N uptakes by rice plants; hence, N use efficiencies were improved. Concentrations of K and Si in rice tissues were much higher for treatments with the full and reduced rates of CRU than for the full rate urea treatment. Lodging of rice only appeared to occur in the urea treatment. Microscopic examination revealed that cells of rice stems provided with CRU treatments were more resistant to lodging than stem cells from plants in the urea treatment.

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Abbreviations: BM, bending moment; CRF, controlled-release fertilizer; CRU, controlled-release urea.

Lodging is a serious problem for rice (*Oryza sativa* L.) production worldwide because it leads to poor grain quality, low yields, and even total crop losses (Setter et al., 1997; Salassi et al., 2013; Zhang et al., 2014a). It reduces photosynthesis and the uptake of water and nutrients, increases mycotoxin contamination, and impedes mechanical harvesting (Setter et al., 1997; Nakajima et al., 2008; Wu et al., 2012). Many factors affecting lodging resistance in rice have been identified, such as plant height, diameter of basal internodes, and contents of Si and K (Duan et al., 2004;

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Kashiwagi et al., 2005; Islam et al., 2007; Zhu et al., 2008; Lang et al., 2012). According to Zhang et al. (2010) and Podgórska-Lesiak and Sobkowicz (2013), increasing the sturdiness of the basal internodes in rice plants improved lodging resistance; therefore, traits that lead to strong basal internodes may be more appropriate targets for improvement efforts than those affecting plant height. Many techniques have been proposed to improve lodging resistance in rice with frequent emphasis on finding genotypes with innate lodging resistance (Kashiwagi et al., 2008; Corbin et al., 2016). However, these efforts tend to be time consuming and expensive.

Judicious application of N fertilizers can increase rice yields (Yang et al., 2012; Tsiboe et al., 2018). With increasing amounts of N fertilizer applied, plant height and biomass are also significantly increased. However, N fertilization may decrease the thickness of culm wall and diameter and resulted in poor lodging resistance in rice plants (Shimono et al., 2007; Kashiwagi et al., 2008; Yang et al., 2009). Proper management of N fertilizers may promote the uptakes of K, Si, and other nutrients that improve the mechanical strength of stems, thereby increasing lodging resistance of rice. Therefore, N fertilizers play a significant role in dictating the physical and mechanical strength of plant stems, as well as affecting the morphology traits of basal internodes in rice (Ookawa and Ishibara, 1992; Zhang et al., 2014b).

Controlled-release fertilizers (CRFs) have many advantages including reducing nutrient loss, improving nutrient use efficiency, and decreasing groundwater pollution, (Wang et al., 2015; Zhang et al., 2018a). Compared with conventional fertilizers, CRFs increase rice yield with the same amount of nutrients applied due to their higher nutrient use efficiencies (Zhang et al., 2016; Zhang et al., 2017). The N release pattern of controlled-release urea (CRU) closely matched the N need of rice to satisfy crop growth, which reduced excessive fertilization (Yang et al., 2012). It has been reported that CRF could improve lodging resistance of early ripening rapeseed (*Brassica napus* L.) (Tian et al., 2016). Tian et al. (2016) proposed that using CRFs increase root growth of plants, improve uptakes of nutrients, and delayed senescence. Many studies had reported that due to continuous release of nutrients, CRFs increased available nutrients in rhizosphere soil and subsequently improved the root system (Yang et al., 2012; Zhang et al., 2018b). The right amount of nutrients especially N at the right time have been reported to trigger the root development (Forde, 2014; Ambreetha et al., 2018). However, there is no study that examines the mechanism of using CRFs to improve rice lodging resistance. The objective of this 2-yr study was to determine effects of CRFs on lodging incidences, nutrient uptakes, growth, and yield of direct-seeded rice.

MATERIALS AND METHODS

Experimental Description

A 2-yr field experiment was arranged in Yaozhuang, Yutai, Shandong Province, China (35°08′ N, 116°53′ E), during the 2015 and 2016 growing seasons. The region is characterized by the monsoon climate typical of medium latitudes with an annual average air temperature of 13.2°C. The annual rainfall is between 648 and 900 mm. The region's predominant soil was classified as a hydromorphic paddy soil, with Typ-Fec-Stagnic Anthrosols based on the Chinese Soil Taxonomy System, and the parent material is a fluvial deposit. The main characteristics of the soil (0–20 cm) at this site were pH (1:2.5, soil/water) of 8.2; total N of 1.46 g kg^{-1}; available P and K of 10.56 and 156.32 mg kg^{-1}, respectively; and 18.52% clay, 72.62% silt, and 8.86% sand.

The plot size was 20 m^2 (6.00 × 3.33 m). Each plot was divided by a ridge (40 cm wide and 40 cm high). There were 14 rows in each plot whereby the rectangular widths were spaced 25 cm apart. The rice cultivar used in this study was Runnong No.11 (*Oryza sativa* L.), with characteristics of pest resistance, disease resistance, and high grain yield. Seeds were sown at the rate of 330 g $plot^{-1}$ with each row containing 23.6 g seeds on 15 June 2015 and 17 June 2016. After the seeding, the field was flooded, and the water was drained at the maturation stage before harvesting. Rice grains were harvested on 22 Oct. 2015 and 20 Oct. 2016.

Description of Fertilizer Treatments

The fertilizer treatments included one rate of urea (360 kg N ha^{-1}), four rates of CRU, and a control that were arranged in random complete block design with three replicates. The application rate of urea was determined based on common practice by growers in the experimental region (Li et al., 2015). The rates of CRU were 120, 180, 240, and 360 kg N ha^{-1} for CRU1, CRU2, CRU3, and CRU4, respectively. Three low rates CRUs were used to determine that the reduced rates of CRUs could result similar effects of the high rate on lodging resistance and nutrient uptakes of direct-seeded rice. The non-controlled-release fertilizers used were urea (46% N), potassium sulfate (50% K_2O), diammonium phosphate (18% N and 46% P_2O_5), and monopotassium phosphate (52% P_2O_5 and 34.02% K_2O) that were purchased from local fertilizer distributors. The CRUs used were polymer coated urea with 42% N and obtained from the Kingenta Ecological Engineering Company. The release longevity of the fertilizer was ∼4 mo. The 90 kg K_2O ha^{-1} and 90 kg P_2O_5 ha^{-1} were applied in all treatments as basal fertilization. All CRUs were applied at seeding, and urea fertilizers were split four times (25% as basal fertilization, and 25% each at 20, 30, and 50 d after sowing).

Measurement of the Nitrogen Release of the Controlled-Release Urea

Under laboratory conditions, 10 g of CRU were put into a bottle with 200 mL of distilled water, and then the bottle was kept at 25 ± 1°C. Solution samples were collected at 1, 10, 20, 30, 40, 50, 60, 70, and 80 d until the total N release rate of CRU reach 80%. The N concentrations in the solution samples were measured using Kjeldahl method (Douglas et al., 1980). In field conditions, the N cumulative release rate was tested using the weight loss bag method (Wilson et al., 2009). Thirty-six mesh nylon bags (10 × 10 cm) with 10 g CRU were buried in the plowed layer at the same time as seeding. Three bags were randomly collected every 10 d after burial over the growth period of rice. The deionized water was used to remove soil off the bags. The bags were then dried in an oven at 60°C until constant weight and the N release rate was calculated based on the weight loss.

Plants Sampling and Analysis

Plant samples were collected from each plot at 20, 30, 50, 80, and 120 d after seeding, dried in an oven at 75°C to a constant weight before they were weighed, and ground to pass through a 100-mesh sieve. An automated chemistry analyzer (AMS Smartchem 200, AMS Alliance) was used to determine the N concentration of the plant tissues. The N uptake of plants was calculated using the N content and the weight of rice straw during each growing stage from the seedling stage to the heading stage. The N accumulation at harvest was determined by considering the N content and yield of rice straw and grain. The K content in rice straw was also tested at the maturity stage after digestion with an H_2SO_4–H_2O_2 mixture and using the flame photometer method. The Si contents in straw were determined at maturity stage using the inductively coupled plasma mass spectrometry (iCAP RQ ICP–MS, ThermoFisher Scientific) after extracted with the method described by Frantz et al. (2008). Light microscope (SZ40, OLYMPUS) analysis was used to observe the morphology of stems at the second internode of rice from aboveground.

Breaking Resistance, Bending Moment, and Lodging Index of the Rice

The length of the second internodes from aboveground (L1) and the total length of rice plants (L2) were measured by a ruler at maturity stage to determine the lodging-related traits in both the 2015 and 2016 growing seasons. The breaking resistance of the center dot of second internode from the soil surface was determined to reveal the physical intensity of the rice stem with a prostrate tester (DIK 7400, Japan) (Wu et al., 2012).

The fresh weights of the stems and the panicle were then determined. The lodging index and bending moment (BM) of the stems were calculated as follows: BM = (L2 − L1) × total fresh weight of whole rice plants including panicle; lodging index of stems (%) = BM/breaking resistance ×100. The rice stem diameter of the portion near the lower node was determined after opening of the sheath. A strength detector (YHKC-2A) was used to test the physical rigidity of rice stems.

Data Analysis

The SAS package version 9.2 (SAS Institute) was used to conduct all statistical data analyses. The comparisons of all treatments were estimated with ANOVA. Significant differences among treatments were determined using Duncan's multiple range test ($p < 0.05$). Regression equations and coefficients between N cumulative release rate and N cumulative uptake rate for CRUs were also calculated.

RESULTS

Cell Morphology of Stems

The micrographs in Fig. 1 were used to observe the microscopic morphology of rice from urea and CRU4 treatments. Optical micrographs showed that rice stem cells from urea treatment were long and irregular, along with the amplification. The walls and membranes of these cells were deformed and elongated, which caused them to lose their activity (Fig. 1A1–1A3). In contrast, rice stem cells from CRU4 treatment were short, compact, and round (Fig. 1B1–1B3). They also had intact cell walls and visible organelles, which indicated the cells remained alive. The results indicated that CRU has benefited cell structure and activity more than the conventional urea.

Nitrogen Release Rates of Controlled-Release Ureas and Nitrogen Uptake of Rice

The N release curve of CRU showed a steady release rate in 25°C water (Fig. 2F), with 80% of supplemental N released within 120 d, which closely matches the growth requirements of rice (Fig. 2E). Nitrogen release characteristics in the paddy field were slightly faster (Fig. 2F), with 84% of N release during the same period.

The N uptake of rice in the control plot relied exclusively on existing N in the paddy soil. There was a remarkable influence on total N uptake of rice from various N fertilizer types and rates (Fig. 2A–2E). Nitrogen supply from the urea treatment matched plant nutrient uptake poorly. Urea release largely overshot plant requirements within the first 60 d after sowing, then decreased dramatically and disappeared completely at 80 d (Fig. 2A). This indicated that the rates of N availability from urea treatments did not match the requirements of rice growth. For CRU treatments, N supply curves indicated a steady, continuous release pattern throughout the growing season, especially for high application rates (CRU3 and CRU4). All CRU treatments also supplied an excess of N during first 60 d. Nitrogen supplies of CRU1 and CRU2 was suboptimal after 70 d, whereas the release rate for CRU3 almost perfectly matched the N uptake rate at the 80th day. The uptake exceeded the supply of CRU3 and was less than or equal to the N supply from CRU4 (Fig. 2B–2E).

Physical Characteristics of Stem and Lodging Index of the Rice

In both the 2015 and 2016 seasons, urea- and CRU1-treated plants exhibited reduced breaking resistances compared with CRU2, CRU3, and CRU4 but showed the better resistances than the control plants (Table 1). Plant height, length from ground to second joint, diameter, and rice straw rigidity were significantly affected by CRU. The CRU1 treatment had the greatest values, followed by CRU3 and then urea and CRU2. In the 2015 season, the BM of CRU4 treatment was also the greatest, followed

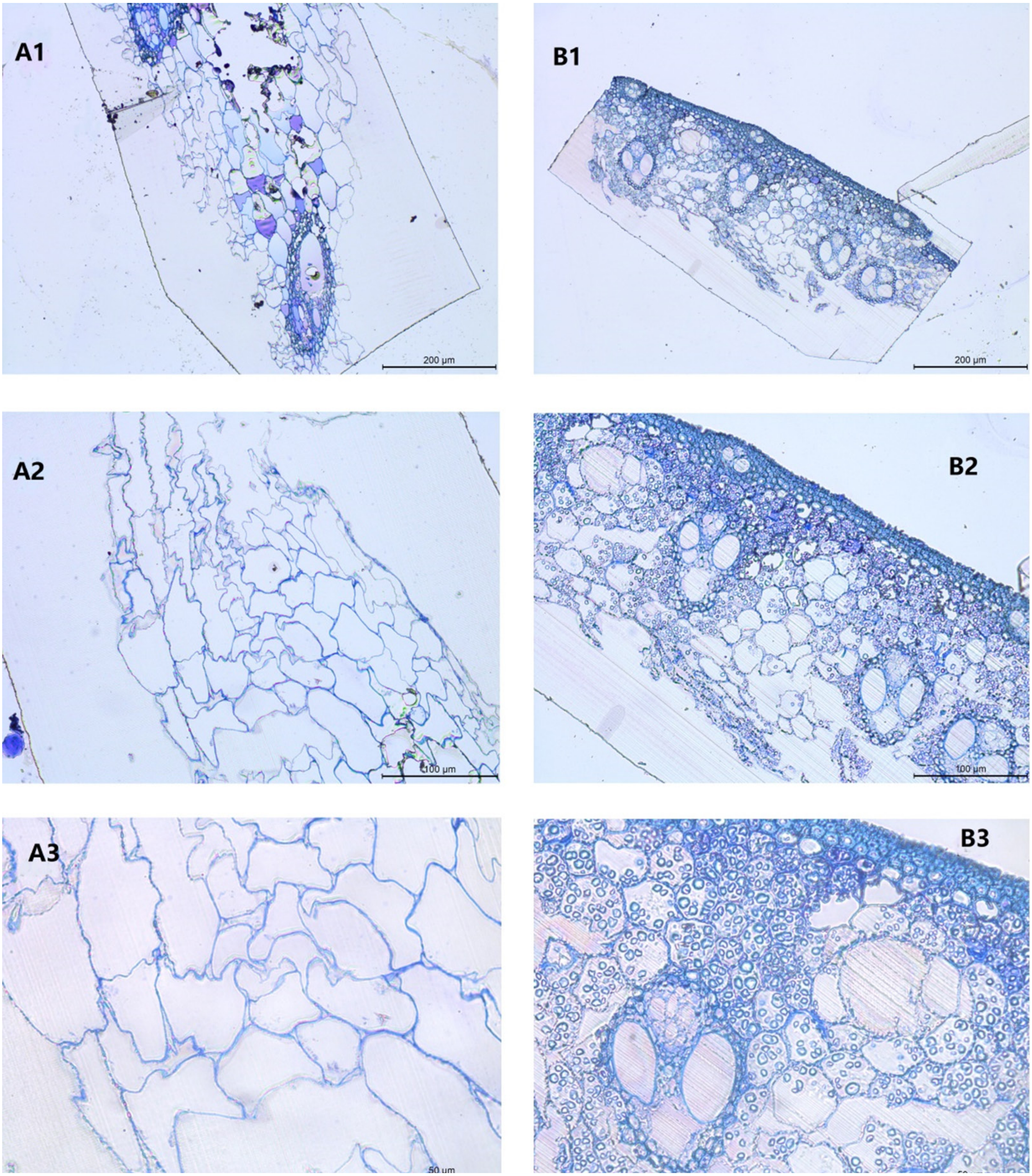

Fig. 1. Images of rice stem cells from urea (A1–A3, image magnification of 100×, 200×, and 400×, respectively). Images of rice stem cells from controlled-release urea (B1–B3, image magnification of 100×, 200×, and 400×, respectively).

by CRU3. In 2016, these treatments were not different. In both seasons, the BM of the urea treatment was similar to CRU2 but greater than CRU1 (Table 1). The lodging index is directly related to the lodging resistance of rice. In both seasons, the lodging indices of the urea treatment were the greatest among all treatments, which means that rice lodging only occurred in the conventional urea-treated plants. In 2015, the lodging indices of the treatments were in descending order as urea > CRU4 > CRU3 > CRU1 > control > CRU2 (Table 1). However,

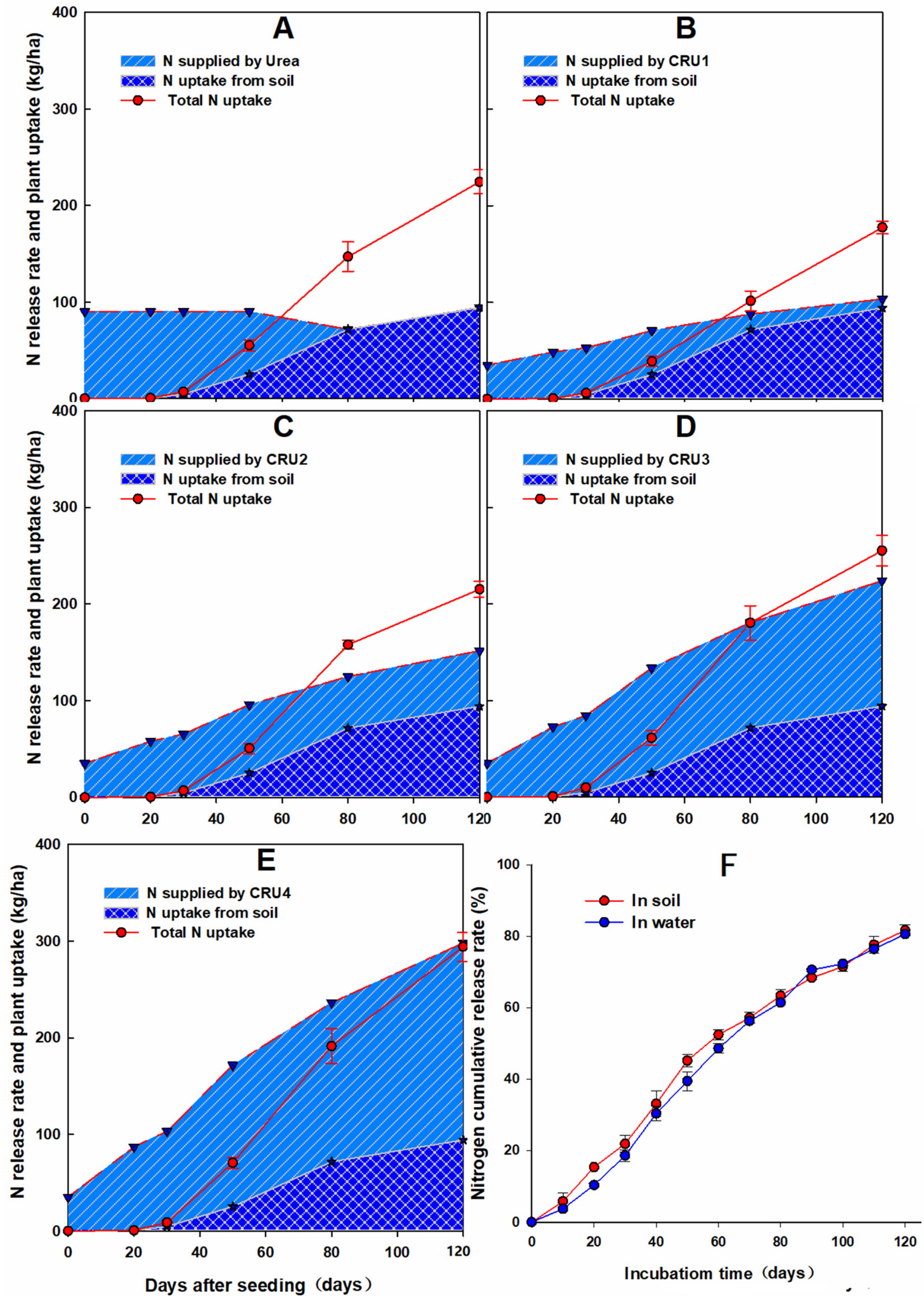

Fig. 2. Comparisons of N releases from treatments with urea or controlled-release urea (CRU) with N uptakes from soil by rice plants during the 2015 to 2016 growing seasons. Fertilizer application treatments were: (A) urea, (B) CRU1, (C) CRU2, (D) CRU3, and (E) CRU4; (F) N cumulative release rate in both soil and 25°C water. Controlled-release urea was applied at 120 kg N ha^{-1} (CRU1), 180 kg N ha^{-1} (CRU2), 240 kg N ha^{-1} (CRU3), and 360 kg N ha^{-1} (CRU4).

indices did not differ between N rates for CRU and were similar to the untreated control. In 2016, the lodging indices increased compared with 2015, indicating that the risk of lodging increased in 2016 (Table 1).

Concentrations of Potassium and Silicon in Rice and Yield

The differences in K concentrations were significant between the treatments, with most of the K concentrated in

Table 1. Physical characteristics of stem and lodging index of the rice affected by various N fertilizer treatments.

Year	Treatment†	Bending moment	Breaking resistance	Lodging index	Length	Length from land to second joint	Diameter	Straw rigidity
		g cm		%	cm		mm	N
	CK	333.00e‡	225.00d	148.81b	61.00d	14.33c	5.69c	11.87b
	U	528.24c	289.67c	182.60a	74.90c	17.00bc	6.26bc	12.83ab
	CRU1	457.13d	302.00c	151.62b	74.57c	17.50bc	6.12c	11.73b
2015	CRU2	503.61cd	364.67b	138.85b	77.33bc	20.00ab	6.79ab	14.67ab
	CRU3	607.70b	396.33b	153.37b	81.00b	21.00ab	6.90a	14.13ab
	CRU4	683.43a	443.67a	154.32b	89.67a	23.67a	7.00a	17.33a
	CK	386.95d	258.00e	150.96c	70.00d	15.50c	5.64e	11.33d
	U	652.55b	306.67d	212.94a	88.67b	17.33bc	6.47c	14.46bc
	CRU1	567.60c	285.33de	199.24a	82.33c	18.83b	6.17d	13.13c
2016	CRU2	646.67b	365.00c	177.20b	88.33b	21.67a	6.80b	16.60ab
	CRU3	758.77a	420.33b	180.64b	95.67a	21.33a	6.98ab	16.63ab
	CRU4	763.70a	468.67a	163.11bc	97.67a	23.67a	7.15a	18.33a

† CK, a controlled treatment with no N fertilizer; U, urea applied treatment at 360 kg N ha^{-1}; CRU1, controlled-release urea was applied at 120 kg N ha^{-1}; CRU2, controlled-release urea was applied at 180 kg N ha^{-1}; CRU3, controlled-release urea was applied at 240 kg N ha^{-1}; CRU4, controlled-release urea was applied at 360 kg N ha^{-1}.

‡ Means within the same column and year not sharing a lowercase letter are significantly different (the Duncan multiple range tests, $p < 0.05$).

the plants (Table 2). In both growing seasons, the contents of K in rice with lodging resistance were higher than in rice with weak lodging resistance, which is in turn linked to the fertilizer treatments. Silicon metrics were similar to those of K. As we previously reported, in the 2015 season, the rice yields of CRU3 and CRU4 were greater than those of the urea treatment, the yield of CRU2 was nearly same as urea, and the yield of CRU1 was less than that of urea. Results in 2016 were similar to those in the 2015 season.

DISCUSSION

In comparison with CRU treatments, the urea treatment failed to satisfy the N needs of rice during the late growing season. In addition, the cumulative amount of N released in CRU4 greatly exceeded that from the urea treatment and CRU3, which was two-thirds of the urea treatment. Even the N release of CRU2 (only half the amount applied in the urea treatment) gave a cumulative N uptake similar to urea by the end of growing seasons. This indicated that the application of CRU commingled with the rice seeds by using one dose in a single application is much more effective than split applications of urea in enhancing N uptake. The direct-seeded rice plants require less N in the early growth stages, and as such, there was no need for high release of N fertilizer for rice plants at these early growing stages. The optimal application rate of the CRU should probably be from 240 to 360 kg N ha^{-1} (less than CRU4 and more than CRU3). (Fig. 2).

Table 2. Concentrations of K and Si in rice straw affected by various N fertilizer treatments.

Year	Treatment†	K concentration	Si concentration
		mg g^{-1}	
	CK	3.75e‡	2.71c
	U	6.60d	3.69b
	CRU1	7.13b	3.79b
2015	CRU2	6.89c	4.10ab
	CRU3	7.53a	4.20a
	CRU4	6.66d	4.20a
	CK	4.23d	2.91e
	U	5.53 c	3.72c
	CRU1	5.61c	3.15d
2016	CRU2	6.03bc	3.85bc
	CRU3	6.23b	4.12a
	CRU4	6.51a	3.99b

† CK, a controlled treatment with no N fertilizer; U, urea applied treatment at 360 kg N ha^{-1}; CRU1, controlled-release urea was applied at 120 kg N ha^{-1}; CRU2, controlled-release urea was applied at 180 kg N ha^{-1}; CRU3, controlled-release urea was applied at 240 kg N ha–1; CRU4, controlled-release urea was applied at 360 kg N ha^{-1}.

‡ Means within the same column not sharing a lowercase letter are significantly different (the Duncan multiple range tests, $p < 0.05$).

Rice lodging usually takes place at the lower internodes (Kashiwagi et al., 2008). Dry weight over length and the diameter of the stem were positively related to breaking resistance (Islam et al., 2007), and the lodging index of rice improved with the increasing of N application (Wu et al., 2012). The larger the lodging index value, the more susceptible the plant is to lodging. These results showed that CRU can improve the mechanical strength of rice stem and enhance lodging resistance (Table 1).

Chemical composition of the stem plays an important role in affecting the stem strength. Numerous studies had indicated that Si and K can promote silicification and lignification in thick-walled rice cells, thicken the collenchyma cells, improve keratinocyte growth, and increase cellulose content (Duan et al., 2004; Zhang et al., 2014a). As a result, the thickness of cell walls and the lodging resistance have a positive correlation with the contents of Si and K in the stem of rice (Zhang et al., 2010). In this study, Si and K concentrations in plants with CRU obviously exceed those of the urea treatment. Yang et al. (2012) reported that rice plants treated with CRUs had much larger root systems than those treated with conventional N fertilizer. As a result, CRU improved the root systems that absorbed more K and Si (Yeo et al., 1999; Yuan et al., 2017). The K and Si enhanced the strength of the stem, which improved the lodging resistance of rice. Hofmann (2016) reported that stem strength was related to the degree of compactness and the structure of cells, and usually the tighter cells had greater mechanical strength of the stem. Images of rice stem cells indicated that CRU improves rice lodging resistance over conventional urea fertilizers because the full, tight, rounded, and highly elastic cells exhibit strong mechanical resistance to external factors (Li et al., 2006; Hofmann, 2016).

Controlled-release fertilizers have played significant roles in increasing grain yield and N use efficiency and decreasing N losses of rice (Zhang et al., 2016). The higher N uptake rate was measured from CRU corresponding with the N demand of the rice, which is similar to the results of Yang et al. (2012). Nitrogen was the main factor influence the yield of crops (Zhang et al., 2018a). Enough N was supplied by CRU in all the growth stages of rice. In addition, in both 2015 and 2016, lodging happened in urea treatments to a different degree, which resulted in a decrease in rice yield. As a result, at the same and low N rates, CRU can improve grain yield of rice.

CONCLUSIONS

Compared with conventional urea, the N release characteristics of CRU found in this study more closely matched the quantities of N required by direct-seeded rice over the course of its growth period. At an equivalent or low rate as urea applied, CRU enhanced rice absorption of K and Si, which benefited lodging resistance of rice. Moreover, the lodging index also indicated that CRU can improve lodging resistance.

Conflict of Interest

The authors declare that there is no conflict of interest.

Acknowledgments

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