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Full Length Article

Polyolefin-coated Urea Improves Nitrogen Use Efficiency and Net Profitability of Rice-rice Cropping Systems

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Abstract

An effective N management could match N availability with crop demand to maximize nitrogen use efficiency (NUE) and to optimize N application rate. Using polyolefin-coated urea (POCU) to replace regular or non-coated urea (NCU) might be an option to achieve such objectives. A 2-year field study with five fertilization treatments was conducted in a rice-rice cropping system, in Qiyang, Hunan, southern China. The treatments include a control, both NCU and POCU at 150 and 300 kg N ha^{-1} yr^{-1}. The results showed that average annual NUE and grain yield over 2-years were significantly greater under POCU (50% and 11.4 t ha^{-1} yr^{-1}, respectively) than under NCU (36% and 10.6 t ha^{-1} yr^{-1}, respectively). Based on their price of both rice grains and fertilizers in 2014 with a quadratic model, an optimal N rate was calculated as 178–203 kg N ha^{-1} yr^{-1} under POCU but 364–374 kg N ha^{-1} yr^{-1} under NCU. A decrease of 46–50% N inputs could be thus achieved under POCU than under NCU. The use of slow release urea fertilizer such as POCU could maintain high grain yield and grower's income, increase NUE and decrease N losses in such rice-rice cropping systems in southern China. Application of POCU was hence agronomically practical and cost-effective over NCU in rice plantation. © 2015 Friends Science Publishers

Keywords: Agronomic-nitrogen efficiency; Grain yield; Grain value and net profitability; Partial factor productivity; Slow release N fertilizer

Introduction

Rice (*Oryza sativa* L.) is an important cereal for two-third of the global population (Patil *et al*., 2010). In general ~15% of total nitrogenous fertilizer in agriculture are used in rice production (Heffer, 2009). At present China has the second-largest rice cultivation and the biggest rice production in the word (~19% and ~29%, respectively) (FAO, 2010), which is achieved by high input of external nitrogen (N) fertilizers (Zhu and Chen, 2002). Farmlands in the southern China have a typical rice-rice (two cultivation seasons yearly called early rice and late rice) cropping system, where the average grain yield is 5.5 t ha^{-1} each season (China Statistical Yearbook, 2011) against the rice-wheat cropping system of South Asia with better system productivity (Farooq and Nawaz, 2014; Rehman *et al*., 2014). The local farmers prefer to apply high N rate for high crop yields. The N application rate per season ranges from 234–267 kg ha^{-1} and higher than the average 180 kg N ha^{-1} in China (Zhu and Chen, 2002; Ji *et al.*, 2007; Zhang *et al*., 2008). The most common rice cultivation practice in local farmers is seedling transplanting and basal fertilization, which has a 20–40% of nitrogen use efficiency (NUE) in Chinese paddy soils (Zhu and Chen, 2002; Wang *et al*., 2007). Such a low NUE is mainly attributed to rapid losses of applied N from NH_3 volatilization and denitrification (Xu *et al*., 2013), which has contributed to severe environmental problems including eutrophication, groundwater nitrate, soil acidification and greenhouse gas emissions (Ju *et al*., 2009).

An effective N management could match N availability with crop demand to maximize NUE, to optimize N application rate and to minimize the negative impact of N on the environment (Malhi *et al*., 2001; Grant *et al*., 2002; Soon *et al*., 2011). The improvement of NUE could be achieved by synchronizing N release from applied N fertilizers for plant N requirement. Different field N management strategies have been employed to improve NUE (Cassman *et al*., 1998; Ohnishia *et al*., 1999; Zhu and Chen, 2002; Ju *et al*., 2009; Haefele *et al*., 2010; Chen *et al*., 2011), or decreasing N losses such as emission of N_2O and NH_3, and leaching of NO_3^- (Shoji *et al*., 2001; Hayashi *et al*., 2008; Soon *et al*., 2011). Meanwhile, reducing the retention time that inorganic N stays in soil prior to crop uptake could decrease the risk of N losses while increasing NUE (Grant *et al*., 2012).

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Using polyolefin-coated urea (POCU) to substitute regular or non-coated urea (NCU) might be an option to achieve the objective (Shoji *et al*., 2001). Studies have showed that the N release rate of POCU could match up with the N requirement of crops including barley (Zhang *et al*., 2000), onion (Drost *et al*., 2002), potato (Pack *et al*., 2006), wheat (El-Sirafy *et al*., 2006), cotton (Chen *et al*., 2008) and rice (Shoji and Kanno, 1994; Blaise and Prasad, 1995; Singh *et al*., 2007; Tang *et al*., 2007). Studies also showed that less emission of N_2O and NH_3 under POCU than NCU (Shoji *et al*., 2001; Hayashi *et al*., 2008; Soon *et al*., 2011; Xu *et al*., 2013). Therefore, NUE is improved and environmental risk is lessened by using POCU over NCU since NUE considers the processes of both N gain and loss (Carreres *et al*., 2003; Blaylock *et al*., 2005; Weih *et al*., 2010).

However, monetary or economic considerations have hindered the adoption of POCU for the local farmers. The cost is more expensive to purchase POCU than NCU while POCU is primarily used on high value ornamental and nursery plants. In contrast, limited research has paid attention to economic efficiency or net economic return of N fertilization under an optimal N fertilization rate, which is major concern from rice growers (Cassman *et al*., 1998; Ohnishia *et al*., 1999; Zhu and Chen, 2002; Ju *et al*., 2009; Haefele *et al*., 2010; Chen *et al*., 2011). Partial factor productivity of N (PFP_N) and nitrogen agronomic efficiency (NAE) are useful measurements because they provide integrative indices that quantify total economic output relative to the utilization of N fertilizer (Cassman *et al*., 1996; 1998). By definition, PFP_N is the grain yield obtained by per unit applied N under N fertilization without the subtraction of grain yield obtained under no-N fertilization. In contrast, a positive NAE represents a net grain yield gain under per unit applied N after the subtraction of grain yield under no-N fertilization. The goal of N fertilization is therefore to obtain maximal grain yield with optimal investment in N input (Haefele *et al*., 2010). Obviously, a higher net economic return in crop production relies on a lower cost of per unit N input through a higher yield. For instance, economic efficiency was greater when using three slow-release N fertilizers, compared to the chemical ammonium nitrate in irrigated turfs (Arrobas *et al*., 2011). However, limited information is available how POCU applications could increase net economic return from rice production (Guo *et al*., 2010).

A financial comparison in the market value of N fertilizer and rice grain are hence needed to optimize N input since the wholesale price is always higher in the purchase of POCU than NCU. We thus compared the differences in grain yield, NUE, NAE and net profitability of rice between the applications of POCU over NCU during four growing seasons in a rice-rice double system in subtropical China. Our objective was to study agronomic performance of POCU application on the rice-rice cropping system and to estimate an optimal rate of POCU application for increasing NUE and net economic return while simultaneously maintaining comparatively high rice yields.

Materials and Methods

Site Description

The field experiment site is located at Qiyang (26°45′N, 111°52′E, 120 m above sea level), Hunan Province, southern China, where has a subtropical mainland monsoon climate, with an annual precipitation of 1,767 mm in 2002 and 1,097 mm in 2003 and about 83% and 75% of which occurred from March to October. The annually averaged temperature is 18.4°C in 2002 and 17.8°C in 2003 with an accumulated temperature 5,600°C (>10°C). The soil classified as Ferralic Cambosols (FAO, 2006). Basic soil properties before the experiment were 1.25 g cm^{-3} bulk density, 6.8 pH (soil: water, 1:2.5), 19.8 g organic matter kg^{-1} soil, 1.38 g total N kg^{-1} soil and available N, P (Olsen-P) and K (exchangeable K) of 135, 8.6 and 84.9 mg kg^{-1} soil, respectively.

Cropping Practice

The cropping system was a rice-rice cropping system with early (*Oryza sativa* cv. 'Pei Liangyou 288') and late rice (*O. sativa* cv. 'Xin Xiangyou 80'). The respective sown, transplanting and harvest date was on 26 March, 28 April, 28 July in 2002 and 27 March, 21 April, 24 July in 2003 for the early rice; and on 28 June, 30 July, 25 October in 2002, and 27 June, 27 July and 19 October in 2003 for the late rice. Herbicides and pesticides were applied during the growth period when needed. Irrigation was kept at 5–cm water level in the first 2 month and 0–cm in the next 2 month for the early or late rice season. Crops were manually harvested by cutting straws close to the ground. Above-ground biomass was removed from the fields. Grain and straw were air dried, threshed, oven dried at 70°C for 72 h and then weighted separately.

Experimental Design

One NCU (46% N) and three types of POCU (MEISTER S9 used in early rice, mixed MEISTER 70 and MEISTER 100 used in late rice, 40% N, Table 1) were selected. There were five N fertilization treatments with four replicates for both early and late rice (Table 1): (i) Control, no-N fertilization, (ii) urea at 75 (NCU-75) or (iii) 150 kg N ha^{-1} (NCU-150), (iv) POCU at 75 (POCU-75) or (v) 150 kg N ha^{-1} (POCU-150) (Table 1). The experiment was a randomized complete block. Each plot has an area of 12 m^2 (4 × 3 m) and separated by plastic boards. Total nitrogen fertilizer for both NCU-75 and NCU-150 were broadcasted as basal fertilization to the paddy soil immediately before rice transplanting in 2002. About 70% of total nitrogen fertilizer was broadcasted as basal fertilization, while the remaining 30% was supplied as top-dressing at the heading stage (on 12 June for early rice and on 7 September 2003 for late rice). Both POCU-75 and POCU-150 were applied as basal fertilization in both 2002 and 2003, immediately before seeding in early rice or transplanting in late rice (Table 1). In POCU treatments, MEISTER S9 was applied to the soil before seeding of early rice. Combination of 40% MEISTER 70 and 60% MEISTER 100 were broadcasted to the soil before transplanting of late rice. All treatments received 100 kg P_2O_5 ha^{-1} (superphosphate, 12% P_2O_5 content) and 110 kg K_2O ha^{-1} (potassium chloride 60% K_2O content) by broadcasting as basal fertilization before rice transplanting.

Soil and Plant Sampling

Soil samples were collected from the top 20 cm before experiment and each year. Straws from three above-ground rice plants were collected once every 10 d and a final harvest for all above-ground biomass (include above-ground straw and grain) was at the 90 d after transplanting in 2002. The above-ground biomass was harvested and removed from the field in 2002 and 2003. Upon harvest, three composited straw and grain samples were sampled in each plot for N analysis. Percentage of N in rice straw and grain was determined by the Kjeldahl method (Thomas *et al*., 1967). Total N uptake (TN) was calculated by above-ground biomass multiply with their N concentrations.

Calculations of N Efficiency and Net Profitability

Calculations of NUE, N agronomic efficiency (NAE) and partial factor productivity of applied N (PFP_N) were respectively accorded to Arrobas *et al*. (2011), Cassman *et al*. (1996 and 1998). Financial budgets were used to estimate cost and return for a 2-yr crop sequence. All prices were adjusted for inflation to 2014 values. Crop and fertilizer prices were derived from the data center of China Grain Network (http://datacenter.cngrain.com, 2014) and local markets. Net profitability was calculated as the difference between the gross revenues and total costs.

NUE (%) = 100 × [total N uptake (kg N ha^{-1}) by rice from treatments with N fertilizer application –total N uptake (kg N ha^{-1}) by rice from treatments with no-N fertilization]/ N fertilization rate (kg N ha^{-1}). (1).

NAE (kg grain kg^{-1} N) = [grain yield (kg grain ha^{-1}) of rice from treatments with N fertilizer application – grain yield (kg grain ha^{-1}) of rice from treatment with no-N fertilization] / N fertilization rate (kg N ha^{-1}). (2).

PFP_N (kg grain kg^{-1} N) = grain yield (kg grain ha^{-1}) of rice from treatments with N fertilizer application/N fertilization rate (kg N ha^{-1}). (3).

Net Profitability ($ ha^{-1}) = grain yield (kg grain ha^{-1}) of rice × unit price ($ kg^{-1}) – N fertilization rates × unit price ($ kg^{-1}). (4).

Statistical Analysis

All data analyses were conducted using the IBM SPSS 19.0 package (SPSS Inc.). A mixed model was used to analyze fertilizer type (F) and N rate effect on grain, above-ground biomass, TN, NUE, NAE, PFPN and net economic return of the rice-rice system. Fertilizer type and N level were considered fixed factors and year and block were considered random factors. Differences in means between fertilizer treatments were compared by the Fisher's protected least significant difference (LSD) procedure at $P < 0.05$ level. A polynomial contrast test was performed to determine the trend of each main effect in response to N rate and a regression equation was then estimated to fit the treatment means (Chen *et al*., 2012). The optimum N application rate for maximum grain yield and maximum net economic return were determined by the peak value of grain yield and net return from the regression equations.

Results

Grain Yield and Above-ground Biomass

Grain yield of rice were influenced by N fertilizer type and N input level (Table 2 and 4). Averaged over years and N levels, greater annual grain yields were significantly ranked as under POCU > under NCU > under control (11.4, 10.6 and 7.2 Mg ha^{-1}, respectively) (Table 2). Grain yields increased with increasing N rates until reaching a peak value, following the quadratic model (Baker *et al*., 2004; Chen *et al*., 2012). Averaged during 2002 and 2003, the regression model indicated that grain yields under POCU and NCU similarly responded to N rates in both early rice and late rice (Fig. 2). Agronomically, the optimal N rate with the maximum grain yield was considered as the optimum N input level for POCU (203 kg ha^{-1}) and NCU (374 kg ha^{-1}) (Table 6). Similarly, significant higher above-ground rice straw was ranked under POCU > under NCU > under control (8.9, 7.3 and 4.5 Mg ha^{-1}, respectively). Overall, all above-ground biomass was increased with N fertilization rate and was significantly higher under POCU than under NCU.

All above-ground biomass and total N uptake (TN) increased with days after N fertilization (Fig. 1). For both early and late rice, above-ground biomass was similar among all treatments within 10 to 30 d after N fertilization, but varied among N fertilization treatments during 35 to 60 d. In general, significantly higher above-ground biomass and TN ranked in the order of POCU-150 > POCU-75 > NCU-150 > NCU-75 > no-N fertilization control ($P < 0.05$) at 70, 80 and 90 d after N fertilization for both early and late rice (Fig. 1). Total N uptake at harvest was affected by N fertilizer type and N input level (Table 3 and 4). Averaged over years, the POCU had the highest total N uptake (100.7, 90.3 and 191.0 kg ha^{-1} for early rice, late rice and total year), and followed by NCU (86.0, 80.1 and 166.1 kg ha^{-1} for

Table 1: Rates of nitrogen fertilization as basal and top-dressing to a rice-rice cropping system

Treatments	Fertilizer	Basal fertilization in 2002 (kg N ha^{-1})		Basal fertilization in 2003 (kg N ha^{-1})		Top-dressing fertilization in 2003 (kg N ha^{-1})	
		Early rice	Late rice	Early rice	Late rice	Early rice	Late rice
Control	–	–	–	–	–	–	–
NCU-75	urea	75	75	52.5	52.5	22.5	22.5
NCU-150	urea	150	150	105	105	45	45
POCU-75	M-S9 or M-70+M-100	75	75	75	75	0	0
POCU-150	M-S9 or M-70+M-100	150	150	150	150	0	0

For 2002, NCU was applied on 27 April for the early rice and 30 July for the late rice; and POCU was on 26 March for the early rice and 30 July for the late rice, respectively

For 2003, the base fertilization or top-dressing fertilization of NCU was on 21 April or 12 June for the early rice and 27 July or 7 September for the late rice, whilst the basal fertilization of POCU was on 27 March for the early rice and 27 July for the late rice, respectively

M-S9 (100%) was applied to the early rice, while M-70 (40%) and M-100 (60%) to the late rice

Abbreviations: M-S9, MEISTER S9; M-70, MEISTER 70; M-100, MEISTER 100; NCU, non-coated urea; POCU, polyolefin-coated urea

Table 2: Grain yield, rice straw and total above-ground biomass (TB) production in a rice-rice cropping system

Treatments	Grain yield (t ha^{-1})		Rice straw (t ha^{-1})		TB (t ha^{-1})	
	2002	2003	2002	2003	2002	2003
Early rice						
Control	2.9±0.1d	4.1±0.2c	1.8±0.2d	2.6±0.3b	4.8±0.2e	6.7±0.4c
NCU-75	5.0±0.3c	5.2±0.1b	3.4±0.2c	3.9±0.2a	8.4±0.4d	9.1±0.2b
NCU-150	5.9±0.1b	5.4±0.3ab	4.1±0.5bc	4.1±0.1a	10.0±0.4c	9.5±0.2ab
POCU-75	6.5±0.2ab	5.8±0.2a	4.5±0.1b	4.3±0.2a	11.0±0.3b	10.1±0.1a
POCU-150	7.1±0.3a	5.2±0.1b	5.7±0.3a	4.3±0.3a	12.8±0.2a	9.7±0.3ab
Late rice						
Control	3.1±0.1d	4.3±0.2c	1.6±0.1d	2.9±0.2c	4.6±0.2c	7.2±0.4c
NCU-75	3.8±0.1b	5.6±0.3b	2.3±0.1c	4.1±0.2b	6.1±0.1b	9.6±0.6b
NCU-150	4.6±0.1a	6.8±0.2a	2.3±0.1c	5.1±0.1a	6.8±0.1a	11.9±0.3a
POCU-75	4.4±0.1a	6.9±0.4a	2.8±0.1b	4.8±0.3a	7.2±0.2a	11.8±0.6a
POCU-150	3.4±0.19c	6.8±0.2a	4.0±0.1a	5.1±0.2a	7.4±0.3a	11.9±0.4a
Total						
Control	6.0±0.2c	8.4±0.4c	3.4±0.2d	5.6±0.4c	9.4±0.4e	13.9±0.7c
NCU-75	8.9±0.3b	10.8±0.2b	5.7±0.3c	8.0±0.3b	14.5±0.5d	18.7±0.6b
NCU-150	10.5±0.1a	12.2±0.5a	6.3±0.5bc	9.1±0.1a	16.8±0.4c	21.4±0.5a
POCU-75	10.9±0.2a	12.7±0.5a	7.3±0.2b	9.1±0.2a	18.2±0.4b	21.8±0.7a
POCU-150	10.5±0.2a	12.0±0.2a	9.7±0.4a	9.7±0.4a	20.2±0.3a	21.6±0.6a

Data were means ± SE (n = 3) and different letters (a, b, c, d) within a column refer to significant differences (P < 0.05) among treatments in the same rice season

Abbreviations: TB, total above- ground biomass; NCU, non-coated urea; POCU, polyolefin-coated urea

early rice, late rice and total year) and control (47.7, 41.6 and 89.2 kg ha^{-1} for early rice, late rice and total year). Total N uptake increased with increasing N input levels until reaching a peak value and also followed the quadratic model (Baker *et al*., 2004; Chen *et al*., 2012) (Fig. 3). Total N uptake were greater under POCU than under NCU and then than under control.

Indices of N-use and Economic Efficiency

The NUE, NAE and PFP_N were affected by N fertilizer type and N input level (Table 3, 5). Compared to NCU, POCU application had significantly higher NUE, NAE and PFP_N (Table 3, 5). Averaged over years and N rates, the NUE was greater under POCU than under NCU in early rice (52.3% from POCU, 36.5% from NCU), late rice (47.8% from POCU, 35.3% from NCU) and annual (50.0% from POCU, 35.9% from NCU). The NAE was greater under POCU than under NCU annual (22.1 kg grain kg^{-1} N from POCU, 15.7 kg grain kg^{-1} N from NCU), but similar in early (26.2 kg grain kg^{-1} N from POCU, 17.7 kg grain kg^{-1} N from NCU) and late rice (18.0 kg grain kg^{-1} N from POCU, 13.7 kg grain kg^{-1} N from NCU). The PFP_N was greater under POCU than under NCU in early rice (61.2 or 52.8 kg grain kg^{-1} N from POCU or NCU), late rice (54.7 or 50.5 kg grain kg^{-1} N from POCU or NCU) and annual (58.0 or 51.6 kg grain kg^{-1} N from POCU or NCU).

The grain monetary value was affected by N fertilizer types (Table 5). Averaged over years and N rates, the annual grain values were greater under POCU (4,706 US$ ha^{-1}) than under NCU (4,336 US$ ha^{-1}) and then than under control (2,944 US$ ha^{-1}) (Table 6). Also averaged over years and N rates, the annual net profitability were similar under POCU and NCU and were greater under both fertilizations than under control (4,215, 4,223 and 2,944 US$ ha^{-1}, respectively). The net profitability increased with increasing N rates until reaching a peak value, following quadratic model (Fig. 4). Averaged during 2002 and 2003, the regression models indicated that a net return under POCU and NCU responded to N rates similarly in both

Table 3: Plant N uptake, nitrogen use efficiency (NUE), nitrogen agronomic efficiency (NAE) and partial factor productivity of applied N (PFP_N) under different fertilization treatments

Treatments	N uptake (kg N ha^{-1})		NUE (%)		NAE (g grain kg^{-1} N)		PFP_N (kg grain kg^{-1} N)	
	2002	2003	2002	2003	2002	2003	2002	2003
Early rice								
Control	42.8±2.0d	52.5±3.4c	–	–	–	–	–	–
NCU-75	75.3±3.5c	85.5±1.4b	43.3±3.4b	44.0±3.2b	27.8±2.6b	14.7±2.1b	66.7±3.6b	69.2±1.1b
NCU-150	89.1±2.8b	94.1±2.4a	30.9±1.7c	27.7±2.4c	19.9±1.1c	8.6±2.3b	39.3±0.6d	35.9±2.0c
POCU-75	96.0±2.8b	100.5±0.7a	71.0±4.1a	64.0±5.0a	47.4±0.9a	22.3±3.4a	86.4±2.5a	76.8±2.2a
POCU-150	113.0±2.1a	93.4±3.2a	46.8±2.0b	27.3±4.3c	27.6±2.3b	7.3±1.4b	47.0±1.8c	34.6±0.2c
Late rice								
Control	38.6±1.3c	44.6±2.4c	–	–	–	–	–	–
NCU-75	62.7±1.2b	78.5±4.5b	32.2±1.0b	45.2±4.2b	10.4±1.5b	17.4±2.8b	51.3±1.0b	74.6±4.3b
NCU-150	80.8±1.3a	98.3±2.5a	28.1±1.2bc	35.8±1.9b	10.0±0.8b	17.0±1.6b	30.4±0.4c	45.6±1.2c
POCU-75	80.7±1.3a	94.6±5.2a	56.2±1.7a	66.7±7.8a	17.9±0.6a	35.1±6.0a	58.7±1.0a	92.3±5.1a
POCU-150	76.8±3.5a	108.9±3.7a	25.5±3.0c	42.9±3.1b	2.4±0.9c	16.5±2.3b	22.8±1.3d	45.1±1.5c
Total								
Control	81.4±2.8d	97.1±1.6c	–	–	–	–	–	–
NCU-75	138.0±4.7c	164.0±4.7b	37.8±1.5b	44.6±2.8b	19.1±0.9b	16.0±1.0b	59.0±2.0b	71.9±1.6b
NCU-150	169.9±2.8b	192.4±4.2a	29.5±0.9c	31.8±1.8c	15.0±0.6c	12.8±1.8b	34.9±0.3c	40.7±1.5c
POCU-75	176.7±3.2b	195.1±5.8a	63.6±1.3a	65.3±4.8a	32.7±0.5a	28.7±4.0a	72.5±1.3a	84.5±3.5a
POCU-150	189.8±2.9a	202.3±5.4a	36.1±1.4b	35.1±2.3bc	15.0±0.9c	11.9±1.0b	34.9±1.0c	39.8±0.8c

Data were means ± SE (n = 3) and different letters (a, b, c, d) within a column refer to significant differences ($P < 0.05$) among treatments in the same rice season

Abbreviations: NAE, nitrogen agronomic efficiency; NUE, nitrogen use efficiency; NCU, non-coated urea; POCU, polyolefin-coated urea; PFP_N, Partial factor productivity of N

Table 4: The ANOVA for grain yield, total above-ground biomass (TB) and total N uptake (TN) during 2002 and 2003

Source	df	Grain yield	Straw	TB	TN
Early rice					
Fertilizer (F)	2	0.001	0.001	0.000	0.000
Nitrogen rate (N)	2	0.237	0.011	0.034	0.005
F×N	1	0.283	0.435	0.753	0.259
Late rice					
Fertilizer (F)	2	0.099	0.232	0.150	0.023
Nitrogen rate (N)	2	0.007	0.000	0.005	0.000
F×N	1	0.035	0.308	0.046	0.012
Total year					
Fertilizer (F)	2	0.000	0.035	0.030	0.003
Nitrogen rate (N)	2	0.037	0.000	0.000	0.000
F×N	1	0.000	0.248	0.080	0.002

Abbreviations: TB, total above- ground biomass; TN, total Nitrogen uotake

early rice and late rice (Fig. 3). The optimal N was determined from the regression equation at which the net return is maximized (Fig. 3). The economically optimal N rate for the maximum net return was then estimated from this net return function (178 kg ha^{-1} for POCU and 364 kg ha^{-1} for NCU, respectively).

Discussion

Agronomic Performance of POCU Fertilization

Nitrogen use efficiency and NAE are major indicators of N efficiency in the field (Moll *et al*., 1982; Weih *et al*., 2010). In general, 20–40% of NUE and 10–20 kg grain kg^{-1} N of NAE could be improved by the decrease of N supplement to rice in the Chinese paddy soils (Cassman *et al*., 2002; Zhu and Chen, 2002; Wang *et al*., 2007; Huang *et al*., 2008; Zhang *et al*., 2008; Peng *et al*., 2010). Results of this study indicated that POCU application had significantly higher aboveground biomass (yield plus straw), NUE, NAE and PFP_N compared to NCU, both in the early and late rice (Table 2-3 and Fig. 2). These advantages of POCU over NCU might be that the N release from POCU could synchronize to plant N requirement (Shoji and Kanno, 1994; Xu *et al*., 2005). Some reports showed that the use of POCUs can be related to an improvement of N_2 fixation in flooded rice (Carreres *et al*., 2003) and the reduction in nutrient concentration in runoff water (Emilsson *et al*., 2007). In addition, the applications of POCU increased the residual N in the soil compared to NCU, particularly in the late growth period of rice (Soon *et al*., 2011), resulting in higher N uptake in rice (Fig. 1). As a consequence, NUE was increased and N losses was decreased under POCU (Xu *et al*., 2013).

One of the best management procedures for NCU was to split its application at different crop growth stages, although it was difficult to operate and labor intensive (Patil *et al*., 2010). Nevertheless, one time application of POCU was similar to the two or three split applications of NCU in terms of yield and reduction of N loading in the environment (Shaviv and Mikkelsen, 1993; Patil *et al*., 2010; Soon *et al*., 2011).

A higher plant N uptake under POCU resulted in a significant increase of NUE compared to NCU (Table 3 or Fig. 1). Suitable N management strategies including a decrease of inorganic N application rate could maintain optimal grain yield (Cassman *et al*., 1998; Dobermann and Fairhurst, 2000; Peng *et al*., 2010). Our results demonstrated that one time application of POCU could meet N

Table 5: The ANOVA for nitrogen use efficiency (NUE), nitrogen agronomic efficiency (NAE), partial factor productivity of applied N (PFP_N), grain yield and net profitability during 2002 and 2003

Source	df	NUE	NAE	PFP_N	Grain value	Net profitability
Early rice						
Fertilizer (F)	1	0.000	0.111	0.000	0.000	0.060
Nitrogen rate (N)	2	0.000	0.000	0.000	0.237	0.927
F×N	1	0.001	0.008	0.008	0.283	0.080
Late rice						
Fertilizer (F)	1	0.013	0.069	0.000	0.099	0.085
Nitrogen rate (N)	2	0.000	0.000	0.000	0.296	0.783
F×N	1	0.000	0.000	0.001	0.000	0.000
Total year						
Fertilizer (F)	1	0.000	0.000	0.007	0.019	0.001
Nitrogen rate (N)	2	0.000	0.000	0.000	0.036	0.732
F×N	1	0.000	0.000	0.000	0.000	0.120

Abbreviations: NAE, nitrogen agronomic efficiency; NUE, nitrogen use efficiency; NCU, non-coated urea; POCU, polyolefin-coated urea; PFP_N, Partial factor productivity of N

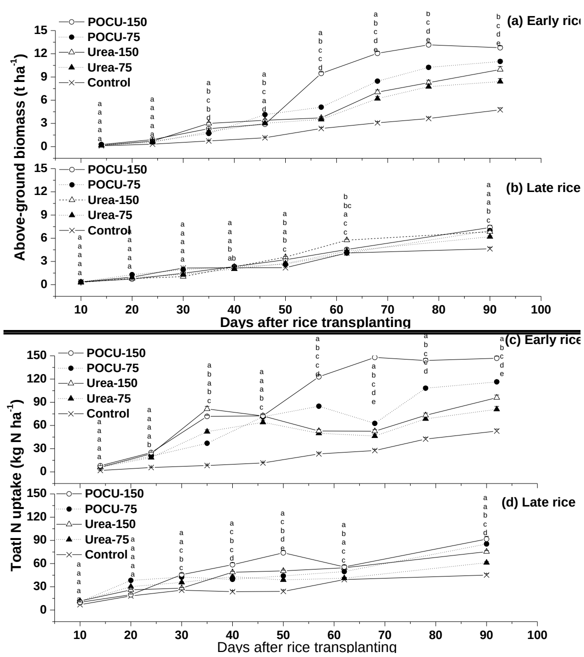

Fig. 1: Above-ground biomass (a, b) and total N uptake (c, d) during the early (a, c) and late rice (b, d) growth season in 2002. Asterisks indicated significant differences at P<0.05 among fertilization treatments

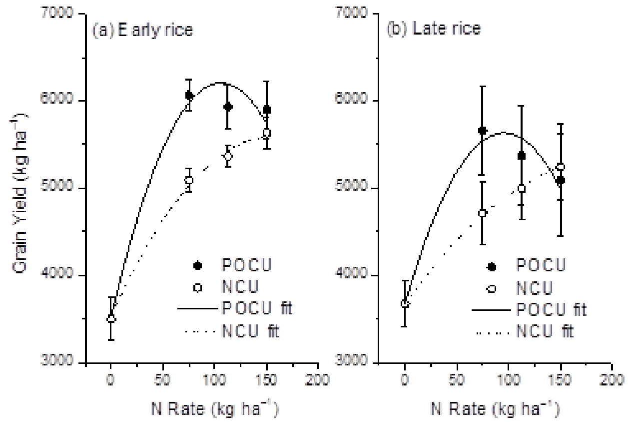

Fig. 2: Grain yield of early (a) and late rice (b) in response to N fertilization rate under POCU and NCU during 2002 and 2003. The error bars in the graphs represent ± standard error. The regression models for the fitting equations are: (a) POCU: Y=3531+50.6X-0.24X^2, R^2=0.94; NCU: Y=3536+26.3X-0.08X^2, R^2=0.97. (b) POCU: Y=3680+40.9X-0.21X^2, R^2=0.97; NCU: Y=3677+16.8X-0.04X^2, R^2=0.99

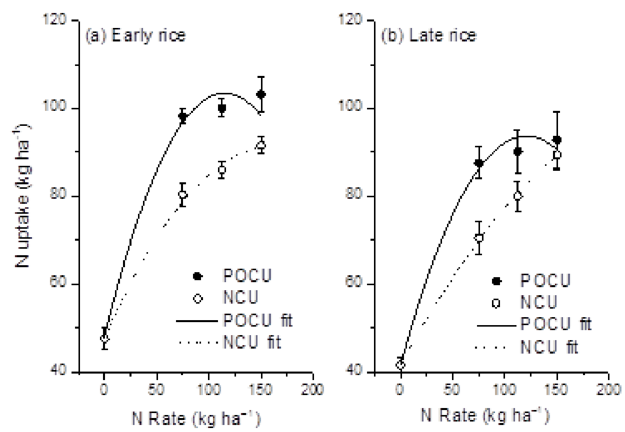

Fig. 3: Nitrogen uptake of early (a) and late rice (b) in response to N fertilization rate under POCU and NCU during 2002 and 2003. The error bars in the graphs represent ± standard error. The regression models for the fitting equations are: (a) POCU: Y=48.3+0.96X-0.004X^2, R^2=0.96; NCU: Y=47.9+0.53X-0.002X^2, R^2=0.99. (b) POCU: Y=41.6+0.86X-0.003X^2, R^2=0.99; NCU: Y=41.6+0.44X-0.001X^2, R^2=0.99

requirement during the whole rice growth period. Calculated by the regression models, a maximal grain yield of rice could be received under the application of POCU or NCU at 203 or 374 kg N ha^{-1} annually to the rice-rice double system (Table 6). A decrease of 46% N inputs could be achieved under POCU than under NCU.

Economic Considerations of POCUs

The net profitability, which is directly associated with yields, input and output prices (Chen *et al*., 2012) could response the benefits of fertilizer more comprehensively. Applications of N fertilizer significantly increased the net economic return in the rice-rice cropping system (Table 5). The maximal net profitability could be reached to 4,527 US$ ha^{-1} yr^{-1} at 178 kg N ha^{-1} with POCU or to 4,570 US$ ha^{-1} yr^{-1} at 364 kg N ha^{-1} with NCU in this rice-rice cropping system (Table 6). Application of POCU could hence reach the same net profitability with 50% of less N

Table 6: The optimum Nitrogen (N) rate for the maximum grain yield and net profitability of a rice-rice cropping system under different N fertilizers treatments from 2002 and 2003

Fertilizers	Optimum N for maximum yield (kg ha^{-1})	Maximum yield (kg ha^{-1})	Optimum N for maximum profitability (kg ha^{-1})	Maximum net profitability ($ ha^{-1})
Early rice				
NCU	164	5698	167	2247
POCU	105	6198	98	2270
Late rice				
NCU	210	5441	198	2323
POCU	97	5671	80	2257
Total year				
NCU	374	11139	364	4570
POCU	203	11869	178	4527

Abbreviations: NCU, non-coated urea; POCU, polyolefin-coated urea

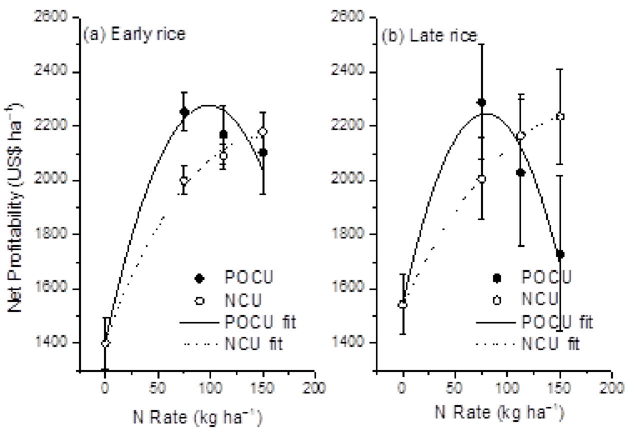

Fig. 4: Net Profitability of early (a) and late rice (b) in response to N fertilization rate under POCU and NCU during 2002 and 2003. The error bars in the graphs represent ± standard error. The regression models for the fitting equations are: (a) POCU: Y=1410+17.6X-0.09X^2, R^2=0.94; NCU: Y=1414+10.0X-0.03X^2, R^2=0.96. (b) POCU: Y=1545+17.7X-0.11X^2, R^2=0.95; NCU: Y=1543+7.9X-0.02X^2, R^2=0.9

rate compared to NCU. The optimal N rate should provide a general guide of N application rate for local farmers (Chen *et al*., 2012; Ahmed *et al.*, 2014), although such an optimal N rate determined by this method might not reflect the yearly variation of net profitability due to the changes of precipitation, price of grain and fertilizer. In addition, one-time POCU application is practical to decrease 30–40 d' labors ha^{-1} yr^{-1} that spend on the NCU application. Applications of POCU were hence cost-effective while maintaining high yield and net profitability.

Conclusions

Our results demonstrated that the application of POCU over NCU had advantages on increasing rice grain yield as well as NUE, NAE, PFP_N and net profitability for both early and late rice. A decrease of 46 – 50% N inputs could be achieved under POCU than under NCU at an optimal N or economically optimal N rate. The optimal N rate for maximum grain yield and net profitability were 178–203 kg N ha^{-1} yr^{-1} under the application of POCU, but 364–374 kg N ha^{-1} yr^{-1} under the application of NCU. The use of slow release urea fertilizers such as POCU could therefore maintain high grain yield and grower's income, increase NUE and decrease N losses in such rice-rice cropping systems in southern China. Application of POCU was hence agronomically practical and cost-effective over NCU in rice plantation.

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