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Use of Controlled-Release Urea to Improve Yield, Nitrogen Utilization, and Economic Return and Reduce Nitrogen Loss in Wheat-Maize Crop Rotations

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Abstract: Excessive nitrogen (N) fertilizer input has become a common phenomenon among most farmers in the winter wheat–summer maize rotation system of north-central China, and has resulted in low nutrient use efficiency and environmental pollution. Controlled-release urea (CRU) is proposed as a solution to excessive fertilization because CRU achieves high yields and reduces N losses. Therefore, CRU mixed with normal urea at rates based on the Nutrient Expert (NE) system was used as fertilizer in a 4-year field experiment to test the preference in crop yields, economic benefits, nitrogen use efficiencies, and N losses. The following fertilizer treatments were established: local farmers' practices (FP); normal urea fertilizer at the rate recommended by the NE system (NE); mixed CRU and normal urea at ratios of 60:40 (CRU1) and 75:25 (CRU2) based on the NE system; and 80% of the recommended N rate of the NE, CRU1 and CRU2 treatments (80% NE, 80% CRU1 and 80% CRU2). The results showed that, compared with the NE treatment at the same application rate of N, mixed CRU and urea increased yields and net benefits while reducing N loss. The application of CRU at 60% for maize and 75% for wheat had the best overall effects. Compared with FP, the average grain yield, recovery efficiency of N fertilizer and net benefits increased by 8.5%, 10.9% and 11.3%, respectively, for maize with CRU1, and increased by 4.5%, 15.1% and 10.3%, respectively, for wheat with CRU2. Furthermore, mixed CRU and urea at the recommended N rate significantly reduced N loss from 38.5% to 40.3% but increased soil NO_3^--N and NH_4^+-N contents at 0–30 cm, although opposite results (NO_3^--N) were observed deeper in the soil (30–90 cm). In the treatments 80% CRU1 and 80% CRU2, the maize yield and overall economic benefits were equivalent to those in the FP treatment, but apparent N loss was significantly reduced. Thus, these results confirmed that the combination of the CRU and the NE system for winter wheat–summer maize in north-central China is efficient and valuable, and has the potential to improve yield, nitrogen use efficiency and net benefit with low N losses.

Keywords: controlled-release urea; net economic benefit; nitrogen use efficiency; apparent nitrogen losses; wheat-maize rotation

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1. Introduction

The winter wheat–summer maize rotation is one of the most important cropping systems on the North China Plain, providing more than 52.4% of wheat and 32.1% of maize production on 25.1% of the cultivated land in China [1]. However, excessive fertilization is also a prominent problem in the region. Driven by the desire for high yields to attain high economic return, most farmers are willing to invest in fertilizer, but tend to ignore the environmental pollution resulting from fertilizer loss, particularly that caused by nitrogen (N). According to farmers' practices, the average chemical N input in intensive wheat–maize systems can exceed 500 kg ha^{-1} y^{-1} [2–4], but for most farmers, the high N input results in N recovery efficiency that is usually less than 25% [3,5]. The N losses cause environmental problems such as pollution of surface and groundwater, and emissions of greenhouse gases [6,7]. Therefore, immediate measures are urgently needed to increase nutrient use efficiency, reduce waste of resources and protect the environment.

Many effective N management practices have been adopted to improve nitrogen use efficiency (NUE), including use of a chlorophyll meter, split fertilization and high-efficiency fertilizers [8–11]. However, the pressures resulting from a decrease in availability of young agricultural labor and an increase in resource input costs bring new challenges to modern agricultural production, especially for small holders in some countries or regions. Controlled-release urea (CRU) was designed to release N to match crop nutrient demand in order to decrease the application frequency and reduce the undesirable environmental effects [12]. In recent years, the production quality of CRU has greatly increased due to the maturing of new technology and the decreasing costs of polymer material. Therefore, the application of CRU has been listed as the primary spread technology and is encouraged in rural areas [12].

The application of CRU can significantly increase crop yields and NUE and have positive effects on the environment [13–16]. Moreover, a one-time application of CRU has led to a model of production that is more labor and time cost-effective than traditional N fertilizer [17]. However, because of the polymer coating of CRU, N release can be too slow to provide the initial N for both straw decomposition and nutrient uptake during early periods of crop growth [18–20]. In addition, CRU is more expensive than normal urea [14], which limits more extensive application in food crops. Therefore, a mixture of CRU and normal urea has been advocated as a better management practice to coordinate the relationships among agronomic, economic, and environmental benefits [21,22].

Fertilizer type and fertilization time under "4R" (right source, right rate, right time and right place) can be achieved using CRU, but a reasonable fertilization rate is the prerequisite and foundation of precision nutrient management. Methods to determine the optimal fertilizer application rate include soil testing [23] and field experiments using different N rates [24], but because these methods require field sampling or establishing an experiment, in addition to their focus on normal urea, the results cannot be applied to other areas or to the use of CRU. The Nutrient Expert (NE) system was developed by the International Plant Nutrition Institute based on crop yield responses and agronomic efficiencies compiled from many previous field experiments, and is an interactive decision support tool that can rapidly provide nutrient recommendations for the fields of an individual farmer [25–28]. Therefore, combining a scientific and flexible fertilizer recommendation method with CRU may help to further increase crop yields and NUEs.

Long-term field experiments with different rates of CRU have been conducted to identify CRU effects [13,17]. As such, a scientific and flexible fertilizer recommendation method is essential to determine a reasonable CRU rate. We hypothesized that potentially positive effects can be further enhanced in measures of agronomic, economic, and environmental performance. Therefore, a 4-year field experiment was conducted from June 2015 to June 2019 in a wheat–maize rotation system in north-central China. The objective was to compare the effect of the application of mixed CRU with normal urea at the rate recommended by the NE system with the local farmers' fertilization practices for the area and with normal urea at the same fertilization rates on crop yields, economic benefits, N use efficiencies and apparent N losses. The results will provide the basis for cleaner production using highly efficient application of fertilizers, in a manner that is more sustainable and beneficial to the ecology.

2. Materials and Methods

2.1. Study Site and Materials

The experiment was conducted in a winter wheat–summer maize rotation from June 2015 to June 2019 in Dong'e County, Shandong Province, north-central China (36°11′9″ N, 116°11′10″ E). A temperate climate is predominant, and the mean air temperatures and precipitation were determined using an automatic meteorological station near the experimental plots in each season (Figure 1). The soil type is fluvo-aquic soil with sandy loam, and the initial soil chemical properties at 0 to 20 cm were the following: pH 8.2 (soil:water 1:2.5); organic matter, 11.1 g kg^{-1}; alkali-hydrolyzable N, 60.6 mg kg^{-1}; Olsen phosphorus, 14.5 mg kg^{-1}; and ammonium acetate (NH_4OAc)-potassium, 92.0 mg kg^{-1} [29]. Before planting, the soil nitrate-N (NO_3^--N) and ammonium-N (NH_4^+-N) concentrations were, respectively, 17.3 and 6.8 mg kg^{-1} at 0 to 30 cm; 14.3 and 6.6 mg kg^{-1} at 30 to 60 cm; and 7.5 and 5.8 mg kg^{-1} at 60 to 90 cm.

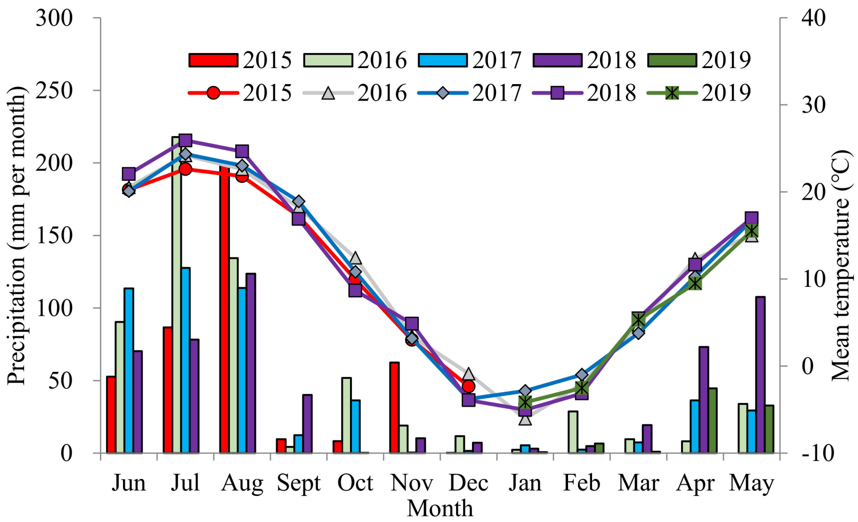

Figure 1. Monthly mean temperature and precipitation from June 2015 to June 2019 at the experimental winter wheat–summer maize rotation site in north-central China.

The maize variety was Zhengdan958, and the wheat variety was Jimai22. In the local farmers' fertilization practice, compound fertilizer and urea were applied as N:P:K at 25.0:6.1:5.8 for maize and 20.0:7.0:7.5 for wheat. The conventional fertilizers were applied as urea (46.0% N), triple superphosphate (7.8% phosphorus) and potassium chloride (49.8% potassium). Agrium Inc. Agrium Advanced Technologies Inc. (Canada) supplied the polymer coating of the polyurethane-coated urea (44.0% N, release longevity of two months).

2.2. Experimental Design

The field experiment was a randomized block design with three replications of eight treatments: (1) local farmers' practices (FP), with fertilizer application based on the traditional farmers' practices of 150 kg ha^{-1} N for maize and 292 kg ha^{-1} N for wheat; (2) Nutrient Expert (NE) [25,26], with the fertilizer recommended rate based on the NE decision support system with normal urea at 182 kg ha^{-1} N for maize and 159 kg ha^{-1} N for wheat; (3) mixed CRU and urea at the ratio of 60:40 based on the NE treatment rate (CRU1); (4) mixed CRU and urea at the ratio of 75:25 based on the NE treatment rate (CRU2); (5) 20% N reduction compared with the NE N rate (80% NE) with normal urea; (6) 20% N reduction compared with the CRU1 N rate (80% CRU1); (7) 20% N reduction compared with the CRU2 N rate (80% CRU2); and (8) control with no N application (CK).

Winter wheat was grown from mid-October to early June, and summer maize was grown from mid-June to late September. The N was applied into two parts, with half applied as basal and half side-dressed by deep application at the stalk elongation stage of maize in the NE and 80% NE treatments, and with half applied as basal and half broadcast before irrigation at the jointing stage of wheat in FP, NE and 80% NE treatments. In the other treatments, N was applied as basal fertilizer once before the planting of maize or wheat. In the FP treatment, the respective phosphorus and potassium fertilizer application rates were 37 and 35 kg ha^{-1} for maize and 42 and 45 kg ha^{-1} for wheat, and in the other treatments were 22 and 45 kg ha^{-1} for maize and 45 and 58 kg ha^{-1} for wheat. All phosphorus and potassium fertilizers were applied in one application before sowing. Irrigation practices (about 60 mm each time) included three applications for wheat before winter, around the stem elongation stage and in the flowing stage, and once for maize at the filling stage. The plot size was 30 m^2 (3.6 × 8.3 m). The density of maize was 67,000 plants ha^{-1}, and wheat seeds were planted at 210 kg ha^{-1}. Weeds, pests and diseases were controlled by spraying of herbicides and insecticides in strict accordance with the practices of local agricultural technicians.

2.3. Sampling and Chemical Analysis

At maize harvest, two rows of plants in the middle of each plot were collected to determine maize yield. Ten well-proportioned maize plants were used to determine moisture content, which was converted to 15.5% of the standard moisture content for the final maize grain yield. Another five plants were collected from each plot and separated into straw and grain to determine the harvest index and straw weight. For wheat, three representative 1 × 1 m subplots in each plot were sampled to determine grain yield. Moisture content was measured in a subsample of grain and converted to 13.5% of standard moisture content for the final wheat grain yield. Separately, the wheat plants in a 50 cm long sample that was collected randomly from each plot were separated into straw and grain to determine the harvest index and straw weight.

To determine dry matter weight, the harvested straw and grain from subsamples were dried to constant weight (60 °C for 72 h). To determine N concentration, the straw and grain samples were ground and then digested with H_2SO_4-H_2O_2 using the Kjeldahl method. To determine initial soil chemical properties, soils were sampled from the 0 to 20 cm soil layer. To determine inorganic N concentrations, soils were sampled at 0 to 30, 30 to 60, and 60 to 90 cm before sowing and after harvest in each plot. The fresh soil samples were extracted using 0.01 mol L^{-1} $CaCl_2$ in 1:10 ratio of soil:solution. Continuous flow analysis (Foss FIAstar 5000, Sweden) was used to determine the inorganic N content (NO_3^--N and NH_4^+-N). The soil water content was measured by oven drying at 105 °C.

2.4. Statistical Analyses

The accumulated recovery efficiency (REN) and the agronomic efficiency (AEN) of N fertilizer application were used to assess NUEs and were calculated as follows:

$$\mathrm{REN}_i = \frac{\sum_{i=1}^{n}(U_{Fi} - U_{CKi})}{\sum_{i=1}^{n} F_{Ni}}$$

$$\mathrm{AEN}_i = \frac{\sum_{i=1}^{n}(Y_{Fi} - Y_{CKi}) \times 1000}{\sum_{i=1}^{n} F_{Ni}}$$

where i is the season (i = 1, 2, …), with maize or wheat counted as one season separately in a rotation; U_F and U_{CK} represent the total N uptake (kg ha^{-1}) in aboveground matter in the N application and control treatments, respectively; Y_F and Y_{CK} represent the yield (t ha^{-1}) in the N application and control treatments, respectively; and F_N is the N fertilizer application rate (kg ha^{-1}).

The annual net benefit ($ ha^{-1} y^{-1}) was calculated to assess the economic effect using the following equation:

$$\text{Net benefit} = \text{gross return} - \text{total fertilizer cost} - \text{labor cost} - \text{other cost}$$

where gross return (\$ ha^{-1}) is the maize (\$0.27 ha^{-1}) or wheat price (\$0.33 ha^{-1}) multiplied by the yield; total fertilizer cost is the sum of the fertilizer price multiplied by the amount of N, phosphorus and potassium fertilizer applied, at the prices of \$1.00 kg^{-1} for CRU-N, \$0.63 kg^{-1} for urea-N, \$0.37 kg^{-1} for phosphorus, and \$0.71 kg^{-1} for potassium. The labor costs were \$22.73 ha^{-1} for basal fertilization and \$68.18 ha^{-1} for topdressing in maize and \$90.91 ha^{-1} in wheat. Other costs included the following: \$170.45 ha^{-1} for machinery costs for maize and \$352.27 ha^{-1} for wheat; \$136.36 ha^{-1} for irrigation of maize (planting stage) and \$272.72 ha^{-1} for wheat (planting and jointing stages); \$100.00 ha^{-1} for maize seed and \$95.45 ha^{-1} for wheat seed; \$22.73 ha^{-1} for pesticide costs for maize and \$90.91 ha^{-1} for wheat; and an average of \$6.06 ha^{-1} y^{-1} for other agricultural consumables. Price data were obtained from local dealers and peasant communes.

To evaluate the environmental effect of the combination of CRU and the NE system, the apparent N balance was estimated in the soil–plant system from June 2015 to June 2019. In this study, the inorganic N accumulation (N_{min}) in each soil layer was calculated and used to estimate apparent N mineralization and apparent N loss, according to the following equations:

$$N_{min} = \frac{S_T \times S_{BD} \times N_C}{10}$$

where S_T is the soil layer thickness (cm); S_{BD} is the soil bulk density (g cm^{-3}), using 1.33 g cm^{-3} at 0 to 30 cm, 1.41 g cm^{-3} at 30 to 60 cm, and 1.43 g cm^{-3} at 60 to 90 cm; N_C represents the soil NO_3^--N and NH_4^+-N (mg kg^{-1}) contents in the different soil layers.

$$Apparent\ N\ mineralization(N_{mine}) = N_{uptake} + N_{residual} - N_{initial}$$

where *apparent N mineralization* (N_{mine}) is the estimate in the control treatment; N_{uptake} is the N uptake by the aboveground part measured at harvest; and $N_{residual}$ and $N_{initial}$ are the amounts of N_{min} in the 0 to 90 cm soil layer after harvest and before sowing, respectively.

$$Apparent\ N\ loss(N_{loss}) = N_{mine} + N_{fertilizer} + N_{initial} - N_{uptake} - N_{residual}$$

where N_{mine} is calculated from the control treatment; $N_{fertilizer}$ is the amount of fertilizer N, and $N_{residual}$, N_{uptake}, and $N_{initial}$ were calculated from the fertilization treatment.

Duncan's multiple range test was performed using SPSS 13.0 software to test differences among treatments at the 0.05 level.

3. Results

3.1. Grain Yields

Nitrogen application significantly increased maize yield ($p < 0.001$) compared with that in the control (Table 1). However, the maize yield of the control was high, with an average of 7.3 t ha^{-1} and ranged from 6.9 t ha^{-1} in 2017 to 7.7 t ha^{-1} in 2015. Compared with FP, the average maize yield increased by 3.3% with normal urea when adopting the NE system, with the increase ranging from 1.1% in 2016 to 4.6% in 2017, whereas the average yield increased by 8.7% in CRU1, with the increase ranging from 5.3% in 2016 to 11.7% in 2018, and by 5.4% in CRU2, with the increase ranging from 4.3% in 2016 to 6.4% in 2018. Thus, the maize yield increased by 5.3% in CRU1 and by 2.0% in CRU2 compared with that in NE at the same N rate. The maize yields were similar in the three treatments with a 20% reduction in the recommended N rate, i.e., 80% NE, 80% CRU1 and 80% CRU2, but the yields remained 2.2% higher than those in FP.

Table 1. Yields of maize (top) and wheat (bottom) in different fertilizer treatments in four growing seasons of a wheat–maize rotation from June 2015 to June 2019 in north-central China.

Treatment	Maize Yield (t ha^{-1}) [a]				Mean (t ha^{-1})	Change (%) [b]
	2015	2016	2017	2018		
FP	9.4 c	9.4 b	8.7 c	9.4 c	9.2 c	—
NE	9.8 b	9.5 ab	9.1 abc	9.8 bc	9.5 bc	3.3
CRU1	10.1 a	9.9 a	9.5 a	10.5a	10.0 a	8.7
CRU2	9.9 ab	9.8 ab	9.2 ab	10.0 ab	9.7 ab	5.4
80% NE	9.7 b	9.4 b	8.9 bc	9.5 bc	9.4 c	2.2
80% CRU1	9.7 b	9.4 ab	8.8 bc	9.6 bc	9.4 c	2.2
80% CRU2	9.8 b	9.5 ab	8.9 bc	9.5 bc	9.4 c	2.2
Control	7.7 d	7.4 c	6.9 d	7.4 d	7.3 d	−20.7
Treatment	**Wheat Yield (t ha^{-1})**				**Mean (t ha^{-1})**	**Change (%)**
	2015–2016	**2016–2017**	**2017–2018**	**2018–2019**		
FP	7.8 bc	8.0 ab	6.3 a	7.6 b	7.4 ab	—
NE	7.9 bc	8.1 ab	6.4a	7.8 ab	7.5 ab	1.4
CRU1	8.0 ab	8.1 a	6.6 a	7.7 ab	7.6 ab	2.7
CRU2	8.3 a	8.3a	6.6 a	7.9 a	7.8 a	5.4
80% NE	7.7 bc	7.6 bc	6.5 a	7.2 c	7.2 ab	−2.7
80% CRU1	7.9 bc	7.8 c	6.4 a	6.9 c	7.1 ab	−4.1
80% CRU2	7.6 c	7.4 c	6.0 a	7.0 c	7.0 b	−5.4
Control	6.1 d	3.3d	3.3 b	4.6 d	4.3 c	−41.9

[a] Values followed by different letters in the same column for different treatments are significantly different at the 0.05 probability level. [b] Compared with farmers' practices (FP).

The average wheat yield in the control was significantly lower ($p < 0.001$) than that in the N application treatments, with an average of 4.3 t ha^{-1} and ranging from 3.3 t ha^{-1} in 2016–2017 and 2017–2018 to 6.1 t ha^{-1} in 2015–2016 (Table 1). The wheat yield increased by 1.4% with normal urea based on the NE system compared with that in FP. The average wheat yield was not significantly different between FP and NE, CRU1 and CRU2, although the yields increased in all three treatments compared with that in FP. In particular, the wheat yield in CRU2 increased by an average of 5.4%, with the increase ranging from 3.8% in 2016–2017 to 6.4% in 2015–2016, compared with that in FP. The yield in CRU2 increased by 3.9% compared with that in NE with the same amount of N in normal urea. However, in the treatments at 80% of the recommended N rate, the average yield decreased, although not significantly, even in the mixed CRU and urea treatments, which indicated that the N rate was not sufficient in the wheat season. There was no difference in yield among 80% NE, 80% CRU1, and 80% CRU2, although the yield with spilt fertilizer application (80% NE) was higher than that with one-time fertilization (80% CRU1 and 80% CRU2).

3.2. Nitrogen Use Efficiencies

In the maize season, the REN ($p = 0.006$) and AEN ($p = 0.001$) in FP were significantly lower than those in the other treatments (Table 2). Compared with FP, the REN was increased significantly by 7.9% in NE, 10.9% in CRU1 and 10.0% in CRU2, and the AEN increased significantly by 2.4 kg kg^{-1} in NE, 4.0 kg kg^{-1} in CRU1 and 3.7 kg kg^{-1} in CRU2. Therefore, compared with NE at the same N rate, the REN improved by 3.0% in CRU1 and by 2.1% in CRU2, and the AEN increased by 1.6 kg kg^{-1} in CRU1 and by 1.3 kg kg^{-1} in CRU2. Although there were no differences in REN or AEN among 80% NE, 80% CRU1 and 80% CRU2, compared with FP, the REN increased significantly, ranging from 11.6% to 13.3%, and the AEN increased significantly, ranging from 4.5 to 4.8 kg kg^{-1}.

Table 2. Nitrogen use efficiencies of maize in different fertilizer treatments in four growing seasons of a wheat–maize rotation from June 2015 to June 2019 in north-central China.

Treatment	Maize REN (%) [a]				Mean	Change
	2015	2016	2017	2018	(%)	(%) [b]
FP	17.1 b	24.3 c	26.8 d	28.1 c	24.1 b	—
NE	18.6 b	32.3 b	37.8 c	39.2 b	32.0 a	7.9
CRU1	20.3 ab	36.9 a	40.8 ab	42.1 ab	35.0 a	10.9
CRU2	19.0 ab	35.5 ab	40.5 b	41.6 ab	34.1 a	10.0
80% NE	22.1 ab	35.4 ab	41.5 ab	43.8 ab	35.7 a	11.6
80% CRU1	22.6 ab	38.5 a	43.1 a	45.5 a	37.4 a	13.3
80% CRU2	24.5 a	35.7 ab	41.6 ab	43.0 ab	36.2 a	12.1
Treatment	Maize AEN (kg kg^{-1})				Mean	Change
	2015	2016	2017	2018	(kg kg^{-1})	(kg kg^{-1})
FP	11.4 b	9.3 c	11.7 c	11.6 c	11.0 c	—
NE	11.4 b	11.5 b	15.1 b	15.3 b	13.4 b	2.4
CRU1	13.1 ab	13.2 ab	16.6 a	17.2 a	15.0 ab	4.0
CRU2	12.4 ab	13.2 ab	16.5 a	16.7 ab	14.7 ab	3.7
80% NE	13.7 ab	13.4 ab	17.2 a	17.8 a	15.5 a	4.5
80% CRU1	14.0 a	14.1 a	17.3 a	17.8 a	15.8 a	4.8
80% CRU2	14.2 a	13.8 ab	17.2 a	17.2 a	15.6 a	4.6

[a] Values followed by different letters in the same column for different treatments are significantly different at the 0.05 probability level. REN is the recovery efficiency of N fertilizer application, AEN is the agronomic efficiency of N fertilizer application. [b] Compared with FP.

In the wheat season, the REN (p = 0.001) and AEN (p = 0.001) in FP were significantly lower than those in the other treatments (Table 3). Compared with FP, the REN was increased significantly by 12.3% in NE, 15.4% in CRU1 and 15.1% in CRU2, and the AEN was increased significantly by 4.1 kg kg^{-1} in NE, 5.5 kg kg^{-1} in CRU1 and 5.6 kg kg^{-1} in CRU2. Therefore, compared with NE at the same N rate, the REN improved by 3.1% in CRU1 and by 2.8% in CRU2, and the AEN increased by 1.4 kg kg^{-1} in CRU1 and by 1.5 kg kg^{-1} in CRU2. Because of the lower N rate, the REN and AEN were higher in 80% NE, 80% CRU1 and 80% CRU2 than those in the other treatments, but the increases were not significant compared with CRU1 and CRU2.

Table 3. Nitrogen use efficiencies of wheat in different fertilizer treatments in four growing seasons of a wheat–maize rotation from June 2015 to June 2019 in north-central China.

Treatment	Wheat REN (%) [a]				Mean	Change
	2015–2016	2016–2017	2017–2018	2018–2019	(%)	(%) [b]
FP	21.7 c	27.4 c	27.7 c	28.0 c	26.2 c	—
NE	32.1 b	40.6 b	40.6 b	40.9 b	38.5 b	12.3
CRU1	36.1 ab	43.5 ab	42.9 ab	43.9 ab	41.6 ab	15.4
CRU2	35.2 ab	43.6 ab	42.8 ab	43.5 ab	41.3 ab	15.1
80% NE	34.1 ab	44.8 a	45.6 a	44.9 ab	42.3 ab	16.1
80% CRU1	38.2 a	46.1 a	46.6 a	46.3 a	44.3 a	18.1
80% CRU2	34.8 ab	43.9 ab	44.4 ab	44.5 ab	41.9 ab	15.7
Treatment	Wheat AEN (kg kg^{-1})				Mean (kg kg^{-1})	Change (kg kg^{-1})
	2015–2016	2016–2017	2017–2018	2018–2019		
FP	7.9 b	11.6 c	11.4 c	11.3 c	10.6 c	—
NE	11.4 a	15.9 b	15.8 b	15.8 b	14.7 b	4.1
CRU1	12.7 a	17.2 ab	17.2 ab	17.4 a	16.1 ab	5.5
CRU2	13.1 a	17.6 a	17.2 ab	17.2 ab	16.2 ab	5.6
80% NE	13.2 a	18.1 a	18.4 a	18.0 a	16.9 a	6.3
80% CRU1	14.0 a	18.3 a	18.3 a	17.8 a	17.1 a	6.5
80% CRU2	13.3 a	18.1 a	17.8 a	17.4 a	16.6 a	6.0

[a] Values followed by different letters for different treatments are significantly different at the 0.05 probability level. REN is the recovery efficiency of N fertilizer application, AEN is the agronomic efficiency of N fertilizer application. [b] Compared with FP.

3.3. Economic Benefits

The fertilizer recommendation based on the NE system decreased N and phosphorus fertilizer rates but increased the potassium fertilizer rate, compared with those in FP, and as a result, reduced the total fertilizer cost, although not significantly (Table 4). However, in NE, there was additional labor cost because of the topdressing applied at the stalk elongation stage in maize. Compared with FP, CRU application increased fertilizer costs while reducing labor costs and improving yields. Compared with FP, the average net benefit increased by 3.5% in NE, 11.3% in CRU1 and 10.3% in CRU2. The net benefit of mixed CRU and urea increased notably compared with that of only urea in NE, increasing by 7.8% in CRU1 and by 6.8% in CRU2 ($p < 0.001$). The net benefit was similar among 80% NE, 80% CRU1 and 80% CRU2. Although fertilizer and labor costs were reduced in 80% CRU1 and 80% CRU2, there was no difference in the net benefit relative to that in FP because of the lower yield of wheat.

Table 4. Gross income, costs, and net benefits ($\$ ha^{-1} y^{-1}$) of different fertilizer treatments averaged over four growing seasons in a wheat–maize rotation from June 2015 to June 2019 in north-central China.

Treatment	Gross Income [a]	Fertilizer Cost	Labor Cost	Other Cost	Net Benefit	Change (%) [b]
FP	4997 c	511 ab	205 b	1257	3024 b	—
NE	5110 b	449 bc	273 a	1257	3131 b	3.5
CRU1	5263 a	525 a	114 c	1257	3367 a	11.3
CRU2	5251 a	544 ab	114 c	1257	3336 a	10.3
80% NE	4962 c	406 c	273 a	1257	3026 b	0.1
80% CRU1	4939 c	467 abc	114 c	1257	3101 b	2.5
80% CRU2	4898 c	482 abc	114 c	1257	3045 b	0.7

[a] Values followed by different letters in the same column for different treatments are significantly different at the 0.05 probability level. [b] Compared with FP for net benefit.

3.4. Apparent Nitrogen Loss and Soil Residual Nitrogen

At 0 to 30 cm, the soil NO_3^--N content was higher in FP than in the other treatments, except in CRU1, but the contents were significantly higher in FP than those in the other treatments in the deep soil layers of 30 to 60 cm and 60 to 90 cm (Table 5). Compared with FP, the soil NO_3^--N concentration was lower in each soil layer in NE, although the decrease was significant only in the two deeper soil layers. Although the differences were not significant (except in CRU1 at 0 to 30 cm), the soil NO_3^--N content increased in the top soil layer but decreased in the deeper soil layers in the treatments with mixed CRU and normal urea compared with the NE treatments with only normal urea at the same N rate. In the 0 to 30 cm soil layer, the soil NH_4^+-N content was significantly higher in all treatments with CRU than in the other treatments. However, in the two deeper soil layers, there were no significant differences in NH_4^+-N content among the treatments. For the contents of both NO_3^--N and NH_4^+-N, there were no significant differences between CRU1 and CRU2 or between 80% CRU1 and 80% CRU2 in any soil layer.

Across all seasons, the highest apparent N loss was 1195 kg ha^{-1} in FP, which was because the high N application rate (1768 kg ha^{-1}) considerably exceeded crop N uptake (1228 kg ha^{-1}) and resulted in high residual N (182 kg ha^{-1}) in soil from 0 to 90 cm (Table 6). Compared with FP, the N loss in NE decreased significantly by 35.1% because of the reduction in N fertilizer input (saving 22.9% of the N fertilizer amount), decrease in residual N and increase in N uptake. Moreover, the mixtures of CRU and urea reduced N loss more than urea only in NE at the same N application rate. The N loss in CRU1 and CRU2 decreased significantly by 40.3% and 38.5%, respectively, compared with that in FP. In addition, by increasing N uptake, the N loss was reduced by 5.2% in CRU1 and by 3.4% in CRU2 compared with that in NE. There were no significant differences in N uptake, residual N or N loss among 80% NE, 80% CRU1 and 80% CRU2. However, the N loss and residual N were reduced significantly in these three treatments, compared with those in FP, and as result, the N loss was reduced by half, without reducing N uptake.

Table 5. Concentrations of soil inorganic nitrogen in three soil layers from 0 to 90 cm in different fertilizer treatments after wheat harvest in June 2019 following four growing seasons in a wheat–maize rotation from June 2015 to June 2019 in north-central China.

Treatment	NO_3^--N (mg kg^{-1}) [a]			NH_4^+-N (mg kg^{-1})		
	0–30 cm	30–60 cm	60–90 cm	0–30 cm	30–60 cm	60–90 cm
FP	14.1 ab	11.0 a	8.3 a	3.9 b	3.2 a	3.4 a
NE	12.1 bc	5.9 b	4.8 b	3.3 b	3.4 a	3.1 a
CRU1	15.2 a	4.4 b	4.7 bc	5.6 a	3.8 a	4.2 a
CRU2	13.1 ab	4.9 b	3.8 bc	6.1 a	3.3 a	3.2 a
80% NE	9.5 cd	3.8 b	3.9 bc	3.4 b	3.3 a	3.4 a
80% CRU1	11.4 bc	2.2 b	2.5 bc	6.8 a	3.4 a	3.3 a
80% CRU2	11.4 bc	2.7 b	2.8 bc	6.5 a	3.7 a	3.6 a
Control	7.9 d	2.9 b	2.7 c	3.9 b	3.8 a	4.1 a

[a] Values followed by different letters in the same row for different treatments are significantly different at the 0.05 probability level.

Table 6. Nitrogen balance in different fertilizer treatments averaged over four growing seasons in a wheat–maize rotation from June 2015 to June 2019 in north-central China.

Treatment	FP	NE	CRU1	CRU2	80% NE	80% CRU1	80% CRU2
$N_{initial}$ (kg ha^{-1})	242	242	242	242	242	242	242
N_{mine} (kg ha^{-1})	595	595	595	595	595	595	595
$N_{fertilizer}$ (kg ha^{-1}) [a]	1768 a	1364 b	1364 b	1364 b	1091 c	1091 c	1091 c
N_{uptake} (kg ha^{-1})	1228 c	1290 b	1331 a	1325 a	1222 c	1237 c	1228 c
$N_{residual}$ (kg ha^{-1})	182 a	135 bc	156 b	141 bc	113 c	121 c	126 bc
N_{loss} (kg ha^{-1})	1195 a	776 b	714 c	735 bc	593 d	570 d	585 d
Change (%) [b]	—	−35.1	−40.3	−38.5	−50.4	−52.3	−51.0

[a] Values followed by different letters in the same row for different treatments are significantly different at the 0.05 probability level.
[b] Compared with FP for N_{loss}.

4. Discussion

4.1. Yield and Economic Benefits of the Application of Controlled-Release Urea

Basal fertilizer plus topdressing is a traditional fertilization practice in agricultural production. However, agriculture currently faces the double pressures of a reduction in availability of agricultural workers and an increase in food demand [30]. Therefore, CRU was designed to meet crop nutrient requirements, and reduce labor requirements and increase crop yields [31]. Controlled-release urea has since been applied in many crops [14,32,33]. However, the widespread use of CRU in agriculture is limited by a higher price than that of ordinary urea. Therefore, instead of using only urea, the use of mixed CRU and urea has been advocated in agricultural production to realize the mutual benefits of reductions in labor costs and increases in crop yields [34].

Compared with urea, CRU increases the yield and net profit of different crops through the continuous supply of N [13,17,19,32,33]. In the current study, the maize and wheat yields increased by 3.5% and 1.0%, respectively, in response to the fertilizer rate recommended by the NE system using normal urea instead of FP, and the maximum yield was further increased by 5.3% (CRU1) in maize and by 3.9% in wheat (CRU2) with mixed CRU and urea (Table 1). In addition, compared with NE, the mixed CRU and urea further increased the net benefit from 6.8% (CRU2) to 7.8% (CRU1) (Table 4), of which about 81.4% and 77.6% of the increased net benefit was attributed to increases in grain yield rather than a reduction in fertilizer and labor costs. The results indicate that the combination of an optimal fertilization rate and CRU can further improve net benefits by increasing yields and decreasing labor costs.

4.2. Nitrogen Use Efficiencies in Response to Controlled-Release Urea

By controlling N release, CRU can achieve synchronization between N supply and crop absorption to maximize NUE [31,35]. REN with CRU improved by more than 20% compared with the use of urea only [17,32]. Optimal fertilizer application not only reduced the N rate but also significantly increased N uptake in aboveground matter and subsequently improved REN. Furthermore, compared with traditional normal urea, REN can be enhanced with mixed CRU and urea at the same recommended N rate. The results indicated that the REN increased from 10% (maize, Table 2) to 15% (wheat, Table 3) compared with the local farmers' practices, and increased from 2% to 3% with mixed CRU and urea compared with normal urea at the same recommended N rate.

However, the N release of CRU is slow in the initial phase, whereas some crops grow rapidly and require more nutrients in this stage. For example, summer maize planted in the hot, rainy season grows rapidly and requires a greater supply of soil available nitrogen in the early stage of growth. In addition, when the straw of a previous crop is returned to the soil, there is a competitive relationship between straw decomposition and crop uptake for N [36,37]. Therefore, some additional supply of available N with CRU in the early stage is necessary to achieve the same effects of splitting fertilization to meet crop growth demands and reduce labor costs. In the current study, 40% (CRU1) and 25% (CRU2) of the total urea as uncoated urea appeared to be reasonable proportions for summer maize and winter wheat, respectively. Application of uncoated urea at 30% reduced fertilizer costs and met crop requirements in the early growth stages in a wheat–maize rotation system [17].

4.3. Effects of Controlled-Release Urea on Residual Soil Nitrogen and Apparent Nitrogen Loss

The high levels of chemical N fertilizer used by farmers significantly increase N loss by increasing ammonia volatilization, N_2O emissions, runoff and leaching, and thus, a positive relationship occurs between N loss and soil subjected to a long-term, high N application rate [38–41]. The gradual N release from CRU as one of important measures was introduced to prevent these losses by promoting crop N uptake. The studies showed that NH_3 volatilization, N_2O emissions and N leaching with CRU can be significantly reduced compared with normal urea [12,30]. In the current study, fertilizer application based on the NE system decreased apparent N loss by 35.1% compared with that in FP by reducing the N application rate and increasing N uptake. In addition, as a result of the slow N release from CRU, the N that is not absorbed by the crop can accumulate in the upper layer of the soil [19]. Compared with only urea, mixed CRU and urea can increase the soil inorganic N content to meet crop requirements during the late growth stage [19]. In the current study, the NO_3^--N and NH_4^+-N concentrations in the 0 to 30 cm soil layer with CRU were higher than those with normal urea at the same N application rate, whereas the opposite trend was observed for the NO_3^--N content in deep soil layers (30 to 90 cm). This result indicated that application of CRU effectively prevented N from leaching into deep soil layers.

4.4. Integrated Management Measures Combined with Controlled-Release Urea

In the local farmers' fertilization practices in this study, the N rate was excessive in the wheat season but was insufficient in the maize season. However, there is little room for increases in yield in intensive production areas when only the amount of fertilizer application is changed without taking any other measures. Previous research showed that winter wheat and summer maize yields only increased by 0.2 and 0.1 t ha^{-1}, respectively, in north-central China [3,4]. In the current study, the combination of the NE system and uncoated urea at 40% for maize and 25% for wheat had the best effects. Although a good fertilizer recommendation method is needed, it is also necessary to combine corresponding agronomic measures in order to achieve high productivity and efficiency. In addition, some agricultural measures have been combined with CRU to further increase yields and decrease N losses, such as deep placement of CRU for machine-transplanted rice [15], combined with water retention agents in maize [42], alternate wetting and drying irrigation for late rice [43], combinations of different fertilizer varieties for wheat and maize [19] and fertilizers with different external coatings [34]. Therefore, integrated technologies that contain a fertilization recommendation method, CRU and agronomic measures will have much greater potential to increase yields and to benefit the environment.

5. Conclusions

Compared with local farmers' practices, across all seasons, the fertilizer recommendation based on the NE system saved 22.9% of the N fertilizer amount, whereas the combination of the NE recommendation and CRU significantly increased grain yields and net benefits by 5.3% and 13.2%, respectively, and decreased N loss by 40.3%. Compared with only normal urea at the same N application rate, mixed CRU and urea further increased the gains in yields and net benefits, and also reduced N losses. In general, the application of 60% CRU for maize and 75% CRU for wheat had the best overall effects. Consequently, use of the CRU rate as recommended by the NE system has great potential to increase wheat-maize yields and reduce fertilizer loss, which provides an effective generic methodology for precision agriculture to improve measures and ensure profitability.

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