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Effects of Different Controlled-Release Fertilizers on Wheat-Maize Yield, N Balance and N Loss in Huang-Huai-Hai Region of China

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Abstract. The appropriate controlled-release fertilizers (CRFs) vary based on different regions and crops. Screening suitable CRF can match the release of nutrients with crop demand according to climate characteristics and nutrient absorption rates, improving fertilizer utilization efficiency. An experiment with wheat-maize rotation was conducted in 2016 and 2017, with treatments including the typical farmer practice (FP), CRF_A, CRF_B, CRF_C, and CRF_D treatments. The effects of different CRFs on crop yield, soil inorganic nitrogen (N) content, and N balance were studied, and N surplus was used to evaluate the use effect of N fertilizers. The results showed that CRF_A and CRF_B maintained the yields of wheat and maize under N reduced by 14.3% and 11.8%, respectively, compared with FP. The yields of wheat in 2016 and maize in 2017 in the CRF_B treatment were significantly higher than in the CRF_C treatment. There were no significant differences between the remaining treatments. There had higher soil inorganic N content of upper soil, lower content of deeper soil in the CRF_A and CRF_B treatments, and significantly lower than in the FP treatment in the 60 cm-80 cm soil at harvest. In CRF_C, there was a higher residual inorganic N in the entire soil profile as well as in the 60 cm-100 cm layer for CRF_D. The results of the N balance analysis in the soil-crop system showed that N uptake was the greatest, N loss was relatively lower for CRF_A in 2016. N uptake for CRF_B in 2017 was remarkably higher than that of CRF_C and CRF_D, and N surplus and N loss were both the lowest. There was no remarkable difference in N uptake between FP and other treatments. Under the same N input, N uptake had a negative relationship with N surplus. There was no apparent relationship for N loss and N surplus in 2016. However, in 2017, N loss increased with the increase of N surplus, and there was no remarkable difference for soil total N among treatments during the two years of experiments. In this region, CRF_A and CRF_B are better able to maintain a stable crop yield, reducing N loss and maintaining N balance. This is an excellent choice for adapting to local soil climatic conditions.

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1. Introduction

Wheat and maize are the most major crops in China, and the utilization of nitrogen (N) fertilizer is the main method used to increase crop yield. However, the problem of low utilization efficiency of N fertilizer, causes a high loss of N to the environment, and increasing environmental risk has become prominent [1]. The results of recent ten years show, the utilization efficiency of N fertilizer in China had increased, but the utilization efficiency of applied N fertilizer in wheat and maize is only 34.8% and 29.1%, respectively [2]. Low utilization efficiency not only wastes resources, but also pollutes rivers and the atmosphere. The accumulation of inorganic nitrogen in deep soil layers under long-term fertilization could pose a great threat to groundwater. While increasing and stabilizing yield, it is also particularly important to reduce N loss and maintain N balance.

Controlled-release fertilizer (CRF) has the characteristics of synchronizing nutrient release with crop demand [3], thus improving the utilization efficiency of fertilizer, increasing and stabilizing yield, reducing N loss, decreasing the risk of agricultural non-point source pollution [4], and reducing the labor force due to one-time application. Therefore, CRF has been increasingly used in agricultural production. Compared with common fertilizers, previous studies have shown that CRFs can increase the crop production and utilization efficiency of fertilizer for wheat, maize [5-7], cotton [8], and potato [9] and reduce environmental pollution in terms of N loss [10, 11], ammonia volatilization [12], N_2O emissions [13], and soil N residues [14]. There are many types of CRFs available, but the effects of different coating techniques on nitrogen release vary based on the soil properties and crop [15]. Therefore, it is of great significance to select a CRF suitable for wheat-maize rotation with high efficiency and low pollution.

There are many indicators for evaluating nitrogen utilization efficiency. However, there are not many indicators for concurrently evaluating the economy, environment, and the conservation of soil fertility conservation; N surplus is one of the comprehensive evaluation indicators. N surplus is obtained by subtracting N uptake from N input, which includes N losses and variation of soil internal circulation, i.e. the content of N in the soil [16]. A certain amount of N surplus can maintain soil fertility under long-term tillage to achieve stable and increasing yield, but excessive N surplus would cause unnecessary N loss and N accumulation. Therefore, it is appropriate to use the relation between the N surplus index and N absorption, N loss, and total N in surface soil to evaluate the application effect of N fertilizer.

Limited research is available reporting systematic studies for crop yield, N loss, and N balance of different CRFs in the same system, so the application effect of CRFs requires further study. In wheat-maize rotation system, the effects of different CRFs on the yield of wheat and maize, N balance (including various N loss pathways), and inorganic N content were analyzed to determine the suitable controlled-release nitrogen fertilizers in this study. This study also provides a scientific evidence for the promotion of CRFs in wheat-maize rotation system in the North China Plain, which allows for cost-saving, increasing efficiency, and reduction of pollution caused by N fertilizer.

2. Materials and Methods

2.1. Experimental Materials

The field experimental site was located in the Science and Technology Park of Dezhou Academy of Agricultural Sciences, Shandong, China from Oct. 2015 to Oct. 2017 (two seasons per year for two years). This area is a typical North China Plain with flat terrain and temperate continental monsoon climate. The average annual temperature, sunshine, rainfall and frost-free period are respectively 12.9°C, 2,592 h, 547.5 mm and 208 d. The soil type at the field site is fluvial soil and sandy loam. Before sowing, the physicochemical properties of the 0 -100 cm soil layer are shown in Table 1.

Table 1. Chemical properties of soil.

Soil layers/ indexes	Organic matter/ $g \cdot kg^{-1}$	Alkaline N/$mg \cdot kg^{-1}$	Olsen-P/$mg \cdot kg^{-1}$	Available potassium/$mg \cdot kg^{-1}$	Total N/$g \cdot kg^{-1}$	pH
0-20 cm	13.17	26.56	34.27	117.00	0.80	8.59
20 cm-40 cm	7.92	20.41	15.40	67.33	0.55	8.69
40 cm-60 cm	8.32	19.43	14.45	79.00	0.55	8.71
60 cm-80 cm	8.06	17.40	11.60	87.67	0.52	8.75
80 cm-100 cm	8.05	15.09	6.41	94.00	0.54	8.63

The fertilizers tested include urea (N 46%), calcium superphosphate ($P_2O_5$43%) as phosphate fertilizer, and potassium sulfate (K_2O 50%) as potassium fertilizer. Controlled-release fertilizer A (CRF_A) is a special CRF produced by Kingenta that is resin coated urea (N 44%), and its field release periods are 150 d for wheat and 90 d for maize. Controlled-release fertilizers B, C, and D are special products for wheat and maize made by the Institute of Resources and Environment, Shandong Academy of Agricultural Sciences. Controlled-release fertilizer B (CRF_B) is a controlled-release nitrogen fertilizer coated with acrylic resin (N 44%). Controlled-release fertilizer C (CRF_C) is a controlled-release nitrogen fertilizer coated with a composite membrane, using acrylic resin as the main body and with an interpenetrating network structure obtained by emulsion polymerization (N 44%). Controlled-release fertilizer D (CRF_D) is composed of mixed CRF_B and CRF_C in a proportion of 3:1 (N 44%). The field release periods of CRF_B, CRF_C, and CRF_D during the wheat season are 120 d, 180 d, and 150 d, respectively, while the field release period in maize is 90 d.

The wheat variety used in this study was Shannong 21, and the maize variety was Luning 184, which ripens twice a year.

2.2. Experimental Design

The field experiment included five treatments: farmer practice (FP), CRF_A, CRF_B, CRF_C, and CRF_D. Each treatment was fertilized and managed by FP before the field experiment, and each treatment triplicated and arranged randomly. The experimental plot covered an area of 90 m^2 with a length of 15 m and a width of 6 m.

The amount of fertilizer applied in each treatment is shown in Table 2. Phosphorus fertilizer, potassium fertilizer, and CRFs as base fertilizers were applied once before cultivation, while urea was applied as basal fertilizer and topdressing fertilizer in the FP treatment. For the FP treatment, the topdressed urea was applied by spraying, and mechanical tillage to 20 cm soil layer was conducted after basal fertilization. The topdressed urea in the wheat and maize fields was carried out at the reviving stage for wheat and the big trumpet period for maize.

Table 2. Fertilizer amounts of treatments.

Treatments	N (kg/hm^2)		P_2O_5 (kg/hm^2)		K_2O (kg/hm^2)	
	Wheat season	Maize season	Wheat season	Maize season	Wheat season	Maize season
FP	315	255	270	45	0	60
CRF_A	270	225	150	45	120	60
CRF_B	270	225	150	45	120	60
CRF_C	270	225	150	45	120	60
CRF_D	270	225	150	45	120	60

2.3. Sample Collection

Soil samples were collected at jointing, filling, and harvest periods during the wheat season and big trumpet, booting, and harvest periods during maize season to measure the contents of nitrate nitrogen and ammonium nitrogen in the soil. Soil samples were respectively collected in 0-20 cm, 20 cm-40 cm, 40 cm-60 cm, 60 cm-80 cm, and 80 cm-100 cm soil layers on the profile of the fertilization furrow. In the same layer at each plot, three sampling points were randomly selected and mixed as a repeat. Soil samples were frozen in freezers or analyzed immediately. Soil samples in 0-20 cm soil layer at the harvest period were dried, ground, and screened by a 100 mesh sieve to measure soil total nitrogen.

Soil N_2O emission flux was monitored by static black box testing-gas chromatography [17], and the ammonia volatilization was measured by the Venting method [18]. The soil leaching water collection device is shown in Figure 1. To maintain the vertical structure of the soil, the device was installed *in situ*. The soil profile was excavated on the side of the leaching tray to place the collector and the water pipe; the leaching tray was placed on the excavated soil. An electric pump was used to conduct the sampling and to measure the volume of leaching water regularly.

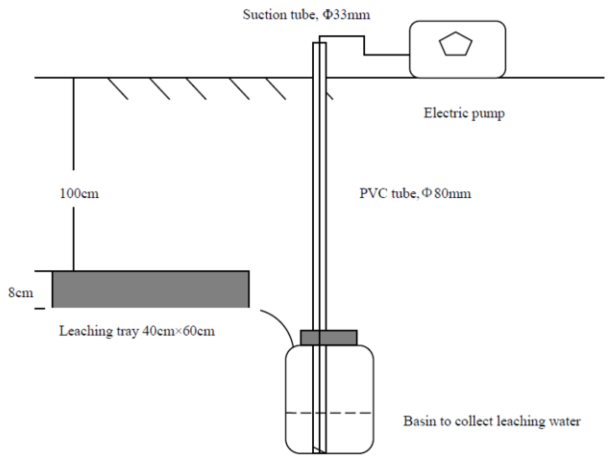

Figure 1. Device used to measure and collect water leaching from the soil.

Figure 2 shows an illustration of the soil water runoff collection device used in each treatment. To install this device, the planting area was not been destroyed. Soil was excavated along the lowest side of the plot and the collection device was installed with a water carrying capacity of 1.2 m^3. The collection device was connected with an outlet of Φ80 mm PVC pipe, and an electric pump was used regularly to sample runoff water and measure its volume. Since N_2O emission and ammonia volatilization devices were just installed in the maize season of 2016, no N_2O emission, and ammonia volatilization data were used in the calculation of N balance in 2016.

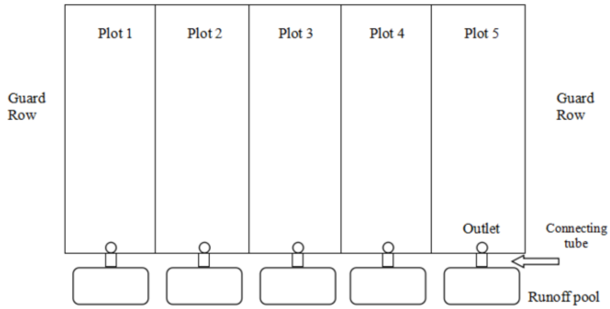

Figure 2. Device to collect water runoff from the soil.

2.4. Sample Analysis

Soil sample analyses were conducted by conventional methods [19]. Nitrate nitrogen and ammonium nitrogen in soil were determined using fresh soil extracted with 1 mol/L KCl, and nitrate and ammonium nitrogen in the filtrate and ammonium nitrogen in the filtrate of ammonia volatilization were determined using Auto Discrete Analyzers (Smartchem 200). Total N content in plants was determined in samples digested with concentrated sulfuric acid and hydrogen peroxide, and the semi-micro Kjeldahl method was used.

2.5. Equations and Statistical Analyses

The following parameters were calculated referring to the methods given by Ju [16] under the condition of straw returning.

$$\text{Nitrogen utilization efficiency (NUE)} = \text{seed N uptake}/\text{total N input}$$

$$\text{N budget} = \text{total N input} - \text{total N output}$$

$$\text{N surplus} = \text{total N input} - \text{seed N uptake}$$

$$\text{N loss} = \text{N leaching} + \text{N runoff} + \text{ammonia volatilization} + N_2O\ \text{emission}$$

SPSS 16.0 was used to analyze the data by one-way ANOVA (P<0.05), and multiple comparisons was made by Duncan's Multiple Range Test. The data were plotted using Origin.

3. Results and Analysis

3.1. Effects of Different CRFs on Wheat and Maize Yields

The yields of wheat and the yields of maize are shown in Table 3. Compared with FP, CRF reduced N by 14.3% at wheat season and 11.8% at maize season, and the effects of different CRFs on wheat yield in the two seasons were similar. The wheat yields in CRF_A and CRF_B were significantly higher than that of CRF_C in 2016. Otherwise, there were no significant differences among other treatments. Compared with maize yields in 2016 and 2017, the results that the effects of four CRFs on maize yield were slightly different. In 2016, there were no significant differences for maize yield among different treatments. In 2017, maize yield in the CRF_C treatment was significantly lower than that in CRF_B and CRF_D, but FP and CRF_A were not significantly different from other treatments.

Table 3. Wheat yields and maize yields under five treatments.

Treatments	Yield (t/hm^2)	Increase (%)	Yield (t/hm^2)	Increase (%)
	Wheat season in 2016		**Wheat season in 2017**	
FP	7.986±0.253ab	-	8.333±0.489a	-
CRF_A	8.474±0.098a	6.1	8.986±1.233a	7.8
CRF_B	8.400±0.543a	5.2	8.852±1.207a	6.2
CRF_C	7.693±0.980b	-3.7	7.616±0.528a	-8.6
CRF_D	7.820±0.411ab	-2.1	7.586±0.868a	-9.0
	Maize season in 2016		**Maize season in 2017**	
FP	11.402±1.384a	-	10.107±1.265ab	-
CRF_A	11.542±1.467a	1.2	10.342±0.378ab	2.3
CRF_B	11.795±0.273a	3.5	11.214±1.701a	11.0
CRF_C	12.283±1.076a	7.7	8.784±1.47b	-13.1
CRF_D	10.949±0.944a	-4.0	10.289±1.800a	1.8

Note: Different lowercase letters indicate significant differences among treatments (P<0.05).

3.2. Dynamic Changes of Inorganic N Content in five Soil Layers of 0 cm*-100 cm*

Soil inorganic N easily transfers to water, so N leaching downward or partly moving upward with water due to the change of water and inorganic N content during crop growth could affect the spatial and temporal distribution of inorganic N content in the soil profile [20].

The dynamic changes of inorganic N content in the wheat season of 2016 are shown in Figure 3. With the growth period, the inorganic N content in the upper two layers decreased first and then increased slightly, while in the 40 cm-100 cm layer, it increased gradually, especially in FP. At the jointing stage, the inorganic N content of soil increased first and therewith decreased as the soil depth increased. The inorganic N content in the 20 cm-40 cm layer of the CRF treatments was relatively high, with an average of 27 mg/kg, while that in the 60 cm-100 cm layer was relatively low, ranging from 6.0 mg/kg to 11.7 mg/kg. Influenced by wheat growth and water content, inorganic N content at the upper layer was transported to the lower layer during the filling stage, and no significant difference occurred among the treatments. At harvest, the inorganic N content in all layers of FP and CRF_C was relatively high, of which the residual inorganic N content in the soil in the FP treatment was the greatest. However, the inorganic N content of the lower soil layer in CRF_A and CRF_B treatments was relatively low, and that in 40 cm-80 cm layer was significantly different from that of FP. No significant difference appeared between other treatments.

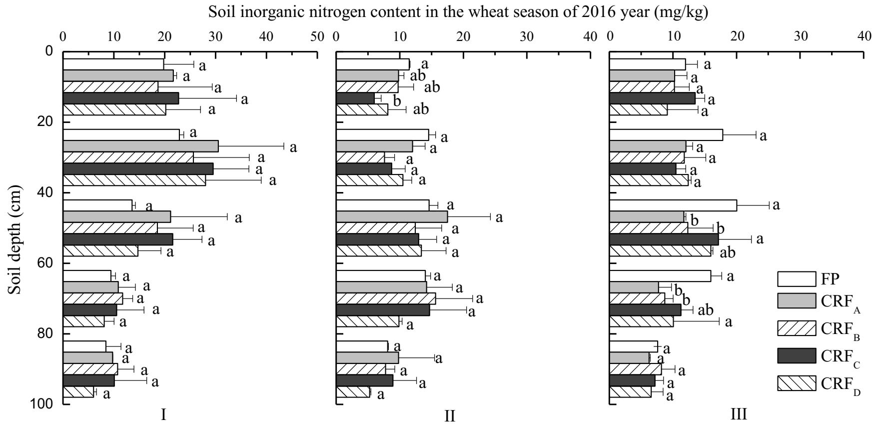

Figure 3. Dynamic changes of soil inorganic N content of 0-100 cm in the wheat season of 2016.

Note: Different lowercase letters indicate significant differences among different treatments (P<0.05). I Jointing stage; II Filling stage; III Harvest period.

The dynamic changes in soil inorganic N content in the maize season of 2016 are shown in Figure 4. Due to the rapid growth and precipitation of maize, the spatial distribution of the inorganic N content varied greatly with the growth period. At the big trumpet period, the inorganic N content was relatively low for all soil layers of the FP and CRF_A treatments. At the 60 cm-80 cm soil layer, the inorganic N content was significantly lower in the FP and CRF_A treatments than that in other treatments. The inorganic N content of CRF_B and CRF_D increased at the beginning and then decreased with the depth of the soil layer, reaching the peak value in the 20 cm-40 cm layer, and that of CRF_C in all layers were higher. At the booting stage, with the depth of the soil increasing the inorganic N content of the FP, CRF_A, and CRF_B treatments gradually decreased. The inorganic N content of CRF_B in the surface layer were higher, but the inorganic N content was lower except for the first layer, while that of CRF_C and CRF_D were higher in all layers. During the harvest period, the inorganic N content of FP, CRF_C, and CRF_D were lower in the upper soil layers, but the levels were higher in the lower layer. The opposite trend was observed in CRF_A and CRF_B, namely, the inorganic N content of CRF_A in the 60 cm-80 cm layer was obviously lower than that of FP.

The dynamic changes in soil inorganic N content in the wheat season of 2017 are shown in Figure 5. Compared with the wheat season in 2016, residual soil inorganic N in 2017 increased significantly. With the growth period, the inorganic N content in all layers showed a decreasing trend. At the jointing stage, the inorganic N content in CRF_D tended to decrease gradually, and in the 80 cm-100 cm layer the inorganic N content was significantly lower than the other treatments. The inorganic N content in all layers remained high in the other treatments, ranging from 18.8 mg/kg to 36.6 mg/kg. At the filling stage, with the depth of the soil layer increasing, the inorganic N content decreased first and then increased, but the variation was not obvious.

Compared with other treatments, CRF_A had higher inorganic N content in the 0-40 cm soil layers. At harvest, the inorganic nitrogen content in the lower layers of the FP, CRF_C, and CRF_D treatments was relatively high, while that of CRF_A and CRF_B decreased with the increasing layers depth. The inorganic N content of CRF_A and CRF_B in the 60 cm-80 cm soil layers was significantly lower than the inorganic N content in FP treatment.

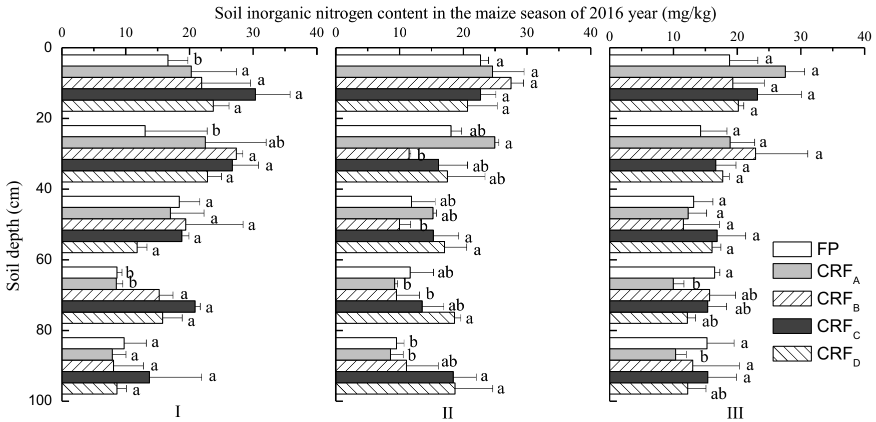

Figure 4. Dynamic changes of soil inorganic N content of 0-100 cm in the maize season of 2016.

Note: Different lowercase letters indicate significant differences among different treatments (P<0.05). I Jointing stage; II Filling stage; III Harvest period.

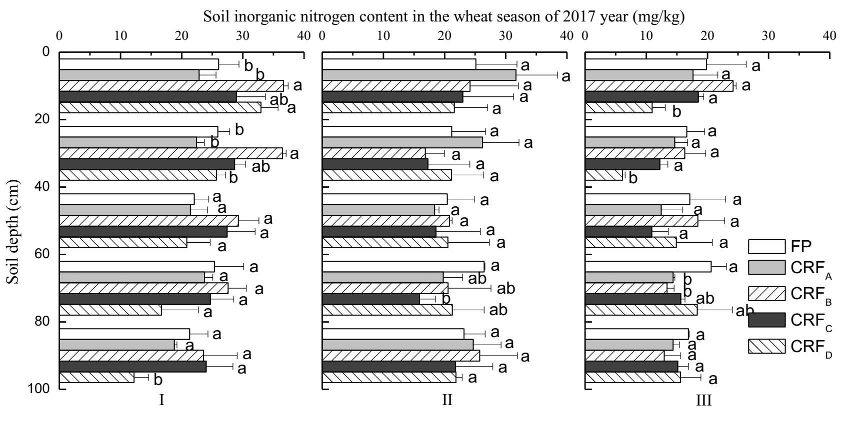

Figure 5. Dynamic changes of soil inorganic N content of 0-100 cm in the wheat season of 2017.

Note: Different lowercase letters indicate significant differences among different treatments (P<0.05). I Jointing stage; II Filling stage; III Harvest period.

3.3. N Balance Analysis under Different CRFs

The N input and N output of each treatment during the wheat-maize rotation at the anniversary of 2016 are shown in Table 4. Due to the straw returning to the field, the total output does not take into account the N uptake by the straw, and the total input does not take into account the N content returned from the straw.

Table 4. Nitrogen balance of wheat-maize rotation at the anniversary of 2016.

	Units (kg N/hm^2)	Treatments					Data sources
		FP	CRF_A	CRF_B	CRF_C	CRF_D	
Total input	Chemical Fertilizer	570	495	495	495	495	Experimental design
	Deposition of drying and wetting	18.9	18.9	18.9	18.9	18.9	Default value [21]
	Non-symbiotic N Fixation	18.75	18.75	18.75	18.75	18.75	Default value [22]
	Seed	4.70	4.70	4.70	4.70	4.70	Reference value
	Total input	612.35	537.35	537.35	537.35	537.35	
Total output	Absorption of seed	265.56	277.97	267.62	265.35	256.59	Measured value
	Leaching	3.18	2.09	2.40	8.40	4.29	Measured value
	Runoff	0.07	0.02	0.06	0.04	0.02	Measured value
	Total output	311.09	314.24	302.51	307.57	294.05	
Income and expense		343.54	257.27	267.27	263.56	276.45	
Surplus		346.79	259.38	269.73	272.00	280.76	
NUE		43.37%	51.73%	49.80%	49.38%	47.75%	

The management of each treatment was consistent. The N input in the CRF treatments was the same, but that in FP was 75 kg/hm^2 greater than that in other treatments (chemical fertilizer input). For the output, CRF_A had the highest N uptake. Compared with FP, CRF_A, and CRF_B decreased by 24.5%-34.4% in N leaching loss, but CRF_C and CRF_D increased. In the runoff loss, the loss of FP was the highest, followed by CRF_B, but their losses were relatively small. N budget and N surplus were the largest in the FP treatment, which was mainly related to a large amount of fertilizer input. In the other treatments, the order of N surplus was $CRF_A<CRF_B<CRF_C<CRF_D$. For NUE, the order was $CRF_A>CRF_B>CRF_C>CRF_D>FP$, which was related to the amount of seed uptake and fertilization.

The N input and N output of each treatment during the wheat-maize rotation at the anniversary of 2017 are shown in Table 5. For seed N uptake, CRF_B was the highest, followed by CRF_A. In addition to leaching, the N loss in FP was the largest with ammonia volatilization of 39.91 kg/hm^2, while that in CRF treatments was reduced by 19.4%-23.1%. The difference in N_2O emission between treatments was not significant. With inorganic N accumulating in the soil, the amount of N loss via leaching increased significantly compared with 2016. Aside from CRF_C, the N loss in other treatments increased by 56.0%-81.1%, but the N loss via runoff was still small. The order of N surplus is $CRF_B<CRF_A<CRF_D<CRF_C<FP$, and the order of effective NUE is $CRF_B>CRF_A>CRF_D>CRF_C>FP$.

3.4. Relationship between N Surplus in soil and N Input Productivity, Environmental Cost, and Soil Fertility

For N utilization, seed N uptake represents N input productivity, N loss (including ammonia volatilization, leaching, N_2O emission and runoff) indicates environmental cost, and total N content in the soil surface after maize harvest indicates certain soil fertility. The relationship between seed N uptake, total N and N surplus in 2016 is shown in Figure 6. As there is no data on ammonia volatilization and N_2O emissions from 2016, there is no N loss. Under the same N input, N surplus was negatively correlated with seed N uptake. For example, CRF_A had the largest N uptake and the smallest N surplus. With nitrogen surplus increasing, the total N in the surface soil decreased. It occurred that total N in CRF_A treatment was significantly higher than other treatments, but no significant difference happened between other treatments, which indicated that there was no obvious relationship between total N and N surplus in the short term.

Table 5. Nitrogen balance of wheat-maize rotation at the anniversary of 2017.

	Units (kg N/hm^2)	Test treatments					Data sources
		FP	**CRF_A**	**CRF_B**	**CRF_C**	**CRF_D**	
Total input	Chemical fertilizer	570	495	495	495	495	Experimental design
	Deposition of drying and wetting	18.9	18.9	18.9	18.9	18.9	Default value
	Non-symbiotic N fixation	18.75	18.75	18.75	18.75	18.75	Default value
	Seed	4.70	4.70	4.70	4.70	4.70	Reference value
	Total input	612.35	537.35	537.35	537.35	537.35	
Total output	Absorption of seed	269.61	271.62	294.94	260.81	262.35	Measured value
	Ammonia volatilization	39.91	32.15	30.69	31.93	30.91	Measured value
	N_2O emission	2.37	2.01	1.74	1.85	2.24	Measured value*coefficient
	Leaching	4.96	3.77	4.06	7.64	7.77	Measured value
	Runoff	0.11	0.03	0.05	0.03	0.02	Measured value
	Total output	316.96	309.58	331.48	302.26	303.29	
Income and expense		295.39	227.77	205.87	235.09	234.06	
Surplus		342.74	265.73	242.41	276.54	275.00	
NUE		44.03%	50.55%	54.89%	48.54%	48.82%	

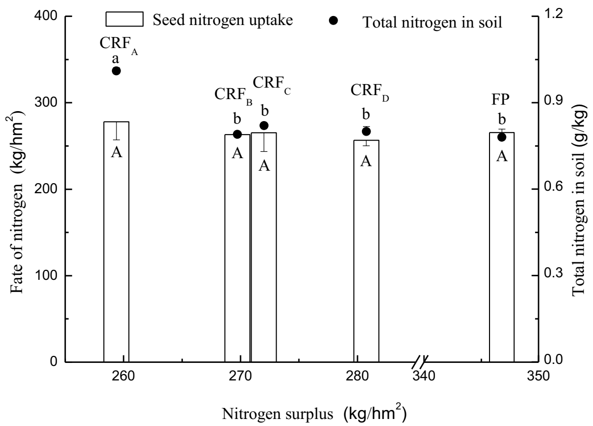

Figure 6. Relationship between N surplus, seed N uptake, and total N of soil in 2016 anniversary.

The relationship between N surplus and those three indicators in 2017 is shown in Figure 7. With the increase of N surplus, seed N uptake still showed a downward trend. Under the same N application, the N uptake of crops grown in CRF_B was significantly higher than that of CRF_C and CRF_D. FP and CRF_A did not show significant differences from the other treatments. For soil total N content, there was an increased trend with the increase of N surplus, but the difference among the treatments was not obvious. Therefore, reducing the N surplus will not decrease seed N uptake, nor will it cause soil nutrient depletion, but a higher N surplus could lead to greater environmental pollution.

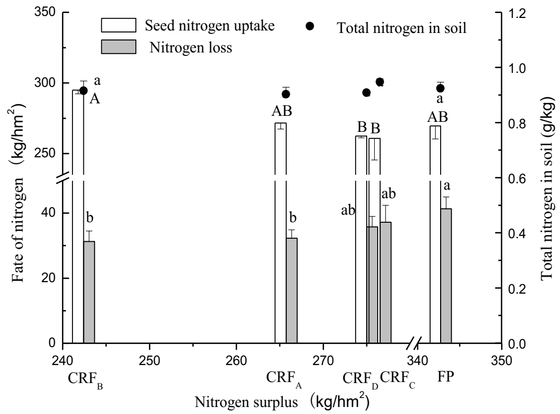

Figure 7. Relationship between N surplus, seed N uptake, N loss, and total N of soil in 2017 anniversary.

4. Discussion

4.1. Effects of Different CRFs on the Yield of Wheat and Maize

Nitrogen is one of the most important factors for crop yield. The relationship between the demand for nitrogen nutrients and the release of fertilizer nutrients at different growth stages of crops is crucial for improving crop yield, saving cost, increasing efficiency, and preventing or minimizing environmental pollution [23].

Compared with FP, the wheat yield of CRF_A and CRF_B increased during the two-year study even though lower levels of N were applied to the field. The wheat yield decreased in CRF_C and CRF_D. In the maize growing season, the effect of CRF_B on maize yield stabilization was more obvious, but the yield in CRF_C and CRF_D was not stable. In the upper two layers the inorganic N content showed that CRF_A released slowly in the early stage of wheat growth when the nutrient requirement was low, but faster in the filling stage when the nutrient requirement was high. However, maize has a shorter growth period, thus the slower nutrient release of CRF_A in the early stage is less effective in increasing maize yield. The nutrient release of CRF_B was relatively balanced, which increased the yield of wheat and maize to some extent. The interpenetrating network structure of CRF_C resulted in relatively rapid nutrient release at an early stage and relatively insufficient nutrient absorption in the later stage. A previous study conducted by Lu et al. [5] on slow/controlled-release fertilizer for wheat and maize yield in northern China indicated that maize yield showed a 20% reduction, which was significantly greater than that in conventional fertilization treatment.

4.2. Effects of Different CRFs on Accumulation and Transport of Soil Inorganic Nitrogen

The ammonization and nitrification of nitrogen have a great influence on the content of ammonium nitrogen and nitrate nitrogen of the soil after fertilizer application [7]. Different nitrogen fertilizers and N uptake rates at different crop growth stages can also lead to different in inorganic N content.

At the jointing stage, the weather became warmer and wheat began to grow rapidly. In the 0-40 cm soil layers inorganic N content decreased rapidly at this stage, but reached a relatively stable state at harvest. In the 60 cm-100 cm layers the inorganic N content in the FP and CRF_C treatments was relatively high, while that in the deeper soil layer in the CRF_A and CRF_B treatments was relatively low. At harvest, the inorganic N content in the FP treatment was relatively high in the entire soil profile, and that in the CRF_A and CRF_B treatments was higher in the upper soil layers and lower in the deeper soil layers. The inorganic N content in the deeper soil layer of the CRF_D treatment was relatively higher. The lower inorganic N content of FP in the big trumpet period of maize was related to not applying topdressing on the field. The lower inorganic N content of CRF_A was related to the nutrient release rate. At harvest, the change of inorganic N content in different treatments and soil layers was similar to that at wheat harvest. The inorganic N content in five soil layers during the wheat season in 2017 was higher, which was related to the accumulation and downward transport of inorganic nitrogen throughout the whole year. The characteristics of large amounts of fertilizer and fast decomposition of urea resulted in higher inorganic N content in each layer of the FP treatment, while the CRF_A and CRF_B treatments showed a trend of higher inorganic N value in the upper layers and lower value in the deeper layers during harvest, which could provide nutrients and alleviate groundwater pollution. A research conducted by Zhang et al. [20] found that CRF could reduce the residual nitrate nitrogen in the soil and further alleviate the risk of nitrate nitrogen pollution in shallow groundwater compared with FP treatment. The higher inorganic N content in the deeper soil layers was related to the downward transport of nitrogen due to the relatively rapid release of nutrients and the inability of crops to absorb the inorganic N content for the CRF_C and CRF_D treatments [24].

4.3 Analysis of N Loss and N Surplus under Different CRFs

Based on the two-year soil-crop N balance analysis, CRF_A and CRF_B treatments can significantly improve N utilization efficiency and reduced N loss compared to FP treatment. For several nitrogen loss pathways, the loss of ammonia volatilization is the largest. CRF can decrease the loss of ammonia volatilization due to the direct contact between coated urea and soil urease, which can reduce the release of urea nitrogen, thus reducing and delaying the ammonia volatilization in soil [25]. Through a simulation experiment, Yan et al. [26] reported that the loss of N through leaching and runoff with the one-time application of the same amount of N fertilizer was the smallest when CRF was applied, compared with FP and straw returning. The application of CRF can address the problem of over-concentration of nutrient supply by common fertilizer application regimes, improve fertilizer utilization rate, reduce the non-point source pollution caused by fertilizer loss, reduce the pollution of soil, groundwater, and air, and save fertilizer and labor costs by reducing the amount and frequency of fertilization.

N surplus includes N loss and variation of the N cycle in soil, mainly including N fixation and N mineralization in soil. During long-term tillage, the variation of the N cycle in the soil is not obvious. When soil N fixation is far greater than mineralization, it could cause soil N accumulation and groundwater pollution. When mineralization is greater than fixation, it could lead to soil N depletion, impacting soil fertility. Considering the principle of maximizing economic benefits and minimizing environmental costs, there is a reasonable N surplus under certain experimental conditions, but due to the large differences in different regions, the value of N surplus is different [27]. In this experiment, the N surplus within two years was between 242.41 kg/hm^2 and 346.79 kg/hm^2, which is much higher than the reference value of N surplus in China (65 kg N/hm^2/yr) [28]. With the increase of N surplus, there was no significant difference in N uptake between treatments, which indicated that crop yield would not increase even with excess N surplus. The relationship of total N and N surplus was not obvious, but N loss and inorganic N content in 0 cm-100 cm layer increased with the increase of N surplus. In this experiment, the value of the N surplus was quite high, which was required to reduce the N input. The application of nitrogenous fertilizer is the main source of N input, accounting for 92.1%-93.1%, so it is necessary to reduce the input of chemical fertilizer. The review paper by Zhang [29] demonstrated that the key to reducing N loss is to decrease the application of N fertilizer and improve the NUE of crops.

5. Conclusions

In the winter wheat-summer maize rotation area of the North China Plain, CRF_A and CRF_B can reduce N loss, increase N utilization efficiency, and maintain N balance in the soil while ensuring crop yield and N uptake. Compared with FP, these two CRFs can significantly decrease the inorganic N content value in the deeper soil layers during the harvest period, thereby reducing the risk of nitrogen leaching.

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