agronomy

MDPI

Article

Effect of Different Long-Term Potassium Dosages on Crop Yield and Potassium Use Efficiency in the Maize–Wheat Rotation System

Bing He, Cheng Xue, Zhimei Sun, Qingkai Ji, Jing Wei * and Wenqi Ma *

Key Laboratory for Farmland Eco-Environment of Hebei, College of Resources and Environmental Sciences, Hebei Agricultural University, Baoding 071000, China
* Correspondence: weijing_199@163.com (J.W.); mawq@hebau.edu.cn (W.M.)

Abstract: Potassium (K) is the second most important plant nutritional element and is used for numerous physiological processes. We established an eight-year experiment comparing the effects of five K fertilization treatments (0, 48, 84, 120 and 156 kg K ha^{-1}) on crop yield, K use efficiency and soil apparent K balance under the maize–wheat rotation system in the North China Plain. The highest maize and wheat yields were achieved in the K_{120} treatment, increasing by up to 16.7% and 25.1%, respectively. The increase in grain yield and K agronomic efficiency (AE_K) with K application was greater in wheat than in maize. The K recovery efficiency (RE_K) and K accumulative recovery efficiency (ARE) significantly decreased with the increase in K fertilization in the maize and wheat seasons. However, the soil apparent K balance and soil available K content increased; the former was deficiency (−24.3 kg ha^{-1} yr^{-1}) in the K_0 treatment, but the latter did not decrease significantly compared with that in the initial year of the experiment. The soil available K content increased by 10.9 mg kg^{-1} per 100 kg ha^{-1}. In conclusion, the yield response to K fertilization was greater in wheat than in maize and alleviated soil K depletion, but the K fertilizer efficiency was lower. We believed that K fertilizer can be increased moderately in the wheat season and decreased in the maize season.

Keywords: potassium application; crop yield; potassium use efficiency; potassium fate

Citation: He, B.; Xue, C.; Sun, Z.; Ji, Q.; Wei, J.; Ma, W. Effect of Different Long-Term Potassium Dosages on Crop Yield and Potassium Use Efficiency in the Maize–Wheat Rotation System. *Agronomy* **2022**, *12*, 2565. https://doi.org/10.3390/agronomy12102565

Academic Editor: Masoud Hashemi

Received: 27 September 2022
Accepted: 14 October 2022
Published: 19 October 2022

1. Introduction

Potassium is one of the essential nutrient elements for crop growth and development. It promotes enzyme activation and protein synthesis and facilitated photosynthesis. Potassium also plays important roles in improving crop quality and enhancing crop resistance [1–3]. To maximize productivity and yield while maintaining quality for crop growers, nitrogen (N) and phosphorus (P) fertilization are usually given more attention than potassium (K) [4,5]. In addition, unreasonable fertilization can also lead to soil nutrient imbalance, soil hardening, CEC anomaly, and other problems [6]. Therefore, improving K fertilization is considered to be crucial for a better understanding of the productivity and sustainability [7] and to recommend management solutions that would promote efficient use of K.

The application of K fertilizer increases wheat and maize yields [8,9]. On the basis of nitrogen (N) and phosphorus (P) fertilization, the application of K fertilizer increased winter wheat yield by more than 10.2% [10] and summer maize yield by 9.9–14.9% [11]. However, crop yield did not increase with continually increasing K fertilizer input [12,13]. Similarly, most studies show that K fertilizer use efficiency decreases with increasing fertilizer [11,14]. It has been reported that the average K recovery efficiency (RE) of maize and wheat in China is still relatively low, 30.3% and 31.9%, respectively [15]. The K fertilizer efficiency varied evidently even under the same K fertilization rates [11]. The environmental conditions, crop varieties, husbandry practices, soil K supply capacity and their interactions all influence the resulting K use efficiency [16,17]. Previous studies were mainly focused on the effect of K fertilizer application on one-season crop yield [2,18], and most studies believed that maize was relatively sensitive to K and that applied K fertilizer had a higher yield effect in maize than in wheat [17,19].

Most of the K in soil is unavailable to crop and is divided into three pools: rapidly available K (including exchangeable K and water soluble K), nonexchangeable K, and mineral K [20,21]. There are dynamic equilibrium reactions between different forms of K in soils. The soil K begins with the release of K into the soil solution from clay minerals [22]. Soil K input is available from the decomposition of crop remains and fertilizers. The crop removal of K can be momentous due to its large amount of plant uptake [6]. The loss of K with eroded soil and K leaching can occur with irrigation water and carelessly soil management practices [23]. According to statistics, soil K deficiency has been shown in a wide range of croplands worldwide [24,25]. The annual apparent soil K deficit was 134–258 kg ha^{-1} with neither K fertilization nor straw return in North China, resulting in soil K depletion [26]. Majumdar [27] showed that removal of K by crop biomass yield makes the annual soil balance deficit 14 million tons in India. The apparent K balance in Bangladesh was also severely deficient (−80–109 kg ha^{-1}) [28]. It has been argued that the soil K balance is affected by excessive N and P fertilizers, straw removal, and high-yielding varieties in recent years [29–31]. To maintain and/or improve soil K fertility in farmland and to achieve stable and high crop yield, additional attention should be given to the balance of soil K. The application of K fertilizer also immediately influenced the soil available K content, and the change in soil available K content was a closely related parameter that directly reflected the K budget in the soil crop system. In addition, long-term field experiments that can evaluate the fertilizer effects and predict nutrient balance with its influencing factors are needed to give more rational fertilization recommendations, thus ensuring the sustainable development of intensive agriculture [32,33].

In order to clarify the effect of long-term different K application rates on crop yield, K utilization and the fate of K of maize–wheat rotation system in North China Plain, an eight-year field experiment (from 2010 to 2018) was conducted. The main objectives were (i) determining the response of crop yield to different K fertilizer application rates, (ii) understanding the variations in K use efficiency with different K fertilization rates, and (iii) identifying the influence of soil apparent K balance under different K fertilization rates.

2. Materials and Methods

2.1. Site Description

The long-term field experiment was conducted from 2010 to 2018 under a maize–wheat rotation system in Qingyuan County (38.77′ N, 115.48′ E), Hebei Province, China. The study site has a warm–temperate, subhumid, continental monsoon climate. The average annual temperature is 12 °C, and the average annual precipitation is 550 mm (Figure S1). The test soil was classified as Loamy fluvo-aquic soil. The basic properties of the plow layer soil prior to the start of the experiment were as follows: pH, 8.3; organic matter content, 16 g kg^{-1}; total nitrogen content, 0.8 g kg^{-1}; available phosphorus content, 13.2 mg kg^{-1}; and available potassium content, 96.7 mg kg^{-1}.

2.2. Experimental Design

The experiment was carried out in a randomized complete block design with three replications (plot size = 44 m^2). Five treatments of different K fertilization rates were applied in each maize and wheat season: (1) K_0, control with no K fertilizer application; (2) K_{48}, K fertilizer application rate at 48 kg K ha^{-1}; (3) K_{84}, K fertilizer application rate at 84 kg K ha^{-1}; (4) K_{120}, K fertilizer application rate at 120 kg K ha^{-1}; and (5) K_{156}, K fertilizer application rate at 156 kg K ha^{-1}. Summer maize was sown in the middle of June after the harvest of winter wheat and was harvested in early October each year. The maize cultivar used in this study was 'Zhengdan 958', which is widely cultivated in the North China Plain. In each maize growing season, a total of 255 kg N ha^{-1} was applied, with 30% of the N broadcast as a basal application, 50% of the N applied at the 11-leaf stage and the remaining 20% applied at the silking stage. Phosphorus fertilizer was basally applied at 120 kg P ha^{-1} to each K treatment in one application.

Winter wheat was planted in early October shortly after the harvest of summer maize and was harvested in the middle of June in the following year. The wheat cultivars used were 'Shixin 539' in 2011–2012 and 'Jimai 22' in the rest of the experimental years. For wheat, a total of 255 kg N ha^{-1} was applied in the form of urea, with 40% of N applied at sowing before the soil was plowed, 50% of N was furrow fertilized at the jointing stage, and the remaining 10% of N was broadcast at the flowering stage. Phosphorus fertilizer was applied at 120 kg P ha^{-1} in each treatment. The P and K fertilizers were all applied at sowing. Straw was returned to the soil surface at the wheat harvest. The fertilizers used in this study were urea (of 46% N), calcium superphosphate (of 12% P), and potassium chloride (of 60% K). The straw was crushed and returned to the soil during maize harvest.

2.3. Sampling and Analysis

Summer maize was harvested from two 15 m^2 areas in each plot, and the grains were dried naturally in the sun to determine the grain yield. For wheat, two 1 m^2 areas in the center of each plot were harvested manually to determine the grain yield. Plant samples were separated into subsamples, grains and other biomass. The subsamples of maize and wheat were dried in an oven at 105 °C for 30 min and then dried to a constant weight at 70 °C. Afterward, subsamples were ground and digested in 70% concentrated H_2SO_4 and 30% H_2O_2 to determine the K content.

Soil samples (0–20 cm) were collected before the initiation of the experiment (June 2010) to determine the soil properties. After each maize harvest season from 2010 to 2017, soil samples (0–20 cm) from three random sites were collected from each experimental plot using a core sampler (5 cm diameter). The soil samples were mixed thoroughly, and the visible roots, organic residues, and stone fragments were removed. Soil samples were then passed through a 1 mm sieve and extracted with 1 mol L^{-1} NH_4OAc to determine the available K content [34].

2.4. Indicator Calculation Methods

K recovery efficiency (RE_K), K agronomic efficiency (AE_K), and K accumulative recovery efficiency (ARE) were calculated using the following equations:

$$RE_K(\%) = \frac{U - N}{F} \times 100 \tag{1}$$

$$AE_K\left(\text{kg kg}^{-1}\right) = \frac{Y - Y_0}{F} \tag{2}$$

$$ARE_n(\%) = \frac{\sum_{i=1}^{n} CU_i - \sum_{i=1}^{n} CN_i}{\sum_{i=1}^{n} CF_i} \times 100 \tag{3}$$

where F is the K fertilization rate; U and N are the aboveground plant K uptake with and without K fertilizer applications, respectively; Y and Y_0 are the grain yield in the K fertilizer application treatments with and without K fertilizer treatment, respectively; ARE_n is the K accumulative recovery efficiency in maize and wheat under the nth season (n = 1–8); CU_i and CN_i are the sums of aboveground plant K uptake in maize and wheat with and without K fertilizer application during the nth season, respectively; and CF_i is the sum of the K fertilization rates in maize and wheat during the nth season.

The apparent K balance was calculated using the following equation:

$$\text{Apparent K balance}\left(\text{kg ha}^{-1}\right) = K_{input} - K_{output} \tag{4}$$

where K_{input} includes the K fertilizer application and the K returning from straw of the previous crop and K_{output} refers to the K uptake in crop aboveground. The amount of straw K returned from wheat cultivation at the start of maize sowing in 2010 was calculated based on the farmers' traditional practice (the farmers' traditional practice application was 270 kg N ha^{-1}, 75 kg P ha^{-1}, and 75 K ha^{-1} before this study, and the straw K content of wheat was 85.0 (kg ha^{-1}) in 2010). K losses by leaching and runoff were not taken into account in the equation. A positive value indicates a surplus, and a negative value shows a deficiency in the soil K balance.

2.5. Statistical Analysis

The effects of K on crop yield, K agronomic efficiency, and K accumulative recovery efficiency were tested using one-way analysis of variance (ANOVA). Vertical T bars in the histogram indicate the standard error (SE). Mean differences were determined based on the least significant difference (LSD) at the 5% level. All statistical analyses were conducted using IBM SPSS Statistics 22.0 (IBM Corporation, Armonk, NY, USA).

3. Results

3.1. Changes of Crop Yield

The application of K fertilizers (K_{48}, K_{84}, K_{120} and K_{156}) generally increased the average maize yield compared with the K_0 treatment (Figure 1). The average maize yield under the K_{120} treatment reached 10.5 t ha^{-1}, which was 16.7%, 7.1% and 7.0% higher than that under the K_0, K_{48} and K_{84} treatments, respectively. However, no significant differences in the average maize yield were found between the K_{156} treatment and the K_{120} treatment. There were large variations in maize yield as affected by different K fertilization treatments among years. The maize yield in 2014 and 2015 were higher than those in other years. The yield increases by K fertilizer application were lower in the first three seasons than in the remaining five seasons.

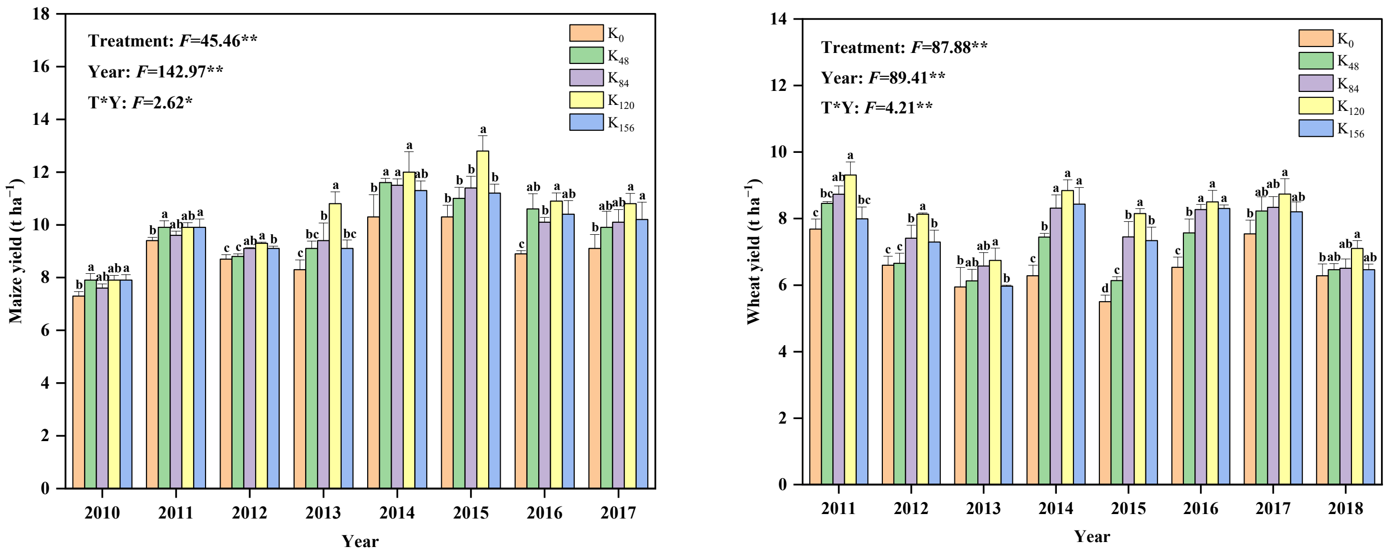

Figure 1. Effects of different K fertilization rates on maize and wheat yield between 2010 and 2018. K_0, no K fertilizer application; K_{48}, 48 kg K ha^{-1}; K_{84}, 84 kg K ha^{-1}; K_{120}, 120 kg K ha^{-1}; K_{156}, 156 kg K ha^{-1}. Vertical T bars in the histogram indicate SE. Different letters indicate significant differences among treatments. Lowercase letters represent significant differences between different fertilization treatments in the same year ($p < 0.05$). * Significant at the 0.05 probability level. ** Significant at the 0.01 probability level.

Similarly, the application of K fertilizers generally also increased the average wheat yield compared with the K_0 treatment (Figure 1). The average grain yield of wheat

(8.1 t ha^{-1}) was highest in the K_{120} treatment, which was significantly enhanced by 25.1%, 14.8%, 6.4% and 9.2% compared with the K_0, K_{48}, K_{84} and K_{156} treatments, respectively. In addition, large variations in wheat yield as influenced by K fertilizer applications fluctuated among years. Specifically, the K_0, K_{48}, K_{84}, and K_{120} treatments had the highest wheat yields in 2011, which were 7.7, 8.5, 8.7, and 9.3 t ha^{-1}, respectively. The K fertilizer applications were positively correlated with wheat yield but not with maize yield (Figure S2), and the increase in grain yield by K_{84}, K_{120}, and K_{156} was greater in wheat than in maize. The theoretical K fertilizer application and optimal K fertilizer application in the maize season by the fitting equation showed a decreasing trend (Figure 2).

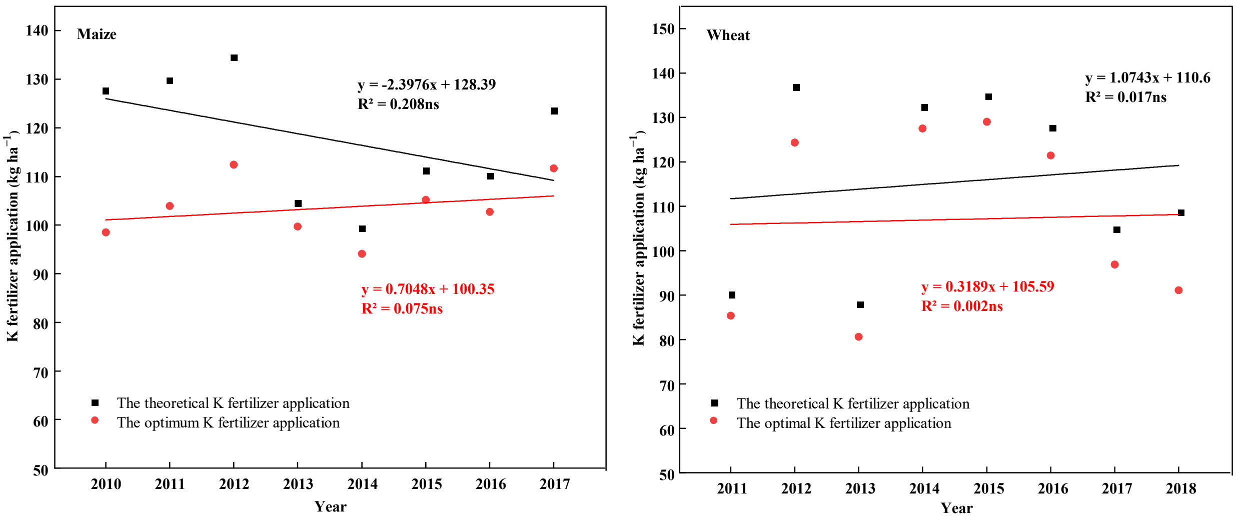

Figure 2. Relationship between the theoretical K fertilizer application and the optimal K fertilizer application of maize and wheat for eight years. The black solid line represents the fitting equation of the theoretical K fertilizer application. The red solid line represents the fitting equation of the optimal fertilizer application. ns, represents nonsignificant differences at the 0.05.

3.2. Changes of Potassium Use Efficiency

The K use efficiency with RE_K for the mean averaging over years in maize seasons significantly decreased with the K application rates (Table 1). The average RE_K from the K_{48} treatments was 39.5%, which was decreased to 16.4% from the K_{156} treatments. The AE_K was highest for the maize season under the K_{48} treatment but was not significantly different under the K_{84} and K_{120} treatments. For the wheat season (Table 2), the mean RE_K also decreased with increasing K fertilizer. Between the K_{120} and K_0 treatments, there were significant differences in AE_K in three of eight years. The RE_K and AE_K in the K_{84}, K_{120}, and K_{156} treatments in the wheat season were higher than those in the maize season. Over the experimental period, the average RE_K decreased from 73.4% in the K_{48} treatment to 44.9% in the K_{156} treatment, and the average AE_K was highest in the K_{120} treatment, which was 12.3 kg kg^{-1}. Furthermore, differences in the ARE were demonstrated among the K fertilization treatments (Table 3). The highest ARE was shown in the K_{48} treatment, ranging between 56.4% and 63.3%, while the lowest ARE was achieved in the K_{156} treatment, ranging from 28.1% to 31.6%. The ARE remained relatively stable in each treatment without obvious variations across years.

Table 1. Effects of different K fertilization rates on K recovery efficiency (RE_K) and K agronomic efficiency (AE_K) in maize season between 2010 and 2017.

Year	RE_K (%)					AE_K (kg kg^{-1})				
	K_0	K_{48}	K_{84}	K_{120}	K_{156}	K_0	K_{48}	K_{84}	K_{120}	K_{156}
2010	-	49.2 a	36.5 b	33.1 bc	20.5 c	-	12.5 a	3.7 b	4.7 b	3.7 b
2011	-	57.1 a	39.7 b	31.4 bc	22.6 c	-	11.8 a	3.3 b	4.4 b	3.5 b
2012	-	58.0 a	44.3 b	32.8 c	20.9 d	-	3.6 a	5.8 a	5.6 a	3.0 a
2013	-	38.3 a	27.6 b	23.0 bc	14.2 d	-	16.0 ab	12.8 ab	20.6 a	4.7 b
2014	-	27.0 a	27.7 a	22.6 ab	16.1 b	-	27.5 a	14.5 ab	14.1 ab	6.5 b
2015	-	24.6 a	24.4 a	18.1 b	13.0 bc	-	12.7 ab	12.6 ab	20.4 a	5.3 b
2016	-	28.7 a	22.4 ab	16.3 b	11.2 bc	-	35.4 a	13.8 b	16.8 b	9.5 b
2017	-	32.9 a	25.7 b	18.6 c	12.5 d	-	16.4 a	11.7 a	14.2 a	7.1 b
Mean	-	39.46 a	31.04 b	24.49 c	16.38 d	-	16.3 a	9.4 ab	12.6 a	5.4 b
F values										
Treatment	**					**				
Year	**					**				
T*Y	**					ns				

Values followed by lower case letter(s) within a column are significant at $p < 0.05$. ** indicated the significant at the 0.01 probability level. ns, represents nonsignificant at the 0.05 probability level.

Table 2. Effects of different K fertilization rates on K recovery efficiency (RE_K) and K agronomic efficiency (AE_K) in wheat season between 2011 and 2018.

Year	RE_K (%)					AE_K (kg kg^{-1})				
	K_0	K_{48}	K_{84}	K_{120}	K_{156}	K_0	K_{48}	K_{84}	K_{120}	K_{156}
2011	-	68.5 a	63.1 ab	48.5 c	35.7 d	-	16.1 a	12.5 a	13.5 a	2 b
2012	-	72.3 a	67 bc	54.1 c	37.9 d	-	1.1 d	9.6 b	12.8 a	4.5 c
2013	-	74.5 a	67.8 ab	65 bc	49.3 c	-	3.8 b	7.5 a	6.7 a	0.2 c
2014	-	75.6 a	67.5 b	66.8 b	49.2 c	-	24.2 a	24.2 a	21.4 a	13.8 b
2015	-	76.3 a	66.3 b	65.8 b	49.2 c	-	13.2 b	23.1 a	22.1 a	11.8 b
2016	-	73.7 a	65.7 b	58.8 c	39 d	-	21.5 a	20.6 a	16.4 b	11.3 bc
2017	-	70.7 a	68.5 ab	67.1 ab	48.1 c	-	14.4 a	9.5 b	10 ab	4.3 c
2018	-	75.4 a	71.5 a	68.5 ab	50.9 c	-	3.9 ab	2.8 b	6.9 a	1.2b c
Mean	-	73.4 a	67.2 b	61.8 c	44.9 d	-	12.3 a	13.7 a	13.7 a	6.1 b
F values										
Treatment	**					**				
Year	**					**				
T*Y	*					ns				

Values followed by lower case letter(s) within a column are significant at $p < 0.05$. *, represents significant differences at the 0.05. **, represents significant differences at the 0.01. ns, represents nonsignificant differences at the 0.05.

Table 3. Effects of different K fertilization rates on accumulative recovery efficiency (ARE) in the maize–wheat rotation periods.

Treatment	ARE (%)							
	2010–2011	2011–2012	2012–2013	2013–2014	2014–2015	2015–2016	2016–2017	2017–2018
K_0	-	-	-	-	-	-	-	-
K_{48}	58.8 a	61.8 a	63.3 a	61.7 a	59.7 a	57.9 a	56.8 a	56.4 a
K_{84}	49.8 b	51.6 b	53.1 b	51.7 b	50.7 b	49.8 b	49.2 b	49.1 b
K_{120}	40.8 c	41.8 c	44.2 c	44.4 c	44.3 bc	43.3 bc	43.1 bc	43.2 c
K_{156}	28.1 d	29.2 d	31.2 d	31.3 d	31.6 d	30.6 d	30.5 d	30.6 d
F values								
Treatment	**							
Year	**							
T*Y	ns							

Values followed by lower case letter(s) within a column are significant at $p < 0.05$. ** represents significant at the 0.01 probability level. ns, represents nonsignificant at the 0.05 probability level.

3.3. Changes of Soil Apparent K Balance

Soil K input included fertilizer K and straw K. The input of straw K for maize and wheat was 62.1–79.3 kg ha^{-1} and 55.7–114.9 kg ha^{-1}, respectively (Figure 3). The output of soil K was the absorption of aboveground crop. In the maize season, the soil K output was 84.7–114.1 kg ha^{-1}. The aboveground maize absorption in the K_0 treatment exceeded the soil K input of wheat straw, and the soil apparent K balance was deficient by −29.0 kg ha^{-1}. The soil apparent K balance increased with increasing fertilizer application rate in the other treatment groups. The K output aboveground in wheat was 54.7–131.6 kg ha^{-1}, which was highest in the K_{120} treatment. The soil apparent K balance was surplus for all five treatments in the wheat season. For the maize–wheat rotation system, the annual straw input was 117.8–185.9 kg ha^{-1}, and the average crop output was 142.1–237.7 kg ha^{-1}. Even with straw return application to the field, the K output exceeded the K input without K fertilizer application (K_0), resulting in a deficiency in the soil apparent K balance of 24.3 kg ha $^{-1}$. For the treatments with K fertilizer applications, the soil K input was higher than the K output, and the soil K exhibited a surplus of 53.7, 120.0, 188.1 and 260.2 kg ha^{-1} in the K_{48}, K_{84}, K_{120} and K_{156} treatments, respectively. The regression equation showed that a significant positive correlation existed between the soil K balance and the K fertilizer input ($y = 0.5417x + 16.835$, $R^2 = 989^{**}$). Consequently, the soil K deficit needs to be replenished by adequate inputs of K as fertilizer and residue returning in the maize–wheat rotation system.

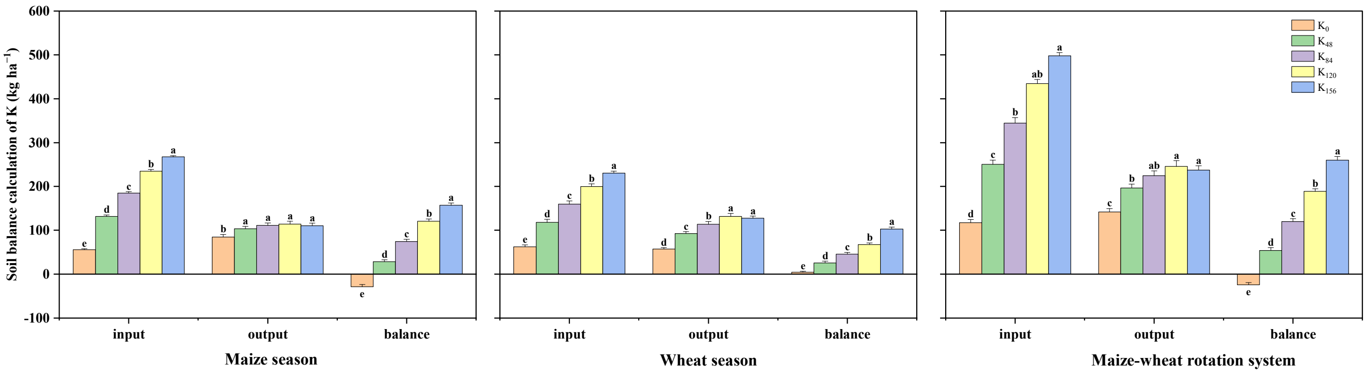

Figure 3. Effects of different K fertilization rates on soil K balance. K_0, no K fertilizer application; K_{48}, 48 kg K ha^{-1}; K_{84}, 84 kg K ha^{-1}; K_{120}, 120 kg K ha^{-1}; K_{156}, 156 kg K ha^{-1}. Vertical T bars in the histogram indicate SE. Different letters indicate significant differences among treatments.

3.4. Soil Available K

The average soil available K content increased with increasing K fertilizer application rates, but the difference between K_{156} and K_{120} treatments was not significant (Figure 4). Compared with the K_0 treatment, the average soil available K content in the K_{48}, K_{84}, K_{120} and K_{156} treatments was significantly increased by 8.1%, 20.8%, 26.5% and 32.7%, respectively. Compared with the initial soil available K content in 2010 (96.7 mg kg^{-1}), the soil available K content in the K_0 treatments was basically at the same level after eight years of rotation. However, the soil available K content in the K_{84}, K_{120} and K_{156} treatments increased with the extension of rotation years and by 18.0%, 25.1%, and 32.5% in 2018 compared with 2011, respectively. The regression equation showed that a significant positive correlation existed between the average soil available K content and the soil K balance (Figure 5). In addition, the soil available K content was affected by the accumulated K balance. For every 100 kg ha^{-1} soil apparent K accumulation, the average soil available K content was increased by 10.9 mg kg^{-1}.

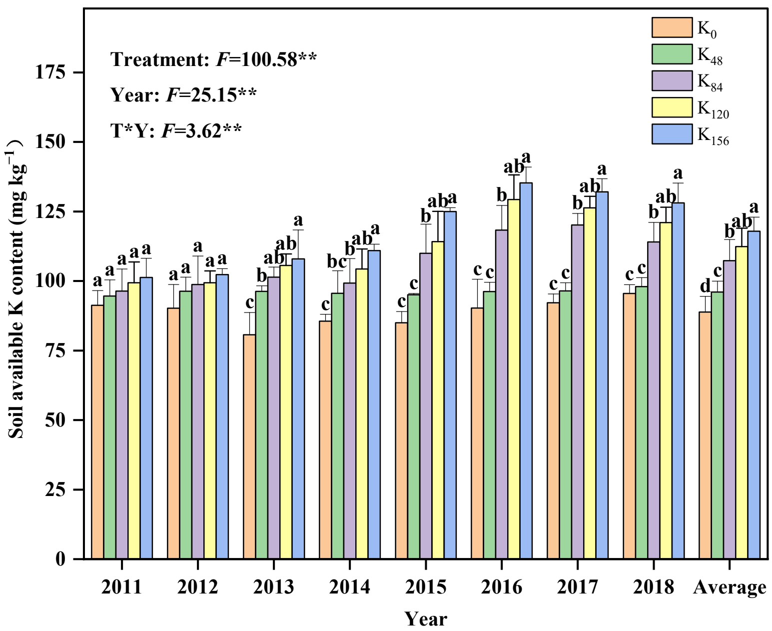

Figure 4. Effects of different K fertilization rates on soil available K content between 2010 and 2018. K_0, no K fertilizer application; K_{48}, 48 kg K ha^{-1}; K_{84}, 84 kg K ha^{-1}; K_{120}, 120 kg K ha^{-1}; K_{156}, 156 kg K ha^{-1}. Vertical T bars in the histogram indicate SE. Different letters indicate significant differences among treatments. ** Significant at the 0.01 probability level.

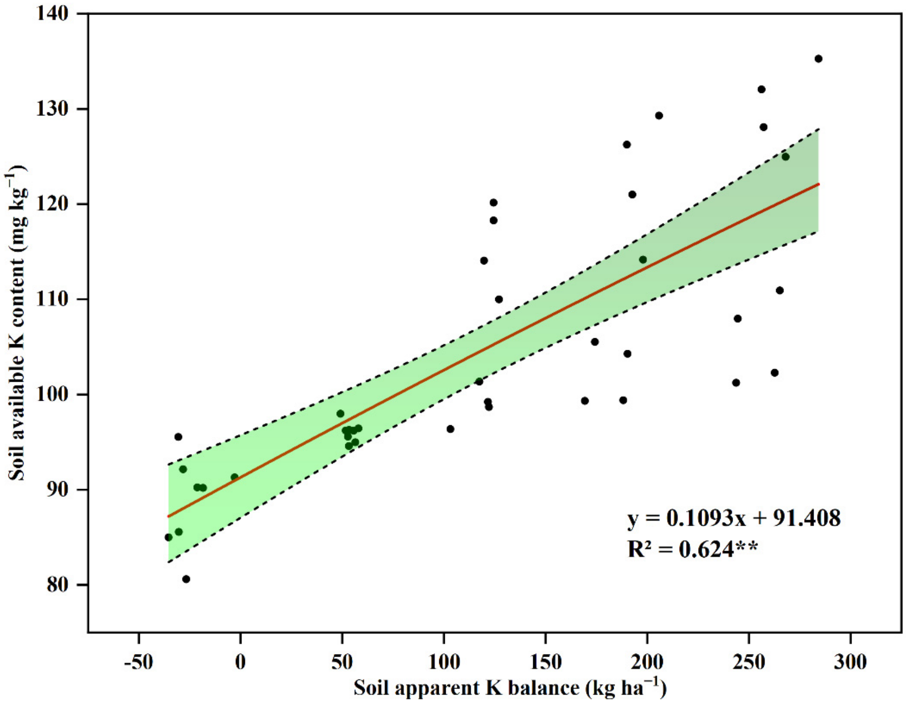

Figure 5. Relationship between soil apparent K balance and soil available K content. Linear regression is shown as a red solid line and dashed curve represents 95% confidence intervals (CI). ** Significant at the 0.01 probability level.

4. Discussion

4.1. Potassium Fertilization Rates versus Crop Yield

Potassium is one of the necessary macronutrients for crop growth. Adequate K supply is of great significance for increasing yield and improving the quality of crop [35]. In the present study, the yields of maize and wheat increased with increasing K fertilizer application rates in the range of 0 to 120 kg K ha^{-1}, while there was a tendency to decreased with further increases in K fertilization rates up to 156 kg K ha^{-1} (Figure 1). This might due to increased the crop chlorophyll content and the photosynthetic efficiency when applied K fertilizer application, leading to enhanced starch-based carbohydrate supply to the grains [36]. However, crop did not absorb luxurious amounts of K at the higher K fertilizer input (K_{156}) (Figure 3), and the grain weigh of maize and wheat have not increased significantly (Tables S1 and S2), which was supported by Singh [37]. The regression test showed that the yield for maize and wheat were achieved with 111 and 115 kg K ha^{-1}, where the crop yields were 10.2 and 7.8 t ha^{-1}, respectively (Figure S2). Furthermore, the yield of maize and wheat varied among the experimental years (Figures S2 and S3). For maize, the yield variation was positively associated with the 1000-grain weight in the present study (Table S3); similar results were reported by others [38,39]. However, the variations in wheat grain yield resulted from not only grain weight but also the number of spikes and grains per spike (Table S3), with correlation coefficients of 0.706**, 0.552** and 0.324*, respectively. The linear regression between yield components and increased yield also indicated that the interannual variation in crop yield was due to the effect of K fertilization on 1000-grain weight (Figure S3), which was in accordance with the findings of Rajicic [40]. Moreover, our study indicated that the yield response of wheat affected by K fertilization was higher than that of maize (Figure S2). This might be due to the maize yield are generally higher than in wheat at this region, so the effect of K fertilizer application on yield is slightly lower than wheat [41]. This result was also supported by the lower soil K recovery efficiency of maize compared to that of wheat (Tables 1 and 2). By fitting the theoretical and the optimal K fertilizer application over 8 years (Figure 2) (The optimal fertilizer application was based on annual maize and wheat prices, as shown in Figures S4 and S5), it can be seen that the K fertilizer application for the maize season tended to decrease with increasing farming years under the return of straw to the field, but this trend was nonsignificant in the wheat season. This may be due to the large variability of the treatment and year in the wheat season. Additionally, it also requires long-term experimental monitoring, which does not obvious over shorter periods.

4.2. Potassium Fertilization Rates versus Potassium Use Efficiency

The RE_K in the maize and wheat seasons was significantly decreased with K fertilization, which was highest under the K_{48} treatment (Tables 1 and 2). This observation was mainly because the K input of the K_{156} treatment was higher than that of the K_{48} treatment (Figure 3). Zhan [12] stated that the K use efficiency decreased once the K application rate exceeded the crop demand. Maize season has the highest AE_K at lower K fertilizer application (K_{48} treatment). However, the AE_K of the K_{120} and K_{84} treatments were higher than K_{48} treatment in the wheat season, which was due to the better yield of wheat increasing in the K_{120} and K_{84} treatments (Figure 1). In addition, the AE_K of the wheat season was higher than that of the maize season in the K_{84}, K_{120}, and K_{156} treatments (Tables 1 and 2), and the yield response increase of wheat under these treatments was also higher than that of maize under K fertilization (Figure S2). Moreover, the RE_K of wheat under the K_{48}, K_{84}, K_{120} and K_{156} treatments was much higher than that of maize, which was in agreement with the findings of Zhang [41] and Bai [42]. This result may be due to the one-time input of straw K and K fertilizer, soil K resulted in a large amount of loss by leaching, runoff and infiltration in the maize season with high temperatures and heavy precipitation (Figure S1) [16,43]. In addition, RE_K was also affected by soil fertility [44], climatic characteristics [16], crop genetic [45], K fertilization rates [13] and other factors. From the perspective of the maize–wheat rotation system, the ARE in the four K fertilization treatments increased during the third rotation system period (2010–2013) and then stabilized without many variations (Table 3). These results indicated that although K fertilization had a residue-effect on accumulative recovery efficiency, it was not expansile with consecutive application of K fertilizers throughout the years.

4.3. Potassium Fertilization Rates versus Soil Potassium Balance

Long-term unbalanced fertilization (i.e., relatively low K input compared to high N and P inputs) in agricultural production will eventually cause severe soil K deficiency in China [46,47]. In the present experiment, the negative soil K balance in the K_0 treatment was −29.0 kg ha^{-1}, other treatments were gradually increased with increasing fertilizer and wheat straw inputs in the maize season (Figure 3). However, for the wheat season, the apparent balance of soil K was greater under the five treatments. This also shows that the K loss of wheat straw in the maize season was influenced by rainfall and irrigation, while the K application combined with straw can supply the needs of crop growth and supplement soil K. In terms of the maize–wheat rotation system, the soil K deficit was 24.3 kg ha^{-1} under the K_0 treatment, which was consistent with the results from Singh [48]. However, Ju [49] showed that the soil apparent K balance was −163 kg ha^{-1} when 38 kg K ha^{-1} was applied. This result may be because the application of K fertilizer combined with the return of maize and wheat straw to the field supplemented the soil K. In addition, the average apparent K balance in the maize–wheat rotation system was surplus in the K_{48}, K_{84}, K_{120}, and K_{156} treatments. These results indicate that the application of K fertilizer with straw return to the field was able to supplement the K removal by crop and achieve a surplus of the soil apparent K balance, which was consistent with previous studies [50,51]. Except for the fraction of which may be uptake by plant, the large amounts of surplus K may be fixed to nonexchangeable K (Figure 6) [52,53]. However, the fraction of fixed K is gradually released for crop uptake when there is rigorous depletion of K from the soil [54]. The soils was 2:1 clay minerals (illite, vermiculite and smectite) in our study region. Shakeri and Abtahi [55] reported that the high negative charge of these minerals increases the absorption capacity of cations such as K. Other researchers have also showed an increase in K fixation of soils by increase in added K levels into the soil [56,57].Therefore, the fixation of K can be seen as potential K reservoir. In the future g study, we will explore the dynamics of K fixation and release of the agricultural use of soils.

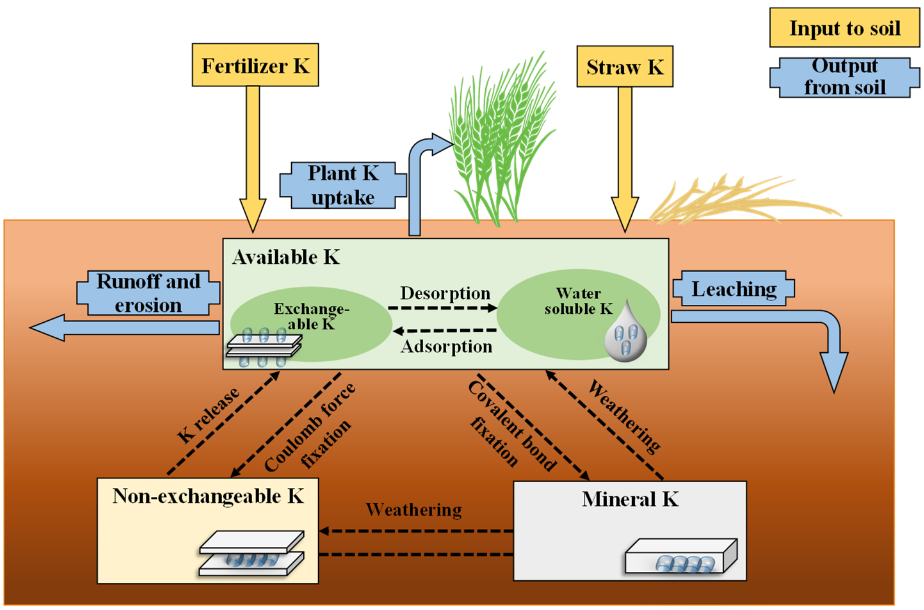

Figure 6. Relationship among available K, nonexchangeable K and mineral K in the soil-plant system.

4.4. Soil Available Potassium versus Soil Potassium Balance

In this study, the soil available K under the K_{48}, K_{84}, K_{120}, and K_{156} treatments was higher than that under the K_0 treatment and increased with increasing K fertilization rates (Figure 4). There was the same K level after eight years of rotation in the K_0 treatments compared with the initial soil available K content in 2010. This may be attributed to the release of nonexchangeable K in the soil, which supplements the depletion of soil available

K [58]. This results also indicated that only straw return to the field can neither alleviate the depletion of soil K, and nor fundamentally maintain the supply capacity of the K reservoir. Although a high soil apparent K balance was surplus in the K_{84}, K_{120} and K_{156} treatments in the present study (Figure 3), the soil available K content after eight years of rotation compared to the initial soil was only increased by 18.0%, 25.1% and 32.5%, respectively (Figure 4), and the soil available K content increased by 10.9 mg kg^{-1} per 100 kg ha^{-1} surplus K. It means that approximately 24.5 kg in 100 kg surplus K was transferred into available K pool in 0–20 cm soil profile and the 75% K surplus would be lost or fixed into nonexchangeable K and mineral K (Figure 6) in the lattice of clay minerals such as vermiculite and mica [59], thus mainly increasing the slowly available K and total K content in the soil [24]. This region has a high rainfall and frequency in summer. The transformation of straw K into water solution K after entering the soil was sensitive to rainfall, which can also lead to loss of K [60]. The variability of transformation into soil available K was greater when the soil K balance was higher than 100 kg ha^{-1}, which could also explain these changes (Figure 5). In soil, there is a gradual change between each form of K (i.e., exchangeable K, water-soluble K and nonexchangeable K), and these forms remain in a dynamic equilibrium. The equilibrium is affected by soil organic, clay content and cation exchange capacity and environmental conditions [14,61].

5. Conclusions

Our studies have shown that the crop yields of maize and wheat were generally higher under K_{120} treatment, and the yield was not increased under excessive fertilization (K_{156}). The RE_K was also significantly decreased with K fertilization supply in maize and wheat season. From the perspective of AE_K, which was higher under the K_{48} treatment in the maize season. While the AE_K in K_{84} and K_{120} treatments were higher in wheat season. The AE_K and yield response increase in the wheat season was higher than that of the maize season. Meanwhile, the K fertilizer application in maize season showed a slight decreasing trend with fertilizer periods. In addition, the four fertilization treatments (K_{48}, K_{84}, K_{120}, and K_{156}) had large surpluses of soil K except for the non-fertilization treatment, and increased soil available K content. However, soil K surplus transformed to soil available K was smaller with massive fertilizer input (K_{120} and K_{156} treatments). In summary, we believe that K fertilizer application in the wheat season can be higher than in the maize season. In order to improve the K fertilizer efficiency and avoid the waste of large K surpluses, it is necessary to pay attention to the transformation between different K forms in the soil after K fertilizer application in the further study.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12102565/s1, Figure S1: Monthly rainfall (mm) and mean temperature (°C) during the maize and wheat growing seasons from 2010 to 2018; Figure S2: Effects of different K fertilization rates on the average yields of maize and wheat; Table S1: Effects of different K fertilization rates on maize yield composition between 2010–2017; Table S2: Effects of different K fertilization rates on wheat yield composition between 2010–2018; Table S3: Correlation analysis of maize and wheat yields, yield composition; Figure S3: Linear regression between 1000-grain weight, grain number, effective spike number and increased of yield in maize and wheat by K application; Figure S4: Regression analysis of maize yield with K fertilizer application in 2010–2017; Figure S5: Regression analysis of wheat yield with K fertilizer application in 2011–2018.

Author Contributions: Formal analysis, B.H.; writing—review and editing, B.H., C.X. and W.M.; writing—original draft preparation, B.H.; supervision Z.S. and W.M.; investigation Q.J.; software B.H. and J.W.; conceptualization, W.M. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key R&D Program of China (2021YFE0101900, 2016YFD0200403), the National Basic Research Program of China (2015CB150405), and the Special Fund for Agro-scientific Research in the Public Interest, China (201103003).

Data Availability Statement: Not applicable.

Acknowledgments: We would like to thank Lingyun Weng, Xiaoqia Yang and Jingjing Sun for management of the field experiments.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lin, Z.; Zoebisch, M.A.; Chen, G.; Feng, Z. Sustainability of farmers' soil fertility management practices: A case study in the North China Plain. *J. Environ. Manag.* **2006**, *79*, 409–419.
2. Pettigrew, W.T. Potassium influences on yield and quality production for maize, wheat, soybean and cotton. *Physiol. Plant* **2008**, *133*, 670–681. [CrossRef] [PubMed]
3. Watanabe, K.; Murayama, T.; Niino, T.; Nitta, T.; Nanzyo, M. Reduction of phosphatic and potash fertilizer in sweet corn production by pre-transplanting application of potassium phosphate to plug seedlings. *Plant Prod. Sci.* **2005**, *8*, 608–616. [CrossRef]
4. Gao, C.; Sun, B.; Zhang, T. Sustainable nutrient management in Chinese agriculture: Challenges and perspective. *Pedosphere* **2006**, *16*, 253–263. [CrossRef]
5. Cao, M.; Yu, H.; Yan, H.; Jiang, C. Difference in tolerance to potassium deficiency between two maize [Zea mays] inbred lines. *Plant Prod. Sci.* **2007**, *10*, 42–46.
6. Yahaya, S.M.; Mahmud, A.A.; Abdullahi, M.; Haruna, A. Recent advances in the chemistry of N, P, K as fertilizer in soil—A review. *Pedosphere* **2022**, in press. [CrossRef]
7. Tripler, C.E.; Kaushal, S.S.; Likens, G.E.; Walter, M.T. Patterns in potassium dynamics in forest ecosystems. *Ecol. Lett.* **2006**, *9*, 451–466. [CrossRef]
8. Kubar, G.M.; Talpur, K.H.; Kandhro, M.N.; Khashkhali, S. Effect of potassium (K^+) on growth, yield components and macronutrient accumulation in wheat crop. *Pure Appl. Biol.* **2018**, *7*, 248–254. [CrossRef]
9. Atapattu, A.J.; Prasantha, B.D.R.; Amaratunga, K.S.P.; Marambe, B. Increased rate of potassium fertilizer at the time of heading enhances the quality of direct seeded rice. *Chem. Biol. Technol. Agric.* **2018**, *5*, 1–9. [CrossRef]
10. Wang, H.; Ji, J.; Wang, B.; Zhao, P. Effects of long-term potassium application and wheat straw return to cinnamon soil on wheat yields and soil potassium balance in Shanxi. *Plant Nutr. Fertil. Sci.* **2010**, *16*, 801–808.
11. Niu, J.; Zhang, W.; Chen, X.; Li, C.; Zhang, F.; Jiang, L.; Liu, Z.; Xiao, K.; Assaraf, M.; Imas, P. Potassium fertilization on maize under different productionp practices in the North China Plain. *Agron. J.* **2011**, *103*, 822–829. [CrossRef]
12. Zhan, A.; Zou, C.; Ye, Y.; Liu, Z.; Cui, Z.; Chen, X. Estimating on-farm wheat yield response to potassium and potassium uptake requirement in China. *Field Crops Res.* **2016**, *191*, 13–19. [CrossRef]
13. Qiu, S.; Xie, J.; Zhao, S.; Xu, X.; Hou, Y.; Wang, X.; Zhou, W.; He, P.; Johnston, A.M.; Christie, P.; et al. Long-term effects of potassium fertilization on yield, efficiency, and soil fertility status in a rain-fed maize system in northeast China. *Field Crops Res.* **2014**, *163*, 1–9. [CrossRef]
14. Dhillon, J.S.; Eickhoff, E.M.; Mullen, R.W.; Raun, W.R. World potassium use efficiency in cereal crops. *Agron. J.* **2019**, *111*, 889–896. [CrossRef]
15. Zhang, F.; Wang, J.; Zhang, W.; Cui, Z.; Ma, W.; Chen, X.; Jiang, R. Nuterient use efficiencies of major cereal crops in China and measures for improvement. *Acta Pedol. Sin.* **2008**, *45*, 916–922.
16. Zhang, H.; Yang, X.; He, X.; Xu, M.; Huang, S.; Liu, H.; Wang, B. Effect of long-term potassium fertilization on crop yield and potassium efficiency and balance under wheat-maize rotation in China. *Pedosphere* **2011**, *21*, 154–163. [CrossRef]
17. He, C.; Zhu, O.; Tian, Z.; Schaffer, H.D. Yield and potassium balance in a wheat–maize cropping system of the North China Plain. *Agron. J.* **2012**, *104*, 1016–1022. [CrossRef]
18. Niu, J.; Zhang, W.; Ru, S.; Chen, X.; Xiao, K.; Zhang, X.; Assaraf, M.; Imas, P.; Magen, H.; Zhang, F. Effects of potassium fertilization on winter wheat under different production practices in the North China Plain. *Field Crops Res.* **2013**, *140*, 69–76. [CrossRef]
19. Sharma, A.; Jalali, V.K.; Arora, S. Non-exchangeable potassium release and its removal in foot-hill soils of North-west Himalayas. *Catena* **2010**, *82*, 112–117. [CrossRef]
20. Moody, P.W.; Bell, M.J. Availability of soil potassium and diagnostic soil tests. *Aust. J. Soil Res.* **2006**, *44*, 265–275. [CrossRef]
21. Syers, J. *Potassium in Soils: Current Concepts*; Feed the soil to feed the people The role of potash in sustainable agriculture; International Potash Institute: Basel, Switzerland, 2002; p. 301.
22. Barré, P.; Montagnier, C.; Chenu, C.; Abbadie, L.; Velde, B.J.P. Soil Clay minerals as a soil potassium reservoir: Observation and quantification through X-ray diffraction. *Plant Soil* **2008**, *302*, 213–220. [CrossRef]
23. Barré, P.; Velde, B.; Fontaine, C.; Catel, N.; Abbadie, L. Which 2:1 clay minerals are involved in the soil potassium reservoir? Insights from potassium addition or removal experiments on three temperate grassland soil clay assemblages. *Geoderma* **2008**, *146*, 216–223. [CrossRef]
24. Römheld, V.; Kirkby, E.A. Research on potassium in agriculture: Needs and prospects. *Plant Soil* **2010**, *335*, 155–180. [CrossRef]
25. Yang, X.; Liu, J.; Wang, W.; Ye, Z.; Luo, A. Potassium internal use efficiency relative to growth vigor, potassium distribution, and carbohydrate allocation in rice genotypes. *J. Plant Nutr.* **2004**, *27*, 837–852. [CrossRef]
26. Zhao, S.; He, P.; Qiu, S.; Jia, L.; Liu, M.; Jin, J.; Johnston, A.M. Long-term effects of potassium fertilization and straw return on soil potassium levels and crop yields in north-central China. *Field Crops Res.* **2014**, *169*, 116–122. [CrossRef]

27. Majumdar, K.; Sanyal, S.K.; Singh, V.K.; Dutta, S.; Satyanarayana, T.; Dwivedi, B.S. Potassium fertiliser management in indian agriculture:current trends and future needs. *Indian J. Fertil.* **2017**, *13*, 20–30.
28. Ali, M.Y.; Waddington, S.R.; Timsina, J.; Hodson, D.; Dixon, J. Maize–rice cropping systems in Bangladesh: Status and research needs. *J. Agric. Sci. Technol.* **2009**, *3*, 35–53.
29. Zhang, H.; Xu, M.; Shi, X.; Li, Z.; Huang, Q.; Wang, X. Rice yield, potassium uptake and apparent balance under long-term fertilization in rice-based cropping systems in southern China. *Nutr. Cycl. Agroecosyst.* **2010**, *88*, 341–349. [CrossRef]
30. Xu, X.; He, P.; Pampolino, M.F.; Johnston, A.M.; Qiu, S.; Zhao, S.; Chuan, L.; Zhou, W. Fertilizer recommendation for maize in China based on yield response and agronomic efficiency. *Field Crops Res.* **2014**, *157*, 27–34. [CrossRef]
31. Heming, S. Potassium balances for arable soils in southern England 1986–1999. *Soil Use Manag.* **2004**, *20*, 410–417. [CrossRef]
32. Dawe, D.; Dobermann, A.; Moya, P.; Abdulrachman, S.; Singh, B.; Lal, P.; Li, S.Y.; Lin, B.; Panaullah, G.; Sariam, O.; et al. How widespread are yield declines in long-term rice experiments in Asia? *Field Crops Res.* **2000**, *66*, 175–193. [CrossRef]
33. Camara, K.M.; Payne, W.; Rasmussen, P.E. Long-term effects of tillage, nitrogen, and rainfall on winter wheat yields in the Pacific Northwest. *Agron. J.* **2003**, *95*, 828–835. [CrossRef]
34. Helmke, P.A.; Sparks, D.L. Lithium, Sodium, Potassium, Rubidiumand Cesium. In *Methods of Soil Analysis, Part 3*; ASA and SSSA: Madison, WI, USA, 1996.
35. Dong, H.; Kong, X.; Li, W.; Tang, W.; Zhang, D. Effects of plant density and nitrogen and potassium fertilization on cotton yield and uptake of major nutrients in two fields with varying fertility. *Field Crops Res.* **2010**, *119*, 106–113. [CrossRef]
36. Xie, J.; Zhou, J.; Hardter, R. *Potassium and Chinese Agriculture*; Hohai University Press: Nanjing, China, 2000.
37. Singh, V.K.; Dwivedi, B.S.; Singh, S.K.; Majumdar, K.; Jat, M.L.; Mishra, R.P.; Rani, M. Soil physical properties, yield trends and economics after five years of conservation agriculture based rice-maize system in north–western India. *Soil Tillage Res.* **2016**, *155*, 133–148. [CrossRef]
38. Sweeney, D.W.; Granade, G.V.; Eversmeyer, M.G.; Whitney, D.A. Phosphorus, potassium, chloride, and fungicide effects on wheat yield and leaf rust severity. *J. Plant Nutr. Soil Sci.* **2000**, *23*, 1267–1281. [CrossRef]
39. Sharma, S.; Duveiller, E.; Basnet, R.; Karki, C.B.; Sharma, R.C. Effect of potash fertilization on Helminthosporium leaf blight severity in wheat, and associated increases in grain yield and kernel weight. *Field Crops Res.* **2005**, *93*, 142–150. [CrossRef]
40. Rajicic, V.; Milivojevic, J.; Popovic, V.; Brankovic, S.; Djuric, N.; Perisic, V.; Terzic, D. Winter wheat yield and quality depending on the level of nitrogen, phosphorus and potassium fertilization. *J. Agric. For.* **2019**, *65*, 79–88. [CrossRef]
41. Zhang, H.; Zhang, L.; Huang, Y.; Ye, Y.; Cui, J.; Sokolowski, E. Eeffect of potassium application on yield and soil potassium balance in maize and wheat rotation system. *J. Triticeae Crops* **2013**, *33*, 988–995.
42. Bai, Y.-L.; Wang, L.; Lu, Y.-L.; Yang, L.-P.; Zhou, L.-P.; NI, L.; Cheng, M.-F. Effects of long-term full straw return on yield and potassium response in wheat–maize rotation. *J. Integr. Agric.* **2015**, *14*, 2467–2476. [CrossRef]
43. Rodríguez-Lizana, A.; Carbonell, R.; González, P.; Ordóñez, R. N, P and K released by the field decomposition of residues of a pea–wheat–sunflower rotation. *Nutr. Cycl. Agroecosyst.* **2009**, *87*, 199–208. [CrossRef]
44. Premi, O.; Kandpal, B.; Rathore, S.; Shekhawat, K.; Chauhan, J. Green manuring, mustard residue recycling and fertilizer application affects productivity and sustainability of Indian mustard (*Brassica juncea* L.) in Indian semi-arid tropics. *Ind. Crops Prod.* **2013**, *41*, 423–429. [CrossRef]
45. Wang, L.; Chen, F. Genotypic variation of potassium uptake and use efficiency in cotton (*Gossypium hirsutum*). *J. Plant Nutr. Soil Sci.* **2012**, *175*, 303–308. [CrossRef]
46. Ju, X.; Zhang, F.; Bao, X.; Römheld, V.; Roelcke, M. Utilization and management of organic wastes in Chinese agriculture: Past, present and perspectives. *Sci. China Ser. C Life Sci.* **2005**, *48*, 965–979.
47. Yang, S.; Li, F.; Malhi, S.S.; Wang, P.; Suo, D.; Wang, J. Long-Term fertilization effects on crop yield and nitrate nitrogen accumulation in soil in Northwestern China. *Agron. J.* **2004**, *96*, 1039–1049. [CrossRef]
48. Singh, V.K.; Sharma, B.B.; Dwivedi, B.S. The impact of diversification of a rice wheat cropping system on crop productivity and soil fertility. *J. Agric. Sci.* **2002**, *139*, 405–412. [CrossRef]
49. Ju, X.; Kou, C.; Christie, P.; Dou, Z.; Zhang, F. Changes in the soil environment from excessive application of fertilizers and manures to two contrasting intensive cropping systems on the North China Plain. *Environ. Pollut.* **2007**, *145*, 497–506. [CrossRef] [PubMed]
50. Xu, X.; Ma, Y.; Zhang, R.; Shen, P. Effect of potassium application on transformation of soil potassium in different soils. *Chin. J. Soil Sci.* **2005**, *36*, 59–61.
51. Tan, D.; Jin, J.; Jiang, L.; Huang, S.; Liu, Z. Potassium assessment of grain producing soils in North China. *Agric. Ecosyst. Environ.* **2012**, *148*, 65–71. [CrossRef]
52. Cassman, K.G.; Bryant, D.C.; Higashi, S.L.; Roberts, B.A.; Kerby, T.A. Soil Potassium Balance and Cumulative Cotton Response to Annual Potassium. *Soil Sci. Soc. Am. J.* **1989**, *53*, 805–812. [CrossRef]
53. Portela, E.; Monteiro, F.; Fonseca, M.; Abreu, M.M. Effect of soil mineralogy on potassium fixation in soils developed on different parent material. *Geoderma* **2019**, *343*, 226–234. [CrossRef]
54. Bakker, E. *The Impact of Plant Growth and Potassium Uptake on Clay Minerals in Soil*; Université Grenoble Alpes (ComUE): Grenoble, France, 2018.
55. Shakeri, S.; Abtahi, S.A. Potassium forms in calcareous soils as affected by clay minerals and soil development in Kohgiluyeh and Boyer-Ahmad Province, Southwest Iran. *J. Arid Land* **2018**, *10*, 217–232. [CrossRef]

56. Ghiri, M.N.; Abtahi, A. Factors affecting potassium fixation in calcareous soils of southern Iran. *Arch. Agron. Soil Sci.* **2012**, *58*, 335–352. [CrossRef]
57. Dhaliwal, A.K.; Gupta, R.K.; Singh, Y.; Singh, B. Potassium Fixation and Release Characteristics of Some Benchmark Soil Series under Rice-Wheat Cropping System in the Indo-Gangetic Plains of Northwestern India. *Commun. Soil Sci. Plant Anal.* **2006**, *37*, 827–845. [CrossRef]
58. Jiang, C.; Zheng, Q.; Zu, C. Research progress on effects of straw returning on soil potassium and its substitute for potassium fertilizer. *Chin. J. Ecol.* **2015**, *34*, 1158–1165.
59. Yu, W.; Jiang, Z.; Shen, S.; Zhang, L. K fertility and K deficit index of aquic brown soil under different fertilization systems. *Chin. J. Appl. Ecol.* **2007**, *18*, 2239–2244.
60. Lu, D.; Dong, Y.; Chen, X.; Wang, H.; Zhou, J. Comparison of potential potassium leaching associated with organic and inorganic potassium sources in different arable soils in China. *Pedosphere* **2022**, *32*, 330–338. [CrossRef]
61. Tan, D.; Liu, Z.; Jiang, L.; Luo, J.; Li, J. Long-term potash application and wheat straw return reduced soil potassium fixation and affected crop yields in North China. *Nutr. Cycl. Agroecosyst.* **2017**, *108*, 121–133. [CrossRef]