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Effects of Long-Term Fertilizer Application on Crop Yield Stability and Water Use Efficiency in Diversified Planting Systems

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Abstract: Exploring crop yield stability and the relationship between the water–fertilizer effect and annual precipitation type in a broomcorn millet–potato–spring corn rotation system under long-term fertilization on chestnut cinnamon soil in loess tableland can provide a scientific basis for rational fertilization in the northwest Shanxi region in years with different precipitation. This study was based on a 33-year long-term fertilizer experiment, using four fertilizer treatments: no fertilizer as control (CT), single fertilizer nitrogen (N), single organic fertilizer (M), and nitrogen fertilizer with organic fertilizer (NM). The results showed that broomcorn millet and maize had the highest yield in wet years, while potatoes had the highest yield in normal years and the yield under NM treatment was the highest. The sustainable yield index (SYI) values for potato and maize were higher than the SYI for the broomcorn millet during years with different precipitation and the SYI for the NM treatment was the highest. The water use efficiency of NM treatment was the highest. The yield of broomcorn millet and maize was affected by nitrogen fertilizer, organic fertilizer, and precipitation during the growth period, while the potato yield was mainly affected by nitrogen fertilizer and organic fertilizer. Therefore, the rotation of potato–maize and the rational allocation of organic and inorganic fertilizer (NM) is the best planting system in this region.

Keywords: fertilizer management; rotation system; crop yield; precipitation years; dry farmland

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1. Introduction

Drought and low soil fertility are still the main factors restricting the development of agriculture in dry land on the Loess Plateau in China [1]. The rational application of fertilizer to achieve compliance with the edict "adjust water with fertilizer, promote fertilizer with water" under different precipitation years is the key to increasing grain production and the sustainable development of agriculture [2]. A long-term fertilization test is an effective technical means of evaluating the sustainability of farmland ecosystems [3]. We can employ the long-term fertilization test yield instability caused by soil, climate, and other factors to evaluate the scientific problems more accurately, such as crop yield and water and fertilizer effects under different long-term fertilization modes [4].

A number of studies have been conducted on the productivity and sustainability of crop systems with long-term fertilization both in China and abroad; measures such as balanced fertilizer fertilization, organic and inorganic fertilizer distribution, tillage methods, and rotation methods have all been shown to affect the sustainability of the crop yield [5–9]. The application of organic fertilizer and the balanced application of nitrogen, phosphorus, and potassium fertilizer can effectively increase the yield stability in a soybean wheat rotation system [10]. Long-term nitrogen, phosphorus, and potassium fertilization as recommended or nitrogen, phosphorus, and potassium fertilizer with organic fertilizer are conducive to maintaining and improving soil fertility, resulting in the inter-annual change in crop yield being small, promoting a high and stable crop yield, and providing the optimal fertilization mode for maintaining the sustainability of the farmland ecosystem [3]. The application of fertilizer in normal years and drought years can increase crop yield and water use efficiency [11]. Precipitation has a significant impact on the yield effect of chemical fertilizer, especially nitrogen fertilizer, but has a small impact on the increase in organic fertilizer or straw fertilizer [12].

In the Loess Plateau of northwest China, the soil is barren, the yield is low and unstable, and the sustainability of agricultural production is poor. A 32-year fertilizer regulation experiment in the dry farming region showed that with the years of extension of the application of organic fertilizer, application of a low amount of organic fertilizer can improve crop yield by improving PUE and can achieve the effect of the application of a high amount of organic fertilizer [13]. Huang et al. found that a combination of moderate amounts of organic and inorganic N application was a comparatively better fertilization model, which ensured sustainable production of soil-crop systems in the Chestnut Cinnamon soil region [14]. Most studies have focused on the effects of water and fertilizer on a single crop's yield in different precipitation years on the Loess Plateau of northwest China, while few studies have explored the rotation of multiple crops. Water and nutrients are the main factors limiting the development of agriculture in this area. Studying the effects of water and fertilizer on crop system productivity and sustainability is of great significance for increasing crop yield. In this study, through the monitoring of the long-term positioning of fertilization in the dry farming area in northwest China and based on the yield stability and potato–corn rotation system, the relationship between the yield and the fertilization amount and precipitation under different precipitation years was analyzed and a scientific basis for rational fertilization in the region under different precipitation years was provided, including the formulation of a suitable rotation system.

2. Materials and Methods

2.1. Overview of the Test Sites

In this study, a long-term fertilizer positioning test in (39°12′18″ N, 111°15′41″ E), Hequ County, Xinzhou City, Shanxi Province, was collated and the data up to 2020 were analyzed. This area is a typical dry-farming area, with a middle temperate semi-arid continental monsoon climate, an annual average temperature of 8.8 °C, an annual average rainfall of 389 mm, and a frost-free period of about 150 days. The experimental site has a light loam loess, classified as Hapli-Ustic Cambosols in the World Reference Base for Soil Resources (WRB). At the beginning of the experiment, the soil nutrient content of 0–20 cm soil was 5.64 g kg^{-1} for organic matter, 0.45 g kg^{-1} for total nitrogen, 34.90 mg kg^{-1} for alkaline nitrogen, and 2.69 mg kg^{-1} for quick phosphorus; the pH was 8.5.

2.2. Experiment Design

The experiment started in 1988 using a randomized complete block design and the following four different fertilizer volumes: (1) no fertilizer control (CT); (2) single fertilizer nitrogen (N); (3) single organic fertilizer (M); and (4) nitrogen fertilizer with organic fertilizer (NM). The amounts of nitrogen fertilizer and organic fertilizer were 120 kg (N) hm^{-2} and 22,500 kg·hm^{-2}, respectively. Phosphate was applied as a base fertilizer before sowing. The test plot was 24 m^2 with three replicates. The test fertilizers were urea (containing N 460 g kg^{-1}) and calcium phosphate (containing P_2O_5 140 g kg^{-1}). The test organic fertilizer was farmyard manure (the annual average N content was 3.64 g kg^{-1}, the annual average P_2O_5 content was 2.46 g kg^{-1}, and the annual average K_2O content was 7.87 g kg^{-1}). The fertilization details are shown in Table 1. The fertilizer and organic fertilizer were applied to the soil before the land was plowed and sown. The crop planting time and classification of precipitation years are detailed in Table 2. The crops were sown annually in early May and harvested in late October and then, from the beginning of November, there was a winter leisure period until the second year of late April. All the treated potato stalks were returned to the field, while other crop stalks were removed from the field. The straws of broomcorn millet and maize were not returned to the field. The test area was rain farming without irrigation.

Table 1. Experiment treatments and fertilization.

Treatments	Chemical Fertilizer ($kg \cdot hm^{-2}$)			Organic Fertilizer ($kg \cdot hm^{-2}$)			Total Nutrient ($kg \cdot hm^{-2}$)		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Single nitrogen fertilizer (N)	120	75	0	0	0	0	120	75	0
Single organic fertilizer (M)	0	0	0	80	55	180	80	55	180
Nitrogen fertilizer + organic fertilizer (NM)	120	75	0	80	55	180	200	130	180
No fertilizer (CT)	0	0	0	0	0	0	0	0	0

Table 2. Crop planting time and classification of precipitation years.

Crop	Years		
	Drought Years	Normal Years	Wet Years
Broomcorn millet Broom corn	1994, 1998, 2000, 2006	1990, 1996	1988, 1992, 2008
Potato	1991, 1993, 1997, 1999, 2001, 2005, 2015, 2018, 2020	1989, 2014, 2016	1995, 2003, 2007, 2017
Maize	2002, 2011	2004, 2009, 2010, 2019	2012, 2013

2.3. Materials and Methods

2.3.1. Crop Yield

At the crop maturity stage, the intact 3 m^2 in each plot was harvested by hand to determine the yield. The yield of broomcorn millet was converted according to the grain moisture content of 13%, the potato yield was calculated according to the actual fresh weight, and the yield of maize was converted according to the grain moisture content of 14%.

2.3.2. Annual Division of Precipitation

The annual division of precipitation was calculated using the annual precipitation [15]. The calculation formula is

$$DI = \frac{P_{An} - M_1}{\sigma} \quad (1)$$

where DI represents the drought index; P_{An} represents the annual precipitation in the growing year; M_1 represents the average annual precipitation from 1988 to 2020; and σ represents the standard deviation of annual precipitation for many years. The annual precipitation was divided into three types: drought years, normal years, and wet years. $DI > 0.35$ was taken to indicate wet years, $-0.35 \leq DI \leq 0.35$ to indicate normal years, and $DI < -0.35$ to indicate drought years [15].

During the 33 years from 1988 to 2020, the average precipitation was 331.7 mm; the highest annual precipitation reached 640.4 mm in 1995 and the lowest was measured in 1991 at 224.7 mm. The growth period of broomcorn millet, potato, and maize is from May to September each year. Analysis of the precipitation during the growth period of 33 years showed that the frequency below 300 mm accounted for 45.7% of the observation years and the frequency lower than 250 mm accounted for 11.4% of the observation years, which was mainly concentrated before the year 2000.

2.3.3. Yield, Yield Stability, and Yield Sustainability

According to the divided precipitation years, the output of the year was averaged and the average output of drought, normal, and wet years were obtained. The yield stability is expressed as a significant coefficient of variation (coefficient of variation, CV), which represents the degree of variation in yield among years, where a larger CV indicates a lower yield stability. The calculation formula is the following, as in [16] as follows:

$$CV = \frac{\sigma}{Y} \times 100\% \tag{2}$$

The yield sustainability is characterized by the sustainable yield index (SYI) and the higher the index, the more sustainable the system. The calculation formula is the following [17]:

$$SYI = \frac{\overline{Y} - \sigma}{Y_{\max}} \times 100\% \tag{3}$$

where σ represents the standard deviation (kg·hm^{-2}); $\overline{Y}$ represents the average yield (kg·hm^{-2}); and $Y_{\max}$ represents the maximum yield (kg·hm^{-2}) in all years.

2.3.4. Water Consumption, Precipitation Utilization Efficiency, and Water Utilization Efficiency during the Growth Period

$$ETa\,(\mathrm{mm}) = We + P - Wb \tag{4}$$

where ETa (mm) represents the water consumption during the growth period; We (mm) and Wb (mm) represent the soil water storage before sowing and harvesting, respectively; and P represents the precipitation during the growth period [18].

$$RUE = \frac{ETa}{p_{An}} \times 100\% \tag{5}$$

where RUE (%) represents the farmland precipitation use efficiency; ETa (mm) represents the water consumption during the growth period; and P_{An} represents the total annual precipitation.

$$WUE\,(\mathrm{kg \cdot mm^{-1} \cdot hm^{-2}}) = \frac{Ya}{ETa} \tag{6}$$

where Ya represents the yield and ETa represents the water consumption during the maize growth period [18].

2.3.5. Model of Precipitation, Fertilization, and Yield

The primary regression equation for yield, precipitation, and fertilization is as follows:

$$Y = b_0 + b_1X_1 + b_2X_2 + \ldots + b_iX_i \tag{7}$$

where Y represents the yield; b_0 represents the constant term; b_i represents the regression equation coefficient; and X_1, X_2, ..., X_i represent the independent variable.

2.4. Statistical Analysis

The data were analyzed using an analysis of variance (ANOVA) and data obtained from each sampling event were analyzed separately. Multiple comparisons were tested with least significant difference (LSD) values. Mean values were compared based on the least significant difference test (LSD 0.05) if the F tests were significant. Excel 2007 was used for basic data analyses. Origin 2021 was used to plot the charts. A data processing system (V 7.05) was used to analyze of variance.

3. Results

3.1. Effect of Annual Precipitation on Crop Yield in Different Treatments

Table 3 shows that the three annual types of precipitation and the amount of fertilizer applied had significant effects on the yields of broomcorn millet, potato, and spring maize. Comparing the yields in years with different types of precipitation showed that the average yield of broomcorn millet was the highest in wet years, fluctuating from 1797 to

3467 kg·hm^{-2}, which was significantly higher than the yield in drought years and normal years. Under different fertilization treatments, the yield in wet years was 10.5–73.9% compared with the yield in drought years and the yield in the normal years was slightly lower than that in drought years. From the average yield of broomcorn millet in all precipitation years, it can be seen that the yield under the NM treatment was significantly higher than that under the other fertilization treatments. The NM treatment increased the yield by 29.0%, 25.7%, and 143.6% compared with the M, N, and CT treatments, respectively.

Table 3. The average yields of crops in different precipitation years and their rates of increase from drought years.

Year	Treatment	Broomcorn Millet		Potato		Maize	
		Yield (kg·hm^{-2})	Increase # (%)	Yield (kg·hm^{-2})	Increase # (%)	Yield (kg·hm^{-2})	Increase # (%)
Drought years	CT	1033 ± 303 B c	–	1497 ± 864 B c	–	1945 ± 535 B c	–
	M	2156 ± 454 A b	–	2531 ± 1639 B b	–	2943 ± 1104 C b	–
	N	1934 ± 429 B b	–	2322 ± 1292 B b	–	3468 ± 1061 C a	–
	NM	2710 ± 631 B a	–	3330 ± 1869 B a	–	2848 ± 1302 C b	–
Normal years	CT	757 ± 476 C d	−26.7	2161 ± 367 A d	44.4 *	3328 ± 788 A c	71.1 *
	M	2233 ± 867 A b	3.6	2898 ± 389 A c	14.5 *	7359 ± 2132 B b	150.0 *
	N	2040 ± 494 B c	5.5	3359 ± 321 A b	44.7 *	6942 ± 1262 B b	100.2 *
	NM	2560 ± 840 B a	−5.5	4259 ± 376 AB a	27.9 *	9073 ± 2836 B a	218.6 *
Wet years	CT	1797 ± 639 A d	73.9 *	1368 ± 157 B c	−8.6	3528 ± 668 A c	81.4 *
	M	2382 ± 463 A c	10.5	2652 ± 373 B b	4.8	8693 ± 888 A b	195.4 *
	N	2979 ± 431 A b	54.0 *	2653 ± 404 B b	14.3	10,351 ± 685A a	198.5 *
	NM	3467 ± 415 A a	27.9 *	4681 ± 1023 A a	40.6 *	10,915 ± 563 A a	283.3 *
F values of variance analysis							
Year		115.7 **					
Treatment		10.8 **					
Year × Treatment		5.3 **					

Note: different uppercase letters in the table indicate significant differences among different precipitation years (p < 0.05); different lowercase letters indicate significant differences among treatments (p < 0.05). # indicates the rate of increased yield between the normal year and dry year and between the wet year and dry year, respectively. * Significant at the 0.05 probability level. ** Significant at the 0.01 probability level.

Comparing years with different precipitation showed that the average yield of the potato crop in normal years was the highest, fluctuating between 2161 and 4259 kg·hm^{-2}, which was significantly higher than the yield in drought years and wet years. Under different fertilization treatments, the yield in normal years was 14.5–44.7% higher than that in drought years and the yield in wet years was −8.6–40.6% higher than that in drought years. In all the precipitation years, the average yield under NM treatment was significantly higher than that under the other treatments and increased by 51.8%, 47.2%, and 144.1% compared with that observed with M, N, and CT, respectively. There was no significant difference in the yield increase for the potato crop between a single application of organic fertilizer and a single application of nitrogen fertilizer. In wet years, the yield under NM treatment was 242.2% higher than that under CT. Meanwhile, in normal years, the yield under NM treatment was 97.1% higher than that under CT. The results show that the yield-increasing effect of long-term nitrogen application combined with organic fertilizer was more obvious in wet years.

The level of precipitation showed significant effects on the yield of maize; the average yield was the highest in wet years. The yield of maize in wet years fluctuated between 3528 and 10,915 kg·hm^{-2}, which was significantly higher than the yield in drought years and normal years. Under different fertilization treatments, the yield in the wet years was 81.4–283.3% higher than the yield in drought years. The yield in normal years was 71.1–218.6% higher than that in drought years. From the average yields of maize in all the precipitation years, it can be seen that the highest yield of maize treated with NM was

7612 kg·hm^{-2}, which was 20.2%, 10.0%, and 159.4% higher than that under M, N, and CT, respectively. The yield of maize with a single application of nitrogen fertilizer was 589 kg·hm^{-2} higher than that with a single application of organic fertilizer. The results showed that precipitation has a significant impact on the effect of fertilization. The yield-increasing effect of nitrogen fertilizer combined with organic fertilizer increased with an increase in precipitation.

3.2. Stability and Sustainability of Crop Yield in Different Precipitation Years

Table 4 shows the average yield variations (CVs) in broomcorn millet under fertilization in different precipitation years: the order was normal years > drought years > wet years. In wet years, the lowest WCV is 20.4%. Under the same fertilization treatment, the coefficients of variation (YCVs) of the broomcorn millet yield in different precipitation years showed an order of CT > M > N > NM. The lowest yield variation coefficient for NM treatment was 36.4%. The results showed that long-term nitrogen fertilizer use combined with organic fertilizer could improve the yield stability of broomcorn millet; the yield stability in wet years was the best. In terms of the effect of fertilization on the broomcorn millet yield sustainability index (SYI), the years with different precipitation ranked as follows: wet years > drought years > normal years. The highest SYI value was 66.9% in wet years. The SYI value for NM treatment was the highest, being 60.3% in drought years, 58.2% in normal years, and 80.8% in wet years, with an average of 66.4%. The results showed that the combination of nitrogen fertilizer and organic fertilizer could achieve a sustainable yield of broomcorn millet and it was more beneficial for the continuous yield increase for crops in wet years.

Table 4. Stability and sustainability indices of crop yields in different precipitation years (%).

Treatment	Drought Years		Normal Years		Wet Years		YCV
	DCV	SYI	NCV	SYI	WCV	SYI	
			Broomcorn millet				
CT	29.3 a	47.9 c	38.6 b	51.4 c	35.6 a	47.5 c	51.7 a
M	21.1 b	61.8 a	45.5 a	54.5 b	19.4 b	68.1 b	43.3 b
N	22.2 b	58.4 b	42.3 ab	57.7 a	14.5 bc	71.1 b	40.4 b
NM	23.3 b	60.3 a	41.8 ab	58.2 a	12.0 c	80.8 a	36.4 c
			Potato				
CT	57.8 b	22.9 b	17.3 a	67.2 c	28.0 a	77.0 a	46.4 a
M	64.8 a	16.5 c	13.5 b	76.9 b	16.4 b	71.8 b	48.6 a
N	55.6 b	24.4 a	9.6 c	79.7 b	18.0 b	69.5 b	42.1 b
NM	56.1 b	22.7 b	8.8 c	84.6 a	28.0 a	56.3 c	41.6 b
			Maize				
CT	27.5 c	62.5 b	23.7 b	58.8 a	18.9 a	58.8 d	29.9 b
M	37.5 b	62.5 b	29.0 a	57.4 a	10.2 b	74.6 c	36.2 a
N	30.6 c	69.4 a	18.2 c	49.5 c	6.6 c	82.5 b	26.8 c
NM	45.7 a	54.3 c	31.3 a	53.0 b	5.2 c	86.0 a	38.6 a

Note: DCV denotes the yield coefficient of variation in drought years; NCV denotes the yield coefficient of variation in normal years; WCV denotes the yield coefficient of variation in wet years; YCV denotes the yield coefficient of variation. Different lowercase letters indicate significant differences among treatments ($p < 0.05$).

The years with different precipitation ranked as follows regarding the coefficients of variation for the effect of fertilization on potato yield: drought years > wet years > normal years. The lowest NCV in normal years was 12.3%. Under the same fertilization treatment, the yield stability of the potato crop increased at first and then decreased in drought years, normal years, and wet years. In terms of the coefficients of variation (YCVs) of the potato yield, the years with different precipitation ranked as follows: M > CT > N > NM. In terms of the effects of fertilization on the SYI value of potatoes, the years with different precipitation ranked as follows: normal years > wet years > drought years; the highest was 77.1% in normal years. Among different fertilization treatments, the highest annual average SYI value for NM treatment was 84.6%. It shows that planting potato crops in the local area can maintain high-yield stability and sustainability in normal years but there is a decrease in yield during wet years. The long-term application of nitrogen fertilizer combined with organic fertilizer can induce a continuous increase in potato yield.

The yield variation coefficient for spring maize decreased with an increase in precipitation. The coefficient of variation (WCV) was the lowest in wet years. The CV values of drought years, normal years, and wet years were 35.3%, 25.6%, and 10.2%, respectively. The results showed that the stability of the maize yield increased with an increase in precipitation. Under different fertilization treatments, the highest DCV value for the NM treatment was 45.7% in drought years and the yield stability for maize was the worst. However, with an increase in precipitation, the yield variation coefficient for NM treatment decreased and the lowest WCV value was 5.2% in wet years when the maize yield stability was the best. Regarding the SYI values for the fertilization treatments of spring maize, the years with different precipitation ranked as follows: wet years > normal years > drought years. The highest SYI value for NM treatment in wet years was 86.0%. It shows that the combined application of organic and inorganic fertilizers to spring maize in wet years is an important guarantee of an increase in sustainable yield.

3.3. Water Consumption during the Growth Period and Farmland Precipitation Utilization Efficiency in Different Precipitation Years

Figure 1 shows that the fertilization treatments during different precipitation years had significant effects on water consumption (ETa) during the growth period of broomcorn millet. The average annual water consumption was 322 mm, which was 16.9% higher than that in drought years. There were significant differences in water consumption during the growth period among the different fertilization treatments. The ETa values for the CT, M, and N treatments ranged from 284 mm to 317 mm, which were almost the same as the values for rainfall (297 mm) during the growth period. The highest ETa value for NM processing was 316 mm, which was 6.1–11.4% higher than the values for other treatments. Figure 2 shows that the effects of different fertilization treatments on the precipitation utilization rate of broomcorn millet farmland were significantly different. The utilization rate of farmland precipitation under NM treatment was significantly higher than that under the CT, M, and N treatments, with an increase of 7.6–13.9%, and the RUE value reached 87.8%. The results showed that long-term nitrogen fertilizer combined with organic fertilizer could increase the water consumption and farmland utilization rate of broomcorn millet in different precipitation years.

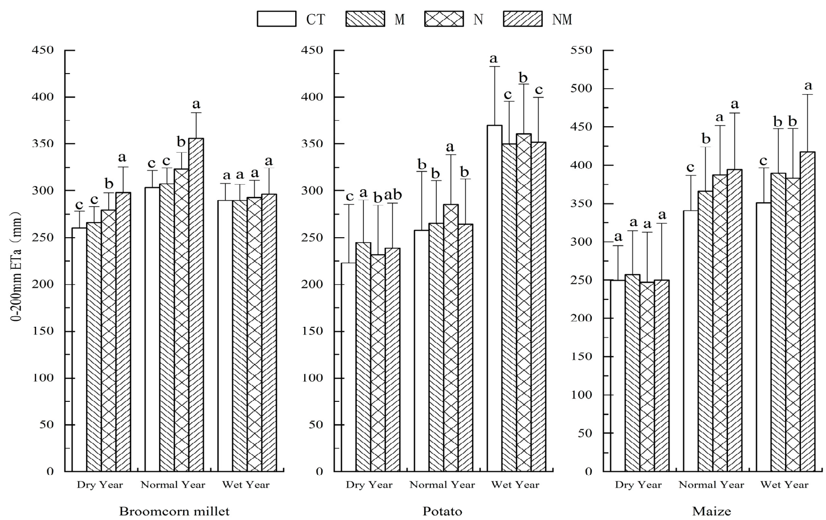

Figure 1. Water consumption during crop growth periods under different fertilization treatments in years with different precipitation. Note: different lowercase letters indicate significant differences between treatments ($p < 0.05$).

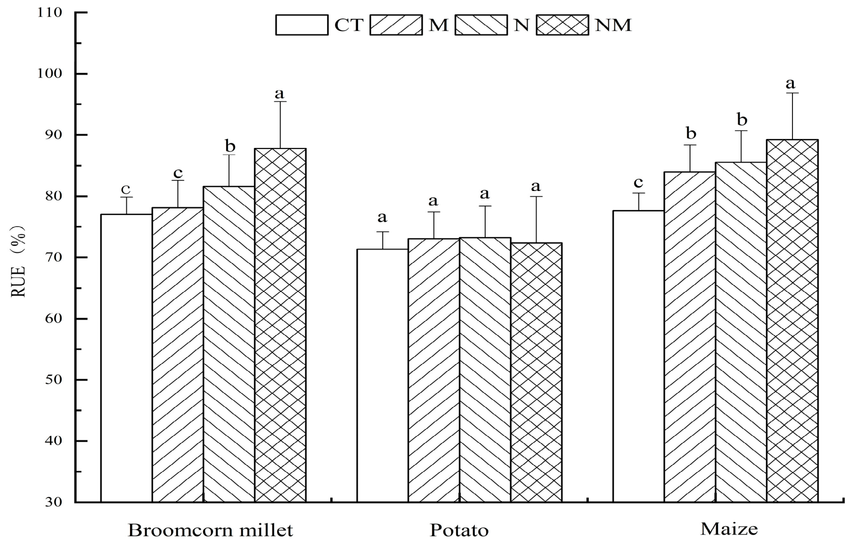

Figure 2. Farmland precipitation utilization rates under different fertilization treatments in different precipitation years. Note: different lowercase letters indicate significant differences between treatments ($p < 0.05$).

Analyzing the effects of years with different precipitation and fertilization treatments on water consumption in the potato crop's growth period shows that, with an increase in precipitation, the water consumption of the potato crop increases. The value of ETa in wet years was 52.7% and 33.5% higher than the values in drought years and normal years, respectively. According to the average water consumption of potatoes in all the precipitation years, the ETa value under different fertilization treatments was higher than that under CT but the increase was not significant. The highest ETa value under N treatment was 293 mm, which was 3.2% higher than that under CT. It can be seen from Figure 1 that the precipitation utilization rate of potato farmland under different fertilization treatments was lower than that of broomcorn millet; the difference between treatments was not significant.

The water consumption of maize was significantly higher than that of broomcorn millet and potato; the average ETa value of maize was 336 mm. The water consumption of the maize growth period in different precipitation years was wet years > normal years > drought years. The average ETa in the wet years was up to 385 mm, which was 53.6% higher than that in drought years. The water consumption of maize in the same precipitation year and different fertilization treatments was similar to that of broomcorn millet. The fertilization treatments increased the water consumption of maize during the growth period, which was 7.5–12.8% higher than that under the CT treatment. In wet years, the water consumption of maize treated with NM was significantly higher than that of other treatments and the ETa value was 418 mm. There was a significant difference in farmland precipitation utilization efficiency of maize with different fertilization treatments. The utilization rate of farmland precipitation under fertilization treatment increased by 8.1–14.9% compared with that under CT and the highest RUE value under NM treatment was 89.2%. It shows that potato is a type of crop with low water consumption. Maize and broomcorn millet are similar water-consuming crops. In the local rotation system, the rotation of potatoes and crops with high water consumption can help to regulate water consumption. This is beneficial to the stability of the ecosystem.

3.4. Water Use Efficiency in Different Precipitation Years

Figure 3 shows that fertilization greatly improved the water use efficiency (WUE) of crops under different precipitation years and the effect of nitrogen fertilizer combined with organic fertilizer was more obvious. The years with different precipitation ranked as follows in terms of the WUE of broomcorn millet: normal years > wet years > drought years. With an increase in precipitation, the WUE of broomcorn millet increased at first and then decreased. In years with the same precipitation type, the average WUEs under M and NM treatments were significantly higher than those under CT and N treatments and the WUEs under M and NM treatments were the same. The average WUEs under M and NM treatments were 16.5% and 104.1% higher than those under N and CT treatments.

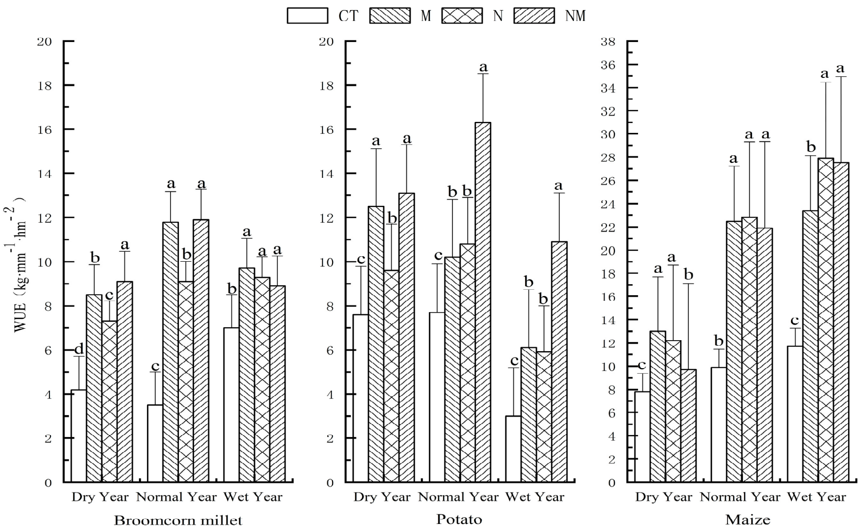

Figure 3. Crop water use efficiency under different fertilization treatments in years with different precipitation. Note: different lowercase letters indicate significant differences between treatments ($p < 0.05$).

In different precipitation years, the WUE of potatoes was as high as that of broomcorn millet in normal years. Under different fertilization treatments, the average WUE of potatoes was significantly higher under treatment with nitrogen fertilizer combined with organic fertilizer than under CT, nitrogen fertilizer, and organic fertilizer treatments. The highest WUE under NM treatment was 13.4 $kg \cdot mm^{-1} \cdot hm^{-2}$, which was 7.3 $kg \cdot mm^{-1} \cdot hm^{-2}$ higher than that under CT, followed by the WUE under M treatment.

In contrast to the WUEs for broomcorn millet and potato, the WUE of maize increased with an increase in precipitation and the average WUE in wet years was 11.9 $kg \cdot mm^{-1} \cdot hm^{-2}$ higher than that in drought years. Fertilization significantly improved the WUE of maize and, on the whole, the WUE of maize was higher than the WUEs of broomcorn millet and potato. Under different fertilization treatments, the highest WUE under N treatment was 20.9 $kg \cdot mm^{-1} \cdot hm^{-2}$, which was 114.3%, 6.6%, and 6.2% higher than the WUEs under CT, M, and NM treatments, respectively.

3.5. Relationship between Precipitation, Fertilizer Application, and Crop Yield

The multiple linear regression equations among crop yield (Y), nitrogen fertilizer (N), organic fertilizer (M), and annual precipitation (P_{An}) were established using the stepwise regression method. The results showed that the yield of broomcorn millet was positively correlated with the nitrogen application rate, organic fertilizer application rate, and annual precipitation; the effects of nitrogen fertilizer application rate and annual precipitation on the yield of broomcorn millet were higher than those of organic fertilizer application rate ($Y = -801.218 + 7.333 \times \mathrm{N} + 0.037 \times \mathrm{M} + 6.296 \times P_{An}$, $R^2 = 0.376$, $F = 8.042$, $p < 0.001$). There was a significant positive correlation between the yield of potatoes and the nitrogen application rate and organic application rate. However, the yield of potatoes was not related to annual rainfall and the effect of the nitrogen fertilizer application rate on the yield of potatoes was higher than those of the organic fertilizer application rate ($Y = 1602.9.9 + 8.431 \times \mathrm{N} + 0.045 \times \mathrm{M}$, $R^2 = 0.230$, $F = 7.405$, $p < 0.001$). There was a significant positive correlation between the yield of maize and nitrogen application, organic fertilizer application, and annual precipitation; the effects of nitrogen fertilizer application rate and annual precipitation on the yield of maize were higher than those of the organic fertilizer application rate ($Y = -4715.740 + 21.979 \times \text{N} + 0.084 \times \text{M} + 26.019 \times P_{An}$, $R^2 = 0.710$, F = 19.811, $p < 0.001$).

4. Discussion

4.1. Impact of Long-Term Fertilization on Stable Stability and Sustainability of Crop Yields

In this study, the three crops did not perform consistently in years with different precipitation, with the annual yields of broomcorn millet and maize being the highest in wet years, while the yield of potato was the highest in normal years. However, some studies [19] have shown that the years with different precipitation ranked as follows in terms of the yield of crops: wet years > normal years > drought years. This may be related to the water consumption characteristics of the crop [20,21]. Potato is a drought-tolerant crop with a high yield during a water-sensitive period. Because of drought and water shortage in the Loess Plateau of northwest China, from the perspective of drought avoidance and drought prevention, potatoes, as a crop of drought avoidance, are a suitable crop for local cultivation. This study also found that the yield of broomcorn millet was slightly reduced in normal years compared with drought years, which may be caused by the increased rainfall (251.4 mm) in 1990 (a normal year) in the late period of growth, resulting in plant lodging and a significant reduction in production.

In this study, we found that broomcorn millet, potato, and maize had the best effect on production increase under NM treatment, which is consistent with the application of chemical fertilizer with organic fertilizer having a stronger effect than the application of a dominant chemical fertilizer or fertilizer alone [19,22–24]. Although the annual yield of potatoes was the highest in the normal years, the yield increasing rate under NM treatment was greater than that under CT in the wet years, indicating that the long-term application of nitrogen and organic fertilizer had a more obvious effect in the wet years. In this study, precipitation significantly affected the effect of fertilization and the yield effect of nitrogen fertilizer combined with organic fertilizer increased with increasing precipitation, which was not consistent with the small internal variation in nitrogen fertilizer yield demonstrated by the results of Song et al. [25]. This may be related to maize being a crop with high water consumption.

The stability of the crop yield is an important indicator for judging the quality of a farmland ecosystem [24,26], while the sustainability of yield is an important indicator for evaluating the sustainability of different nutrient management systems [27,28]. This study found that the yield stability and sustainability of broomcorn millet and maize were the best in wet years, while those for potatoes were the best in normal years, being consistent with the yield. In our study, in relation to the sustainability of the three crops under different precipitation years, potato and corn had high SYI values; therefore, potato and corn rotations are more conducive to the stability of the ecosystem. Broomcorn millet, potato, and maize had the lowest yield variation coefficients under NM treatment and had the highest SYI values, indicating that long-term nitrogen fertilizer application can achieve a sustainable crop yield.

4.2. Effects of Long-Term Fertilization on Precipitation Utilization Efficiency and Water Use Efficiency in Years with Different Precipitation

Precipitation use efficiency and water use efficiency are comprehensively influenced by crop type, soil conditions, climate, fertilization measures, and other factors [29–31]. This study found that the water consumption in the growth periods of the crops increased with an increase in precipitation and the application of nitrogen fertilizer increased the water consumption of broomcorn millet, with that of maize being fundamentally the same; meanwhile, the water consumption of the potato crop is lower than the rainfall (297 mm) during the growth period. Through analysis of the proportion of water consumed by crops compared with the total amount consumed in all the precipitation years, it was found that nitrogen fertilizer can improve the utilization efficiency of broomcorn millet, potato, and maize. The RUE values of broomcorn millet and maize under NM treatment were 87.8% and 89.2%, respectively, while the farmland utilization efficiency of potatoes was low and the RUE value was 72.3%.

This study found that, with an increase in precipitation, the water use efficiency of broomcorn millet and potato tended to increase first and then decrease, with the highest WUE in normal years. The water use efficiency of maize increased with an increase in precipitation and the WUE was the highest in wet years. This is consistent with the results of Wang, showing that the years with different precipitation ranked as follows in terms of water utilization efficiency: drought years > wet years > normal years [4]. In general, maize has a high yield, high water consumption, and high water use efficiency; potato has lower water consumption and is second in terms of water use efficiency; and broomcorn millet has a low yield, high water consumption, and the lowest water use efficiency. This study found that long-term organic fertilizer application could greatly improve the water use efficiency of crops under the same levels of precipitation. This is related to the input of organic materials that can inhibit the evaporation of soil water and increase the water-holding performance of soil [32]; the application of organic fertilizer can improve the water use efficiency of crops by 6–30% [33] and play the role of "transferring water with fertilizer and promoting fertilizer with water". Therefore, in terms of the regional rainfall characteristics and matching degree, a potato and maize rotation is better than a potato and broomcorn millet rotation.

4.3. Relationship between Long-Term Fertilization, Precipitation, and Crop Yield

Zhang et al. stated that, for agricultural production on dry land, based on known soil moisture, it was possible to determine the amount of fertilizer that needed to be applied and estimate the yield according to the rainfall amount to reasonably implement the coupling of water and fertilizer [34]. Nitrogen fertilizer application and annual precipitation are constraints affecting the maize yield in drought, normal years, and wet years [4]. This study found a significant positive correlation between nitrogen and organic fertilizer and annual precipitation, indicating that an increased application of nitrogen and organic fertilizer is an effective way to increase broomcorn millet and maize production in years with sufficient precipitation. However, the yield of potatoes only showed a significant positive relationship with nitrogen and organic fertilizer. Another study found that the potato yield was the highest in normal years and the yield effect was not obvious in wet years [35]. The reason is that, if the water is excessive during the growth period, the potato stems and leaves are prone to flourish, causing lodging, which affects the yield but also causes rot in the tubers. To summarize, more measures should be taken to store water and conserve soil moisture in production so that soil reservoirs can participate in water conservation and water diversion. In order to further optimize fertilization to ensure a stable crop yield, the appropriate input of phosphate fertilizer and potassium fertilizer should also be considered.

5. Conclusions

In the 33-year-long broomcorn millet–potato–maize rotation system, the application of nitrogen fertilizer combined with organic fertilizer in drought, normal, and wet years significantly improved the stability and sustainability of the crop yield and also improved the efficiency of precipitation and water use in farmland. The rotation of potatoes with high water consumption crops (maize) and the rational allocation of organic and inorganic fertilizer (NM) is the best planting mode for the sustainable development of the planting system in this region.

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