EFFECTS OF NITROGEN APPLICATION RATE UNDER DIFFERENT GROWING SEASON PRECIPITATION LEVELS ON WATER AND NITROGEN UTILIZATION EFFICIENCIES, GRAIN YIELD, AND QUALITY IN DRYLAND WHEAT (*TRITICUM AESTIVUM* L.)

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Abstract. High interannual variability of precipitation and unbalanced N application rate has a considerable impact on wheat (*Triticum aestivum* L.) production in the drylands of the Loess Plateau, China. In this study, we conducted field experiments in Wenxi County, Shanxi Province, under six N application rates (0, 90, 120, 150, 180, and 210 kg ha^{-1}) for three consecutive years from 2014 to 2017. The years were classified as the wet (2014–2015), dry (2015–2016), and normal growing seasons (2016–2017) based on total precipitation during the growth period. The results showed that in the wet growing season, the optimum N application rate was 180 kg ha^{-1}, improved the total water consumption during the growth period by 1.9%-13.8%, the spike number by 0.6%–10.9%, the yield by 2.8%–14.3%, N recovery efficiency (NRE) by 15.2%–47.0%, and the economic by 4.4%–21.1%. In the normal and dry growing seasons, the optimum N application rate was 150 kg ha^{-1}, the total water consumption increased during the growth period by 0.5%–16.3%, the spike number by 0.9%–19.8%, the yield by 0.3%–23.3%, water use efficiency by 2.5%–12.9%, and NRE by 12.9%–59.1%, the economic improved by 0.6%–74.7%.
Keywords: *Loess Plateau, wheat cultivation, amount of precipitation, water use efficiency, nitrogen fertilizer recovery efficiency*

Introduction

Dryland farming accounts for one third of the cultivated area in China. Approximately 40% of the cultivated land in the Loess Plateau is dryland, covering an area of 63×104 ha^{-1} (Yang et al., 2021). Winter wheat production in this dryland is of importance in ensuring regional food security (Ren et al., 2016; Liu et al., 2021). In the Loess Plateau dryland, where irrigation is not available, precipitation is the only source of water for wheat production. Precipitation levels are low and unevenly distributed, and summer rainfall accounts for approximately 60% of the annual precipitation (Ren et al., 2016). Furthermore, annual precipitation fluctuates considerably (Yang et al., 2021). Because of limited water resources, the main planting approach in this area is to plant one crop (winter wheat) per year and leave the land fallow in the summer (Sun et al., 2019;

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Yu et al., 2021). In recent years, the frequency, duration, and severity of drought in this area have increased substantially due to climate change (Jiang et al., 2016; Yu et al., 2021). Drought is the main limiting factor of winter wheat production in the drylands of the Loess Plateau (Wang et al., 2019).

Soil fertility, especially N levels, in the Loess Plateau dryland is low (Cao et al., 2017). While the rainfall in wheat growing season is generally scarce, extensive yearly variabilities make it difficult to synchronize the soil N supply capacity with the wheat growth demand (Mon et al., 2016). The imbalance of soil water and N supply is the main cause of low and unstable wheat yield in the dryland (Zhang et al., 2017). The application of N fertilizers can significantly increase grain yield and water use efficiency (WUE) of winter wheat (Xia et al., 2016). Li et al. (2022) showed that fertilizers can reduced the effect of soil moisture on productivity in dryland soil while improving the wheat yield and WUE. The effects of water and N on crop yield are synergistic rather than individual. As the effects of water on yield and grain quality are influenced by N fertilizer, yield responses to N fertilizers vary with the annual precipitation level. A study on N application rate in the Loess Plateau for four consecutive years showed that when 180 kg N ha^{-1} was applied, wheat yield in the dry years increased by 14.0% relative to no N application, whereas it increased by 32.8% in the wet years (Wang et al., 2018).

Excessive N fertilization can have negative effects on crop yield and the environment (Lai et al., 2022). Several studies in the Loess Plateau have shown that N application rates of 75–150 kg ha^{-1} could result in a higher yield and higher N use efficiency (NUE), but the positive effects are considerably reduced when the N application rate exceeds 210 kg ha^{-1} (Li et al., 2022). The excessive use of N fertilizers poses several negative effects on the environment (Liu et al., 2016). A study in the Loess Plateau has shown that with the use of controlled release nitrogen fertilizers, the crop yield, NUE, and accounts returns increased by 8.5%, 10.9%, and 11.3%, respectively (Xu et al., 2021). Another study on N application rates in the Loess Plateau reported that the application of an appropriate amount of N fertilizer increased the content and composition of wheat proteins, leading to an improvement in baking quality of wheat flour (Raymbek et al., 2017). With an increase in the N application rate, the investment on N fertilizer increases. Appropriate N application should be determined based on the economic return (Liu et al., 2019). Furthermore, a survey of farmers in dry farming areas in the Loess Plateau in 2011 showed that 42% of the farmers applied more than 200 kg ha^{-1} N, and achieved an average yield of 4,500 kg ha^{-1} (Cao et al., 2017). Apparently, the amount of N applied by farmers in the area exceeds the level of N required to achieve high yield. Considering the variety of agricultural practices, outlining an effective guidance on how to apply fertilizers according to varying annual precipitation for improved grain yield and quality as well as high water and fertilizer use efficiency in the dryland wheat region of the Loess Plateau is essential for the farmers and has been the focus of many studies.

Previous studies have shown that optimizing N application in different growth periods and precipitation amounts can effectively improve yield and increase the efficiencies of water and N use (Wang et al., 2018; Xu et al., 2021). However, the problem of blind fertilization to achieve high yield, efficient water and N use, and sustainable winter wheat cropping system still exists in most areas of the Loess Plateau (Cao et al., 2017) due to the lack of systematic and comprehensive observation of precipitation and N fertilizer application during the growth period. In this study, field experiments with different N application rates (0–210 kg ha^{-1}) on dryland wheat were conducted for three consecutive years in the experimental site in the eastern part of the Loess Plateau, Shanxi Province,

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China. We aimed to determine (1) the effects of N application rates on growth, N accumulation of the plant, grain yield, grain quality, economic return, WUE, and NRE in the three years with differing growing season precipitation levels. (2) The optimal N application rates were determined based on grain yield, grain quality, and economic return in planting years with different growing season precipitation levels.

Materials and Methods

Experimental site

The experiment was carried out in the experimental site of Shanxi Agricultural University in Wenxi County, Shanxi Province, China (110°59′–111°37′E, 35°09′-35°34′N, *Figure 1*) in 2014–2017. Basic nutrients in the 0–20-cm layer of the calcareous cinnamon soil are shown in *Table 1*.

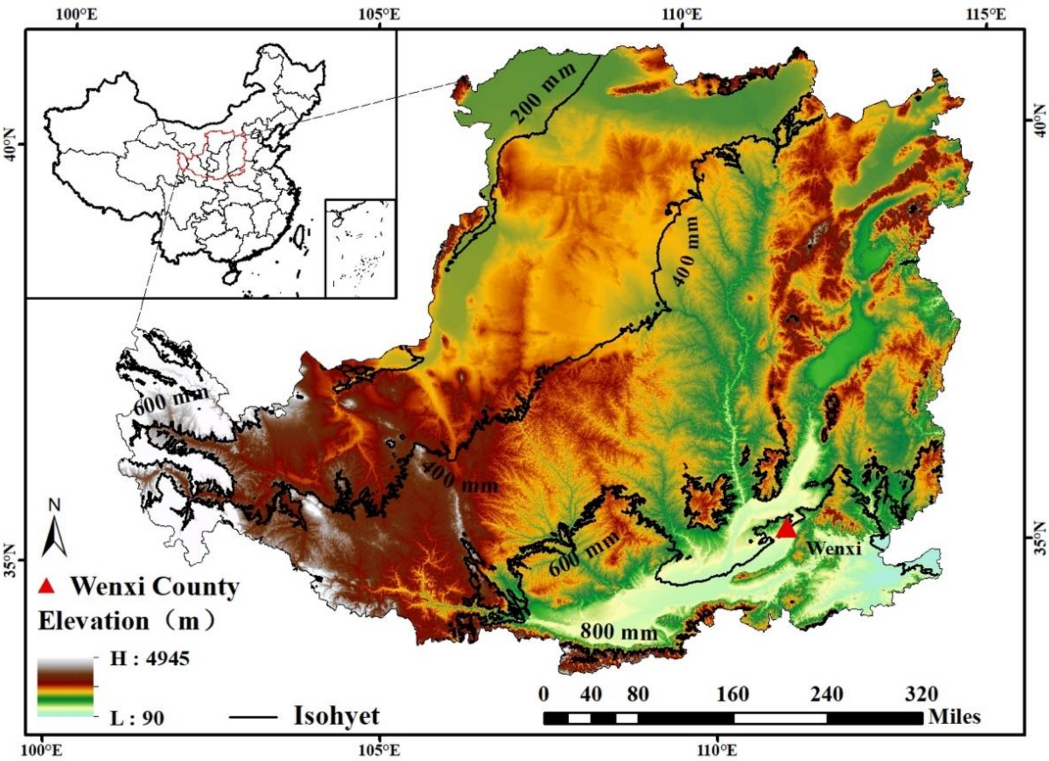

Figure 1. *Study area. Elevation and isohyet on the Loess Plateau in China*

Table 1. *Soil nutrient content in the 0–20-cm soil layer before wheat sowing*

Year	Organic matter (g kg^{-1})	Alkali-hydrolyzable nitrogen (g kg^{-1})	Available phosphorus (mg kg^{-1})	Available potassium (mg kg^{-1})	PH (2.5:1)
2014–2015	9.9	38.2	21.0	112.5	8.2
2015–2016	11.9	38.6	24.6	108.9	8.4
2016–2017	15.3	38.1	28.1	117.6	8.1

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Experimental design and field management

A completely randomized design was used in the experiment with six application rates of N fertilizer (0, 90, 120, 150, 180, and 210 kg ha^{-1}) and three replicates. The plot size was 4 m × 20 m. Before sowing, 150 kg P_2O_5 ha^{-1} and 150 kg K_2O ha^{-1} were evenly applied to the plots. Winter wheat seeds (variety Yunhan 20410) were sown in early October each year. A rotary seeder (2BMF-12/6; Dandong Virtue River Technology Co., Ltd., Shandong Province, China, *Figure 2*) was used for strip sowing. Straw residues from the previous season were plowed into the soil to a depth of 10–15 cm with the rotary seeder, and N fertilizer (urea content of 46% N) was applied at six rates (0, 90, 120, 150, 180, and 210 kg ha^{-1}) underneath the seeds. The sowing depth was 3–5 cm, row width was 12–13 cm, and plant spacing was 2–3 cm. Artificial herbicide was sprayed in the spring; before jointing, powdery mildew, red spiders, and aphids were controlled by UAV. *Fusarium* head blight was controlled at the anthesis stage. At the initial stage of filling, aphids and other pests were controlled. Wheat plants were harvested in early June in the following year.

Figure 2. *Wheat strip sowing and emergence of seedlings in the experimental site. Note: The picture on the left shows the strip sowing machine and the picture on the right shows the emergence of seedlings one month after sowing*

Classification of annual precipitation

Annual precipitation was used to classify the growing season using the drought index (DI). DI = (P – M)/σ [22]; where P is the growing season precipitation (mm), M is the average growing season precipitation from 2009 to 2019 (the value of M is 434.7 mm), and σ is the mean square deviation of the multiyear mean precipitation. The planting year of 2014–2015 was classified as a wet growing season, 2015–2016 as a dry growing season, and 2016–2017 as a normal growing season (*Table 2*).

Table 2. *Classification of year type for three planting seasons from 2014 to 2017*

Year	Growing season precipitation (mm)	Drought index (DI)	Growing season type
2014–2015	516.7	0.69	Wet
2015–2016	342.9	-0.78	Dry
2016–2017	406.3	-0.24	Normal

DI, drought index (DI < -0.35 classified as a dry growing season, DI > 0.35 as a wet growing season, and -0.35 ≤ DI ≤ 0.35 as a normal growing season)

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Measurement of soil moisture content and evapotranspiration and calculation of WUE

Soil samples from a depth of 200 cm was collected after harvesting the previous wheat crop. Soil samples (0–200 cm) were also collected by drilling in the pre-sowing, pre-wintering, jointing, anthesis, and maturity stages. Fresh soil weight was recorded, and then the soil was dried to a constant weight at 105 °C. Soil moisture content was calculated as a percentage of the difference between dry and wet weight (Ren et al., 2021).

Precipitation (mm) and consumption of soil water stored (mm) in the 0–200 cm layer were used to calculate crop water consumption in different growth periods. The total crop water consumption from sowing to plant maturity corresponds to the evapotranspiration (ET) rate for a given cropping season. ET was calculated using the following equation (Dong et al., 2019):

$$\mathrm{ET} = \mathrm{S}i + \mathrm{P}r + \mathrm{K} \tag{Eq.1}$$

where Si is the sum of soil water consumption (mm) in all growth stages, Pr is the sum of precipitation (mm) in all growth stages, K is groundwater recharge (mm), and K is negligible when the groundwater depth is greater than 2.5 m.

WUE was calculated as grain yield (kg ha^{-1}) /crop water consumption (mm) (Sadras and Lawson, 2012).

Measurement of grain yield and its components

Wheat plots of 0.667 m^2 were randomly selected at maturity to determine yield components (spike number, grain number, and 1000 grain weight). For the grain yield measurements, a 20 m^2 area in each plot was harvested at maturity.

Measurement of grain protein and starch content and calculation of NUE

Wheat grains were ground to flour using a miniature high speed grinder (FZ102; Beijing, China). The total N content in the flour was determined using the colorimetric method described by Ren et al. (2019), and the total grain protein content was obtained by multiplying the total N by 5.7. Albumin, globulin, gliadin, and glutenin were isolated by continuous extraction and N contents were determined using the same colorimetric method (Ren et al., 2019). Starch content was determined by hydrolyzing starch into glucose with hydrochloric acid and measuring the glucose using the enthrone colorimetry method described by Ren et al. (2021).

NRE, the plant N uptake per kilogram of N fertilizer applied, was calculated using the following equation (Wang et al., 2019):

$$\text{NRE (\%)} = \{[\text{N uptake at treat plot (kg ha–1)} - \text{N uptake at N0 plot (kg ha–1)}] / \text{Fertilizer N application rate (kg ha}^{-1}\text{)}\} \times 100 \tag{Eq.2}$$

Calculation of economic return

The economic return and the yield income were calculated in terms of United States dollar (USD) per hectare using the following equations:

$$\text{Economic return (USD ha}^{-1}\text{)} = \text{yield income (USD ha}^{-1}\text{)} - \text{production cost (USD ha}^{-1}\text{)} \tag{Eq.3}$$

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$$\text{Yield income} = \text{grain yield (kg ha}^{-1}) \times \text{market price (USD ha}^{-1}) \qquad \text{(Eq.4)}$$

The market price of winter wheat was 0.34 USD kg^{-1} and the production cost (*Table 3*) included the input of seeds, fertilizers, and field management (USD ha^{-1}) (Duc-Anh et al., 2018).

Table 3. *Production cost of winter wheat*

Seed and fertilizer cost (USD·kg^{-1})				Field management (USD·ha^{-1})				
Urea	Superphosphate	Potassium sulfate	Seed	Tillage	Sowing	Reaping	Weed	Spraying pesticide
0.3	0.26	0.6	0.7	139.2	116.0	116.0	162.4	69.6

Statistical analyses

All procedures were performed using SAS software (SAS, 2008, NC, USA) to calculate the analysis of variance. The significance of differences was tested using the least significant difference, and the significance level was set at $\alpha = 0.05$.

Results

Effects of N application rates on water consumption by dryland wheat in the three years with different growing season precipitation levels

Water consumption by winter wheat during the growth period was significantly affected by the annual precipitation level. The average total water consumption (ET) under all N application rates in the wet growing season was the highest among the three cropping years (*Table 4*). The water consumption during the growth period increased until reaching the optimal N application rate and then decreased with the increasing rate. The highest water consumption in the growth period was observed at 180 kg ha^{-1} for the wet growing season and at 150 kg ha^{-1} for the normal and dry growing season.

Effects of N application rates on yield components, yield, and WUE of dryland wheat in the three years with different growing season precipitation levels

The average number of spikes for all N application rates (from 0 to 210 kg ha^{-1}) in the wet growing season was significantly higher than that in the normal or dry growing season (*Table 5*). The spike number and grain number per spike peaked at 150 kg ha^{-1} in all growing seasons except for the highest number of spikes obtained at the N application rate of 180 kg ha^{-1} in the wet growing season (*Table 5*). The highest yield was recorded at 180 kg ha^{-1} in the wet growing season and 150 kg ha^{-1} in normal and dry growing season (*Table 5*). The N application rate of 180 kg ha^{-1} in the wet growing season increased the yield by 2.9% relative to 150 kg ha^{-1}, whereas the rate of 210 kg ha^{-1} reduced yield by 8.0%. In both the normal and dry growing seasons, the N application rate of 150 kg ha^{-1} increased the yield by at least 10.2% relative to 120 kg ha^{-1}. The WUE was the highest at 150 kg ha^{-1} in all three years studied (*Figure 3*) and in the dry growing season, it was approximately 40% lower than that in wet or normal growing season. These results indicated that the N application rates of 180 and 150 kg ha^{-1} are adequate for achieving high yield in the wet growing season and in both normal and dry growing season, respectively. The spike number was found to be a major contributor to the high yield.

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Table 4. *Effects of N application rates on crop water consumption (mm) in the four growth stages in the three planting years with different growing season precipitation levels*

Growing season type	N application rate (kg ha^{-1})	SS-WS	WS-JS	JS-AS	AS-MS	ET
Wet growing season	0	44.7 e	144.1 d	107.5 e	95.3 a	391.5 d
	90	48.8 d	155.7 c	112.0 d	88.3 b	404.8 c
	120	52.3 c	160.0 bc	118.6 c	85.1 c	416.0 b
	150	54.8 bc	164.9 b	124.0 b	80.2 d	423.9 b
	180	57.5 ab	171.7 a	128.6 a	96.3 a	454.0 a
	210	59.7 a	176.6 a	118.9 c	89.9 b	445.2 a
	Mean	53.0 ± 5.6	162.2 ± 11.7	118.3 ± 7.7	89.2 ± 6.1	422.6 ± 23.8
Normal growing season	0	56.8 e	124.9 d	84.6 e	97.3 a	363.7 e
	90	60.7 c	124.3 d	90.9 d	87.4 b	363.3 e
	120	58.4 d	137.8 c	100.7 c	89.9 b	386.8 d
	150	67.5 a	141.1 ab	109.3 a	98.3 a	416.1 a
	180	65.7 b	144.0 a	105.6 b	98.8 a	414.1 b
	210	65.1 b	138.0 bc	104.2 b	98.6 a	406.0 c
	Mean	62.4 ± 4.4	135.0 ± 8.4	99.2 ± 9.5	95.1 ± 5.0	391.7 ± 24.2
Dry growing season	0	30.6 d	85.4 d	79.9 e	98.1 a	294.0 f
	90	33.8 c	90.4 c	86.4 d	99.3 a	309.9 e
	120	39.3 b	90.6 c	96.6 c	99.3 a	325.8 d
	150	48.4 a	107.5 a	104.8 a	90.8 b	351.4 a
	180	45.6 a	104.9 a	101.1 b	89.7 b	341.3 b
	210	41.0 b	96.6 b	100.4 b	97.3 a	335.4 c
	Mean	39.8 ± 6.8	95.9 ± 8.8	94.9 ± 9.6	95.7 ± 4.4	326.3 ± 21.2
F value						
precipitation growing season (P)		1590.7**	11628.4**	7401.0**	461.6**	11620.0**
N application rate (N)		181.2**	450.2**	1875.5**	85.5**	1239.3**
P×N		8.5**	22.3**	28.8**	198.2**	21.5**

ET, evapotranspiration during the entire growth period. SS-WS, the period from sowing to pre-wintering. WS-JS, the growth period from pre-wintering to jointing. JS-AS, the period from jointing to anthesis. AS-MS, the period from anthesis to maturity. Different letters in the same column of a given year indicate that the difference between treatments was significant ($P < 0.05$). * and ** denote a significant difference at 5% and 1%, respectively

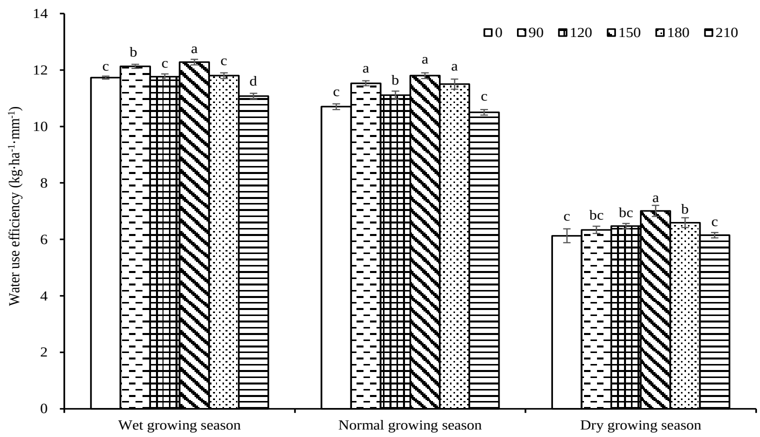

Figure 3. *Effects of N application rates on water use efficiency of dryland wheat in the three planting years with different growing season precipitation levels. Note: Error bars in the figure represent standard errors. Different letters represent a significant difference (P < 0.05) between the N application rates in a given year. In the legend, 0, 90, 120, 150, 180, and 210 represent different N application rates, and the unit is kg ha^{-1}*

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Table 5. *Effects of N application rates on yield and its components of dryland wheat in the three cropping years with different growing season precipitation levels*

Growing season type	N application rate (kg ha^{-1})	Spike number (10^4 ha^{-1})	Grain number per spike	1000-grain weight	Yield (kg ha^{-1})
Wet growing season	0	480.0 d	31.1 cd	39.6 b	4592.3 e
	90	514.0 b	30.9 d	38.9 c	4909.7 d
	120	526.5 ab	31.1 cd	39.7 b	4893.8 d
	150	536.0 a	32.3 a	39.7 b	5205.2 b
	180	539.0 a	32.5 a	40.3 a	5357.1 a
	210	499.0 c	31.4 bc	38. 9 c	4929.3 d
	Mean	515.8 ± 22.9	31.6 ± 0.7	39.5 ± 0.6	4981.2 ± 267.6
Normal growing season	0	397.8 d	31.6 bc	38.9 d	3878.3 d
	90	428.6 c	31.3 cd	38.6 e	4188.6 c
	120	441.6 bc	31.0 d	39.6 b	4296. 9 b
	150	496.1 a	32.2 a	40.0 a	4801.3 a
	180	491.2 a	31.9 ab	39.7 b	4786.6 a
	210	443.6 b	31.0 d	38.7 e	4367.6 b
	Mean	449.8 ± 37.7	31.5 ± 0.5	39.2 ± 0.6	4386.5 ± 357.2
Dry growing season	0	225.3 d	30.4 e	37.3 de	1801.9 d
	90	251.1 bc	30.7 d	37.3 de	1963.6 c
	120	246.9 c	30.2 f	37.4 d	2107.8 b
	150	268.6 a	31.6 a	39.5 a	2350.5 a
	180	265.4 ab	31.4 b	39.2 b	2316.6 a
	210	248.5 c	30.9 cd	37.2 e	2099.3 b
	Mean	251.0 ± 15.5	30.9 ± 0.6	38.0 ± 1.0	2106.6 ± 208.3
F value					
precipitation growing season (P)		16532.2**	151.6**	668.8**	48477.7**
N application rate (N)		264.7**	155.3**	227.4**	796.8**
P×N		26.4**	11.9**	32.4**	27.3**

Different letters in the same column of a given growing season indicate that the difference between treatments was significant ($P < 0.05$). * and ** denote a significant difference at 5% and 1%, respectively

Effects of N application rates on plant N accumulation and NRE of dryland wheat in the three years with different growing season precipitation levels

With an increase in the N application rate from 0 to 210 kg ha^{-1}, plant N accumulation and NRE peaked at 180 kg ha^{-1} in the wet growing season, whereas in the normal and dry growing season it peaked at 150 kg ha^{-1} (*Figure 4A and 4B*). Plant N accumulation at 180 kg ha^{-1} in the wet growing season was 9.1% higher than that at 150 kg ha^{-1}, but it was 4.1% lower than that at 210 kg ha^{-1} (*Figure 4A*). Compared to plant N accumulation, the NRE at 180 kg ha^{-1} in the wet growing season was 18.0 % higher than that at 150 kg ha^{-1}, but was 29.8% lower than that at 210 kg ha^{-1} (*Figure 4B*). In the normal and dry growing season, plant N accumulation at 150 kg ha^{-1} was at least 13.0% higher than that at 120 kg ha^{-1} (*Figure 4A*) and NRE was at least 24.8% higher (*Figure 4B*). These results indicated that the N application rate of 180 kg ha^{-1} in the wet growing season can lead to the highest plant N accumulation level and NRE, and the N application rate of 150 kg ha^{-1} can help achieve the highest plant N accumulation level and NRE in normal and dry growing season.

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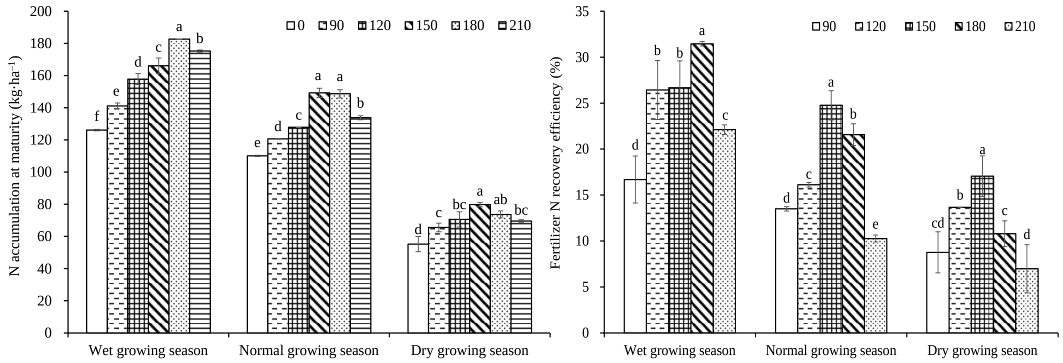

Figure 4. *Effects of N application rates on plant N accumulation (A) and fertilizer N recovery efficiency(B) of dryland wheat in the three planting years with different annual precipitation levels. Note: Error bars in the figure represent standard errors. Different letters represent a significant difference (P < 0.05) between the N application rates in a given year. In the legend, 0, 90, 120, 150, 180, and 210 represent different N application rates, and the unit is kg ha^{-1}*

Effects of N application rates on grain quality of dryland wheat in the three years with different growing season precipitation levels

In the three planting years, different growing season precipitation levels significantly affected the total grain protein content, protein composition, and starch content. The content of total grain protein and composition of proteins on average of all N application rates were the highest in the dry growing season followed by the normal growing season and the wet growing season (*Table 6*). In contrast, the starch content was the highest in the wet growing season followed by the normal growing season and the dry growing season (*Table 6*). The total grain protein content and protein composition peaked at 180 kg N ha$^{–1}$ in the wet growing season (*Table 6*), whereas the total grain protein content and protein composition peaked at 150 kg N ha$^{–1}$ in the normal and dry growing season (*Table 6*). In the wet growing season, the protein content at 180 kg N ha$^{–1}$ was 2.5% higher than that at 150 kg N ha$^{–1}$, and there was no significant difference in the protein content between 180 and 210 kg N ha$^{–1}$. In the normal and dry growing season, at least 3.8% increase in protein content was found at 150 kg N ha$^{–1}$ relative to that at 120 kg N ha$^{–1}$ (*Table 6*). In contrast to protein content, the starch content in grains peaked at 180 kg N ha$^{–1}$ in all growing season tested (*Figure 5*). The effects of N application rate and year type (based on precipitation) on the four proteins tested were similar (*Table 6*). These results indicated that higher annual precipitation can lead to more starch accumulation in grain, but lower grain protein content and protein composition. The N application rate of 180 kg ha$^{–1}$ can result in the highest total grain protein content and protein composition in the wet growing season, whereas the N application rate of 150 kg ha$^{–1}$ can result the highest total grain protein content and protein composition in both normal and dry growing season.

Effects of N application rates on economic returns of dryland wheat in the three years with different growing season precipitation level

Positive economic return peaked at the N application rate of 180 kg ha^{-1} in the wet growing season and at 150 kg ha^{-1} in the normal growing season. However, in the dry growing season negative returns were recorded across all N application rates (*Figure 6*). The lowest negative return was observed at the N application rate of 150 kg ha^{-1} in the

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dry growing season (*Figure 6*). In the wet growing season, the economic return at 180 kg N ha^{-1} was 4.6% higher than that at 150 kg N ha^{-1}, whereas it was 16% higher than that at 210 kg N ha^{-1}. In both normal and dry growing season, the economic return at 150 kg N ha^{-1} was at least 25.2% higher than that at 120 kg N ha^{-1}. These results indicated that the optimal rates of N applied can increase economic returns in normal and wet growing season and reduce the economic loss in the dry growing season.

Table 6. *Effects of N rates in three planting years with different precipitation during growth period on protein content and composition of dryland wheat*

Growing season type	N rate (kg ha^{-1})	Albumin (%)	Globulin (%)	Gliadin (%)	Glutenin (%)	Total protein content (%)
Wet growing season	0	2.18 e	1.05 d	3.21 e	3.13 e	9.57 e
	90	2.22 d	1.14 c	3.62 d	3.67 d	10.65 d
	120	2.26 c	1.19 b	3.78 c	3.92 c	11.15 c
	150	2.32 b	1.23 ab	3.92 b	4.21 b	11.68 b
	180	2.38 a	1.27 a	3.98 a	4.34 a	11.97 a
	210	2.36 a	1.25 a	3.94 b	4.32 a	11.87 a
	Mean	2.29±0.08	1.19±0.08	3.74±0.29	3.93±0.47	11.15±0.92
Normal growing season	0	2.21 e	1.21 e	4.16 e	4.34 d	11.92 f
	90	2.28 d	1.23 de	4.20 d	4.42 c	12.13 e
	120	2.31 d	1.25 cd	4.25 c	4.48 b	12.29 d
	150	2.47 a	1.33 a	4.38 a	4.59 a	12.77 a
	180	2.42 b	1.30 ab	4.32 b	4.50 b	12.54 b
	210	2.36 c	1.27 bc	4.29 b	4.51 b	12.43 c
	Mean	2.34±0.09	1.27±0.04	4.27±0.08	4.47±0.09	12.35±0.30
Dry growing season	0	2.24 d	1.42 c	4.25 d	4.24 e	13.54 f
	90	2.39 c	1.42 c	4.32 c	4.36 d	13.96 d
	120	2.38 c	1.45 bc	4.37 c	4.45 c	13.83 e
	150	2.50 a	1.53 a	4.51 a	4.66 a	14.51 a
	180	2.46 ab	1.50 a	4.45 b	4.56 b	14.18 b
	210	2.43 bc	1.46 b	4.42 b	4.51 b	14.04 c
	Mean	2.40±0.09	1.47±0.05	4.39±0.10	4.46±0.15	14.01±0.33
F value						
precipitation growing season (P)		217.0**	288.5**	2937.3**	1960.2**	15246.8**
N rate (N)		388.0**	29.9**	264.9**	528.0**	912.3**
P×N		47.8**	1.9	76.2**	149.6**	195.3**

Different letters in the same column of a given growing season indicate that the difference between treatments was significant ($P < 0.05$). * and ** denote the significant difference at 5% and 1%, respectively

Correlation analysis of water consumption and yield, grain quality, and N accumulation of dryland wheat at different growth stages under different precipitation types of N application rates

Under the condition of N application rate of 0–210 kg ha^{-1} in the wet growing season, sowing to pre-wintering, pre-wintering to jointing, and jointing to anthesis water consumption were significantly correlated with grain protein, starch content and nitrogen accumulation (*Table 7*). Jointing to anthesis water consumption was significantly correlated with spike number, grain number per spike and yield. In the normal growing season, water consumption of sowing to pre-wintering and jointing to anthesis was significantly correlated with spike number, yield, grain protein, starch content, and N accumulation. Water consumption of pre-wintering to jointing was significantly correlated with grain protein, starch content and N accumulation. In the dry growing

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season, water consumption of sowing to pre-wintering and pre-wintering to jointing was significantly correlated with grain starch content. Water consumption of jointing to anthesis was significantly correlated with spike number, yield, grain protein content, and N accumulation.

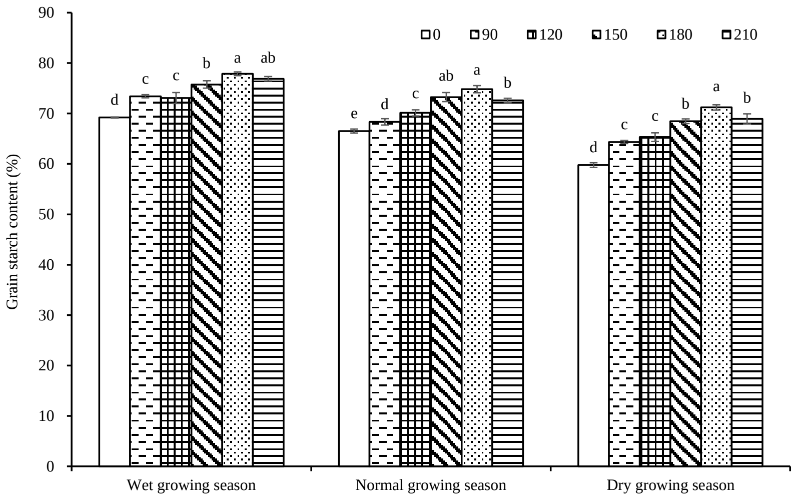

Figure 5. *Effects of N application rates on grain starch content of dryland wheat in the three planting years with different growing season precipitation levels. Note: Error bars in the figure represent standard errors. Different letters represent a significant difference (P < 0.05) between the N application rates in a given year. In the legend, 0, 90, 120, 150, 180, and 210 represent different N application rates, and the unit is kg ha^{-1}*

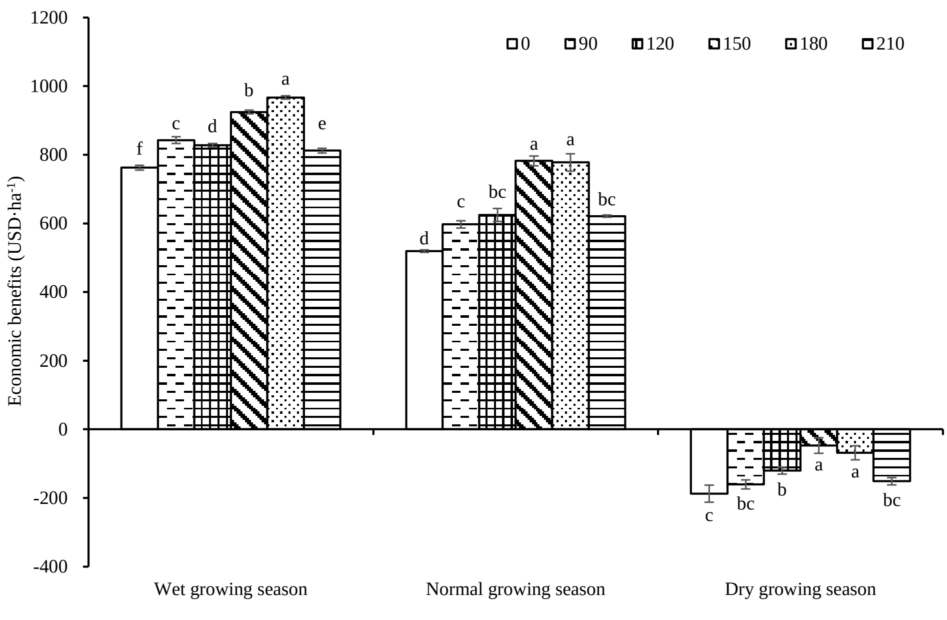

Figure 6. *Effects of N application rates on economic returns of dryland wheat in the three planting years with different growing season precipitation levels. Note: Error bars in the figure represent standard errors. Different letters represent a significant difference (P < 0.05) between the N application rates in a given year. In the legend, 0, 90, 120, 150, 180, and 210 represent different N application rates, and the unit is kg ha^{-1}*

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Table 7. *Relationship between plant water consumption and yield, grain protein content, grain starch content, and N accumulation at different growth stages*

Growing season type	Factor	SS-WS	WS-JS	JS-AS	AS-MS
Wet growing season	Spike number	0.5085	0.5001	0.8455*	-0.4119
	Grain number per spike	0.6215	0.5882	0.8833**	0.0061
	1000-grain weight	0.0844	0.0206	0.5512	0.2453
	Yield	0.7140	0.7124	0.9462**	-0.1617
	Grain protein content	0.9639**	0.9605**	0.9107**	-0.2713
	Grain starch content	0.9419**	0.9553**	0.8810**	-0.1144
	N accumulation at maturity	0.9702**	0.9585**	0.9295**	-0.0977
Normal growing season	Spike number	0.8366*	0.6818	0.8693*	0.3820
	Grain number per spike	0.3853	0.0172	0.1932	0.4971
	1000-grain weight	0.3101	0.4593	0.5472	0.3281
	Yield	0.8579*	0.7044	0.8839**	0.3936
	Grain protein content	0.8207*	0.7641*	0.8748**	0.4532
	Grain starch content	0.9278**	0.8708**	0.972**	0.5164
	N accumulation at maturity	0.8766**	0.7686*	0.9141**	0.4638
Dry growing season	Spike number	0.7008	0.6575	0.8032*	-0.3042
	Grain number per spike	0.5735	0.6464	0.6039	-0.4432
	1000-grain weight	0.5070	0.4706	0.5921	-0.2111
	Yield	0.8103*	0.7130	0.9104**	-0.4026
	Grain protein content	0.6252	0.6055	0.7453	-0.2983
	Grain starch content	0.9575**	0.9318**	0.9632**	-0.7060
	N accumulation at maturity	0.7236	0.6104	0.8694*	-0.2669

SS-WS, the period from sowing to pre-wintering. WS-JS, the growth period from pre-wintering to jointing. JS-AS, the period from jointing to anthesis. AS-MS, the period from anthesis to maturity. * and ** denote a significant difference at 5% and 1%, respectively

Discussion

Optimal N application rates for high yield vary among the years with different growing season precipitation levels

As the growing season precipitation varied in the three cropping years studied, the optimal N application rates were also different among these years (*Table 2*). In the wet growing season, the optimal N application rate for high yield was 180 kg ha^{-1}, whereas 150 kg ha^{-1} ensured the high yield in normal and dry growing season (*Table 5*). The application of 180 kg N ha^{-1} in the wet growing season could increase the yield by 2.9% relative to that of 150 kg N ha^{-1}, and the application of 150 kg N ha^{-1} in normal and dry growing season could increase the yield by at least 11.4% relative to that of 120 kg N ha^{-1} (*Table 5*). The increase in the yield is most likely correlated to the increased water consumption, due to the optimal N amounts, at jointing anthesis stage, which promotes the development of tillers, thereby increases the number of panicles per unit area (*Table 4*). The optimal rates fertilization in different precipitation years can also reduce production costs (*Figure 4*) and environmental pollution Noor et al. (2022). The higher yield and lower production cost can boost economic return (*Fig. 4*). Liu et al. (2019) reported that the highest grain yield and higher economic returns and environmental benefits can be achieved at the optimal N application rate.

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Optimal N application rates under different annual precipitation levels improve grain quality in dryland wheat production

Our results showed that increasing N up to the optimal rate enhanced the total grain protein content and protein composition in all years studied regardless of growing season precipitation level (*Table 6*). In the wet growing season, the application of 180 kg N ha^{-1} could increase the grain protein content by 2.5% relative to 150 kg N ha^{-1}, and the application of 150 kg N ha^{-1} in both normal and dry growing season could increase grain protein content by at least 3.8% relative to 120 kg N ha^{-1} (*Table 6*). Similar to grain protein content, the starch content in grain was enhanced with increasing N up to the optimal rates in both wet and normal growing season (*Figure 3*). Optimal N application increased the water consumption of SS-WS, WS-JS, JS-AS plants, resulting in increased grain protein and starch content (*Table 7*). In the wet growing season, the higher starch content in grain was associated with the lower content of grain protein, whereas in the dry growing season, the lower starch content in the grain was associated with the higher content of grain protein (*Table 6 and Figure 3*). This is a result of the “dilution effect”; as the grain protein content is relatively constant, an increase in grain starch content reduces the grain protein content (Eser et al., 2020). In addition, the content of grain protein in dry and normal growing season was higher than that in the wet growing season (*Table 6*). A higher grain content results in not only a higher market price, leading to a higher economic return (Alghory et al., 2018), but also a higher nutritional value for human consumption (Farinde et al., 2021).

Optimal N application rates for different precipitation growing season maximizes WUE and NUE for sustainable wheat production in dryland

The optimal N application rate in the normal and dry growing season led to the highest WUE (*Figure 1*). However, in the wet growing season, the optimum N application rate resulted in the highest yield and water consumption during the growing period of crops t, but the highest WUE was not achieved. The optimal N application rates under different precipitation conditions could also increase NRE (*Figure 2B*) by at least 18.0% relative to the lower N application rate (*Figure 2*). When the higher rate (210 kg N ha^{-1} in the wet growing season or 180 kg N ha^{-1} in the normal and dry growing season) was applied, NRE was reduced by 12.9%–36.8% (*Figure 2*). Excess N fertilization results in the accumulation of residual N in the soil (Noor et al., 2021). The residual N could be lost due to runoff, erosion, and leaching, or through denitrification and volatilization (Habbib et al., 2017), leading to environmental pollution. The rational application of N fertilizer based on annual precipitation improves WUE and NRE, making wheat production sustainable in the dryland in the Loess Plateau.

The annual precipitation levels fluctuate considerably in the Loess Plateau, as observed in this study and that by Yang et al. (2021). Precipitation is also unevenly distributed within a year. Summer rainfall accounts for approximately 60% of yearly precipitation (Ren et al., 2019). The amount of soil water stored at sowing stage could be used as a guide for applying the basal amount of fertilizer. Additional N fertilization as top dressing could be applied when rainfall is higher than expected in the growth season. The implementation of this “basal and top dressing" strategy based on monitoring the progression of seasonal rainfall can further improve the yield, grain quality, NUE, WUE, and the farmers’ profitability in wheat production.

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Conclusions

When the N application rate was 180 kg ha^{-1} in a wet growing season, compared with other N application rates, the jointing to anthesis water consumption increased along with the total water consumption, the spike number and yield, and the NRE, while the protein content and starch content of the grain increased at the same time, thus the economic benefit increased. When the combined N application rate of dryland wheat was 150 kg ha^{-1} in the normal and dry growing season, compared with other N application rates, the jointing to anthesis water consumption, total water consumption, spike number at maturity, and yield all increased, the WUE and NRE improved, and the protein content of the grain also increased, ultimately increasing the economic benefits. In summary, the optimal N application rate varies with the annual precipitation. The recommended N application rate is 180 kg ha^{-1} in the wet growing season and 150 kg ha^{-1} in the normal and dry growing season. The optimal N application rate in different precipitation growing seasons can improve the growth period water consumption, yield, WUE, NRE, and grain quality, resulting in economic benefits for the farmers of dryland wheat.

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