Journal of Soil Science and Plant Nutrition (2022) 22:585–596
https://doi.org/10.1007/s42729-021-00671-1

ORIGINAL PAPER

Nitrogen Fertilization and Precipitation Affected Wheat Nitrogen Use Efficiency and Yield in the Semiarid Region of the Loess Plateau in China

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Received: 29 October 2020 / Accepted: 27 October 2021 / Published online: 12 November 2021

Abstract

The yield of rainfed crops is greatly affected by the annual pattern of precipitation, whereas the tillage method and nitrogen fertilizer dose also exert a certain regulatory effect. We hypothesized that in the semiarid region of the Loess Plateau, with more precipitation, more nitrogen fertilizer is needed for the optimal wheat yield. Here, the following three nitrogen treatments were tested over 5 years at the Wenxi Experimental Station: 90 kg·ha^{-1}, 150 kg·ha^{-1}, and 210 kg·ha^{-1}, designated as N90, N150, and N210, respectively. The yield was classified into three levels: high, intermediate, and low. The relationships between dominant yield components and dry matter, nitrogen translocation accumulation, and nitrogen use efficiency were studied. A high yield was achieved by increasing the spike number and 1000-kernel weight. Spike number was related to pre-anthesis nitrogen translocation, while 1000-kernel weight was related to pre-anthesis dry matter translocation, as well as pre-anthesis and post-anthesis nitrogen accumulation. Additionally, the regulation of nitrogen fertilizer use was related to precipitation distribution. Sufficient precipitation during fallow and early plant growth stages promoted high yields. In years precipitation occurs in short supply, once accumulated precipitation has reached a threshold at the late plant growth stage, increasing nitrogen fertilizer application can improve yield. Grain yield under the N210 treatment was highest in wet years, whereas N150 allowed for the highest grain yield in normal or dry years.

Keywords Yield level · Annual type · Nitrogen application · Yield components · Nitrogen transformation

1 Introduction

The Loess Plateau is a typical dryland-farming region in China. Winter wheat (*Triticum aestivum L.*) is the main food crop in the area. It is of great interest to improve wheat yield in the Loess Plateau. Currently, one of the primary means to improve wheat production is to improve wheat yield per unit area. Moreover, increasing unit yield is considered the main strategy available to maintain continuous increases in the wheat crop yield (Zhang et al. 2016).

The Loess Plateau is categorized as a semiarid climate, and most of its agriculture is rainfed, with the rainfall varying greatly year to year. Therefore, crop yields in the planting area, such as that of winter wheat, change with rainfall distribution and amount (He et al. 2014). Nitrogen (N) is an important mineral element for plant growth and development, and N fertilizer application reportedly increases soil fertility and crop productivity (Ahmad et al. 2013; Wang et al. 2012). For example, Liu et al. (2016a, b) showed that wheat yield and water use efficiency increased with N application in the drylands of the Loess Plateau. Moreover, Gao et al. (2009) showed that wheat grain yield increased significantly but N use efficiency (NUE) decreased significantly with increasing N application from 120 to 240 kg ha^{-1} in the rainfed farming area of the Loess Plateau. Although N is the most important nutrient for ensuring both high grain yield and quality (Khan et al. 2017), the heavy application of N fertilizer represents a significant cost and also causes serious environmental problems due to the loss of large amounts of applied N into the environment (Ma et al. 2019). In addition, excessive nitrogen will increase water use in the early growth stage and promoted the vegetative growth of wheat plants, delayed reproductive growth, and further led to tiller sterility and plant lodging (He et al.

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2014). Excessive nitrogen application also increases the risk of nitrate leaching and NOx emission (Yang et al. 2019). Lack of water resources and low soil fertility are two main factors restricting crop yields in semiarid areas (Zhang et al. 2018). However, the relationship between water and N is complex, and the impact on crop growth might be positive or negative, depending on the specific situation (Majrashi et al. 2019). Matching fertilizer to precipitation is a major challenge for dryland agriculture (Sadras et al. 2016). Wheat yield is reportedly associated with soil water storage at the time of sowing (Schillinger et al. 2008), as well as soil moisture and N topdressing at the early jointing stage (Zhao et al. 2016). Long-term field positioning tests on the Loess Plateau showed that the wheat yield varied with the application amount of N fertilizer, but to a greater extent depended on precipitation fluctuations. Moreover, the yield of 90–180 kg N ha^{-1} was positively correlated with the precipitation in the fallow period, but not significantly with the precipitation in the growing season. The optimal N application rates were 45 kg N ha^{-1}, 135 kg N ha^{-1}, and 180 kg N ha^{-1} in dry, normal, and wet years, respectively (Guo et al. 2012). A study has proved that in a dry farming system, adjusting nitrogen fertilizer input according to the change of summer rainfall can improve wheat yield and crop water productivity (Yu et al. 2021). Thus, N application had obvious regulatory effects on wheat yield, but precipitation distribution varied with time and location and was not controlled. These facts highlight the need to better understand the interactions among N fertilizer, precipitation, and crop yield, optimize the N fertilizer application rate, improve the precipitation utilization rate, and realize sustainable agricultural production.

The increase in wheat yield mainly depends on the source–sink ratio; however, further improvement of the harvest index is becoming increasingly difficult (Fischer 2011). Some studies have been conducted on wheat populations showing different yields. Dai et al. (2016), for example, showed that the biomass and harvest index of high-yield wheat crops were significantly higher than those of intermediate- or low-yield wheat crops. This is due to differences in N accumulation and utilization among wheat populations with different yield levels, indicating that adequate N accumulation and translocation capacities are important determining factors of high yield (Slaton et al. 2005).

To date, agronomists have conducted numerous studies focused on farming methods, sowing methods, field management practices, and other aspects of crop production aiming to increase wheat yield. At the same time, there are many studies on the mechanism of high-yield formation of dryland wheat in the Loess Plateau, but there are few reports from the perspective of high-yield population characteristics and nutrient utilization characteristics combined with precipitation. Therefore, a 5-year field experiment was conducted in the semiarid area of the Loess Plateau. The relationship between yield and N uptake and utilization efficiency was studied among different yield levels. In addition, the response of wheat yield to nitrogen fertilizer under different precipitation conditions was explored. The objectives of this study were (1) to clarify the difference in dry matter accumulation in wheat at different yield levels; (2) to analyze the differences and relationships among N accumulation, translocation, and utilization in wheat at different yield levels; (3) to elucidate the relationships between wheat yield and composition, dry matter and N accumulation, and N translocation at different yield levels; and (4) to clarify the effect of precipitation and N application on wheat yield. We hypothesized that in different years of precipitation, the N use of crops is different and the performance span of yields is large. In addition, greater precipitation means more N fertilizer is needed for crop growth.

2 Materials and Methods

2.1 Research Site

The experiment was conducted during the winter-wheat cropping seasons between 2011 and 2016 at the Wenxi Dryland Wheat Agriculture Station (35°20 N, 111°17E) in the Shanxi Province, China. The test station is located southeast of the Loess Plateau. It is a typical semiarid area, with an average annual ambient temperature of 11–13℃ and an annual precipitation of 342.90 to 671.30 mm (2011–2016). Its elevation is 696 m above sea level. Precipitation during the fallow and growing seasons during the experimental period and the 35-year average from 1981 to 2016 is shown in Table 1. The mean annual precipitation over the last 35 years (1981–2016) was 490.90 mm. Based on the generalized precipitation classification (Ren et al. 2019), the annual precipitation pattern is divided into three types: dry years ($P \leq 25\%$), normal years ($25\% < P < 25\%$), and wet years ($P \geq 25\%$). *P* was calculated as follows:

$$\text{Precipitation} = (\text{the year precipitation} - 490.90)/490.90$$

Therefore, the 2012–2013 and 2015–2016 seasons are hereafter referred to as dry years, while the 2013–2014 season is referred to as a normal year, and the 2011–2012 and 2014–2015 seasons are referred to as wet years. The experimental site was flat and limited by a boundary all around, with no water runoff during the course of the experiments. All precipitation could be stored within a depth of 3 m into the soil, and deep drainage did not generally occur below this limit (He et al. 2016).

The soil at the experimental site is classified as loam soil (sand 43.2%, silt 32.5%, and clay 10.5%), according to the

Table 1 Precipitation distribution of the experimental site from 2011 to 2016 during the fallow season and the growth stage of winter wheat (mm)

Year	Fallow season	Growth stage				Whole year
		SS-JS	JS-AS	AS-MS	Total	
1981–2017	**284.59**	**88.61**	**37.55**	**80.16**	**206.32**	**490.90**
2011–2012	436.09	136.48	24.42	74.32	235.21	671.30
2012–2013	205.06	57.51	36.62	43.71	137.84	342.90
2013–2014	305.44	54.58	22.05	92.13	168.76	474.20
2014–2015	338.27	42.28	57.20	78.95	178.43	516.70
2015–2016	126.80	117.53	50.69	91.78	260.00	386.80

Data are from the Meteorological Observation Station of Wenxi County, Shanxi Province, China. Fallow period: from the last 10 d of Jun. to the last 10 d of Sep.; SS-JS (sowing stage–jointing stage): from the first 10 d of Oct. to the first 10 d of Apr. in the following year; JS-AS (jointing stage–anthesis stage): from the middle 10 d of Apr. to the first 10 d of May; AS-MS (anthesis stage–maturity stage): the middle 10 d of May to the middle 10 d of Jun. Dry years: 2012–2013 and 2015–2016; normal year: 2013–2014; wet years: 2011–2012 and 2014–2015

Table 2 Basic soil properties of 0 ~ 20 cm layer in experimental location in 2011–2016

Time	Organic carbon ($g·kg^{-1}$)	Total nitrogen ($g·kg^{-1}$)	Available nitrogen ($mg·kg^{-1}$)	Available phosphorus ($mg·kg^{-1}$)
2011–2012	8.72	0.78	40.16	19.87
2012–2013	8.88	0.61	38.62	14.61
2013–2014	10.88	0.85	39.32	28.10
2014–2015	10.55	0.68	37.65	17.64
2015–2016	9.27	0.86	41.31	10.25

international standard for soil texture classification. Soil organic matter was determined using the modified Walkley–Black method (Wang et al. 2016). Total N was measured by the Kjeldahl method. Available phosphorus (Olsen-P) was measured by extraction with 0.5 mol L^{-1} $NaHCO_3$, followed by colorimetric measurement of P using the molybdate-ascorbic acid method. Available potassium (K) was determined by extraction with 1 mol L^{-1} ammonium acetate and analyzed by a flame photometer, and soil pH in water was determined with a 1:2.5 soil-to-water ratio. The basic soil properties are shown in Table 2.

2.2 Experimental Design and Field Management

Local winter wheat (*Triticum aestivum L.*) cultivar "Yunhan 20,410" was provided by the Wenxi Agriculture Bureau for this study. The following three N treatments were used: N90 (90 kg N ha^{-1}), N150 (150 kg N ha^{-1}), and N210 (210 kg N ha^{-1}). Among them, 150 kg N ha^{-1} nitrogen application rate is the local conventional recommended nitrogen application rate. And 90 kg N ha^{-1} and 210 kg N ha^{-1} nitrogen application rates are set to explore the potential of nitrogen reduction and high yield. The test plot is a uniform plot, which is divided into five blocks along the ridge, and one of them is selected for the test every year to avoid the influence of nitrogen fertilizer residue on the test results. All treatments were arranged in a randomized complete block design with three replicates in each experimental season. Each plot was 50-m long and 6-m wide, consisting of 30 rows of wheat spaced 0.2 m for all treatments. A mechanical seed drill (2BX-12, Hebei Nonghaha, China) was used for seeding. Before sowing, N fertilizer (urea containing N 46%) was applied by hand at the three rates (N90: 90 kg ha^{-1}; N150: 150 kg ha^{-1}; N210: 210 kg ha^{-1}) with 150 kg ha^{-1} of phosphorus fertilizer (16% P_2O_5) and 75 kg ha^{-1} of potassium fertilizer (KCl, 52% K_2O).

Winter wheat in this region is usually cultivated as a single crop per year, followed by more than three months of summer bare fallow. Wheat was harvested mechanically at the beginning of June every year. After that, the height of stubble was 20–30 cm. Deep plowing (25–30 cm) was performed 10–15 days after harvesting. In late August, rotary tillage was performed in preparation for planting. Wheat was sown in early October each year from 2011 to 2016. The sowing dates were 1 Oct 2011 and 2012, 2 Oct 2013, 1 Oct 2014, 3 Oct 2015, and 1 Oct 2016. The planting density was 315×10^4 plants ha^{-1}. Weeds were removed manually, and no irrigation was provided in any cropping season.

2.3 Sampling and Measurements

2.3.1 Yield and Yield Components

At the seedling stage, 100 plants were selected from each plot for tagging, and fifty plants from each plot were randomly sampled at maturity from the previously marked sample population to determine yield components, including spike number, grains per spike, and 1000-grain weight. Grain yield was determined by harvesting all plants in a 20-m^2 area in each experimental plot, shelling them mechanically, and air-drying the grain to a constant mass.

2.3.2 Plant Dry Matter and Nitrogen

Twenty plants were randomly collected from each treatment, and their roots were cut. This operation is repeated three times. Then, they were divided into different organs (sowing stage: total plant; jointing stage: stem + leaf sheath and leaf; flowering stage: stem + leaf sheath, leaf, and ear; maturity stage: stem + leaf sheath, leaf, cob + glume and grain) to determine the dry matter accumulation and nitrogen concentration of plants at sowing stage, jointing stage, flowering stage, and mature stage. We calculated the dry matter accumulation at different growth stages and calculated the proportion of dry matter accumulation at each growth stage to the accumulation of the whole plant at the maturity stage. Take SS-JS as an example to explain the formula.

$$\begin{aligned}&\text{Dry matter accumulation in SS} - \text{JS}\left(\text{kg} \bullet \text{ha}^{-1}\right)\\&= \text{DM at jointing stage}\left(\text{kg} \bullet \text{ha}^{-1}\right) - \text{DM at the sowing stage}\left(\text{kg} \bullet \text{ha}^{-1}\right)\end{aligned}$$

$$\begin{aligned}&\text{Ratio of the Dry matter accumulation in SS} - \text{JS}(\%)\\&= \text{DM in SS} - \text{JS}\left(\text{kg} \bullet \text{ha}^{-1}\right)/\text{DM at maturity stage}\left(\text{kg} \bullet \text{ha}^{-1}\right) \times 100\%\end{aligned}$$

Plant samples and grains were oven-dried at 105℃ for 30 min, then at 75℃ for 48 h for the dry weight. Dry plant samples were cut to 4–5 cm in length and ground using a plant ball mill (FZ102, Beijing, China). Dry grains were ground into a powder using the FZ102 mill. Ground samples (0.25 g) were digested with $H_2SO_4 \cdot H_2O_2$, and the total N concentration was determined using the standard indophenol-blue colorimetric method (Meyer 1983). The calculation of N accumulation, translocation, and NUE was performed as described by Przulj and Momcilovic (2003).

$$\begin{aligned}\text{Plant N accumulation amount}\left(\text{kg} \cdot \text{ha}^{-1}\right) &= \text{plant dry weight}\left(\text{kg} \bullet \text{ha}^{-1}\right)\\&\quad \times \text{plant N concentration}(\%)\end{aligned}$$

$$\begin{aligned}\text{Pre} - \text{anthesis organs N}\left(\text{kg} \cdot \text{ha}^{-1}\right) &= \text{anthesis organs N}\left(\text{kg} \bullet \text{ha}^{-1}\right)\\&\quad - \text{maturity organs N}\left(\text{kg} \bullet \text{ha}^{-1}\right)\end{aligned}$$

$$\begin{aligned}&\text{Contribution of pre} - \text{anthesis organs N}(\%)\\&= \text{pre} - \text{anthesis organs N}\left(\text{kg} \cdot \text{ha}^{-1}\right)/\text{grainN}\left(\text{kg} \cdot \text{ha}^{-1}\right) \times 100\%\end{aligned}$$

$$\text{Post} - \text{anthesis N}\left(\text{kg} \cdot \text{ha}^{-1}\right) = \text{maturity N}\left(\text{kg} \bullet \text{ha}^{-1}\right) - \text{anthesis N}\left(\text{kg} \bullet \text{ha}^{-1}\right)$$

$$\begin{aligned}&\text{Contribution of post} - \text{anthesis N translocation amount to grain}(\%)\\&= \text{post} - \text{anthesis N accumulation}\left(\text{kg} \cdot \text{ha}^{-1}\right)\\&\quad /\text{grainN accumulation}\left(\text{kg} \cdot \text{ha}^{-1}\right) \times 100\%\end{aligned}$$

$$\begin{aligned}&\text{Nitrogen use efficiency}\left(\text{kg} \cdot \text{kg}^{-1}\right) = \text{grainyield}\left(\text{kg} \bullet \text{ha}^{-1}\right)\\&/\text{plant N accumulation amount}\left(\text{kg} \cdot \text{ha}^{-1}\right)\end{aligned}$$

$$\begin{aligned}\text{Nitrogen harvest index} &= \text{grain N accumulation amount}\left(\text{kg} \bullet \text{ha}^{-1}\right)\\&\quad /\text{plant N accumulation amount}\left(\text{kg} \bullet \text{ha}^{-1}\right)\end{aligned}$$

$$\begin{aligned}&\text{Partial factor productivity of applied N}\left(\text{kg} \bullet \text{kg}^{-1}\right)\\&= \text{grain yield}\left(\text{kg} \bullet \text{ha}^{-1}\right)\\&\quad /\text{N rate}\left(\text{kg} \bullet \text{ha}^{-1}\right)\end{aligned}$$

2.4 Statistical Analysis

Normal analysis, variance heterogeneity tests, analysis of variance (ANOVA), and the least significant difference (LSD) were performed using SPSS Statistics 25.0 software (SPSS Inc., Chicago, IL, USA) to determine treatment effects and identify significant differences among treatments. The test results show that the data followed a normal distribution and homogeneity test of variance. Differences were considered significant at $P < 0.05$. Figures were plotted using SigmaPlot 12.5 and Microsoft Excel 2018.

3 Results

3.1 Yield Level Category

From 2011 to 2016, the successive cropping seasons were characterized as wet, dry, normal, wet, and dry. Over these cropping seasons, the grain yield ranged between 1780.80 kg ha^{-1} and 5621.50 kg ha^{-1} (Fig. 1a). According to cluster analysis, the yield was divided as follows: < 3000 kg ha^{-1} was defined as the low yield level (LY), $3000 - 4500$ kg ha^{-1} was defined as the intermediate yield level (MY), and ≥ 4500 kg ha^{-1} was defined as the high yield level (HY) (Fig. 1b).

3.2 Dry Matter Accumulation and its Relationship with Yield at Different Growth Stages

The amount of accumulated dry matter at different growth stages during the growth process and its proportion relative to the total dry matter accumulated at maturity differed significantly. Furthermore, the accumulated dry matter at jointing and its proportion relative to total accumulated dry matter at anthesis were the highest indices across all three yield levels (Table 3).

We found that dry matter accumulation from jointing to flowering stage was the most correlated with grain yield at high yield level, intermediate yield level, and low yield level. The relationship between accumulated dry matter and

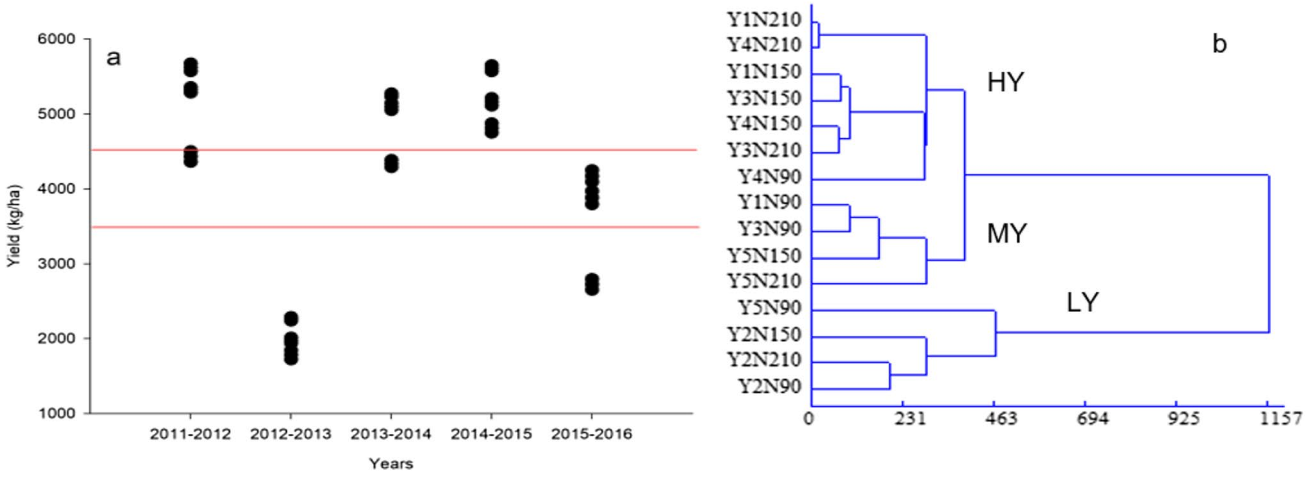


Fig. 1 Wheat yield under different treatments in 2011–2016 and yield cluster analysis diagram. HY, high yield level; MY, intermediate yield level; LY, low yield level

final yield at various growth stages for the three different yield levels showed different trends (Fig. 2a–c). Thus, at the high yield level, the yield increased with increasing dry matter accumulation, and the correlation between yield and accumulated dry matter up to anthesis was higher (Fig. 2a, b). Conversely, at the intermediate yield level, the yield was significantly related to dry matter accumulation from anthesis to maturity (Fig. 2c), whereas at the low yield level, the yield was significantly related to dry matter accumulation between jointing and maturity (Fig. 2b, c). These results indicated that dry matter accumulation in the early and intermediate growth stages was the main determinant of high yield in wheat.

3.3 Nitrogen Accumulation and its Relationship with Yield at Different Growth Stages

The amount of accumulated N increased gradually with growth, and high yield was concomitant with high accumulated N (Fig. 3a). The relationship between accumulated N at different growth stages and yield differed with yield level (Fig. 3b–e). Yield increased with increasing N accumulation at the high yield level, and the correlations between yield and accumulated N at jointing, anthesis, and maturity were higher (Fig. 3c, d). In turn, the yield was mainly related to accumulated N at anthesis and maturity at the intermediate yield level (Fig. 3d, e), whereas at the low yield level, it was more closely related to accumulated N in the wintering, jointing, and maturity stages (Fig. 3b, c, e).

3.4 Nitrogen Translocation and its Contribution to Grain Yield

Pre-anthesis N translocation and post-anthesis N accumulation in the developing grain increased gradually with increasing yield (Table 4). Pre-anthesis N translocation at different yield levels ranged between 37.43 kg ha^{-1} and 89.28 kg ha^{-1}, and the contribution to grain ranged from 75.72 to 83.38%. In turn, post-anthesis N accumulation varied from 7.84 to 25.78 kg ha^{-1}, while its contribution to grain yield was 16.62 – 24.28%. Clearly, pre-anthesis N translocation contributed significantly to N translocation into the grain at different yield levels.

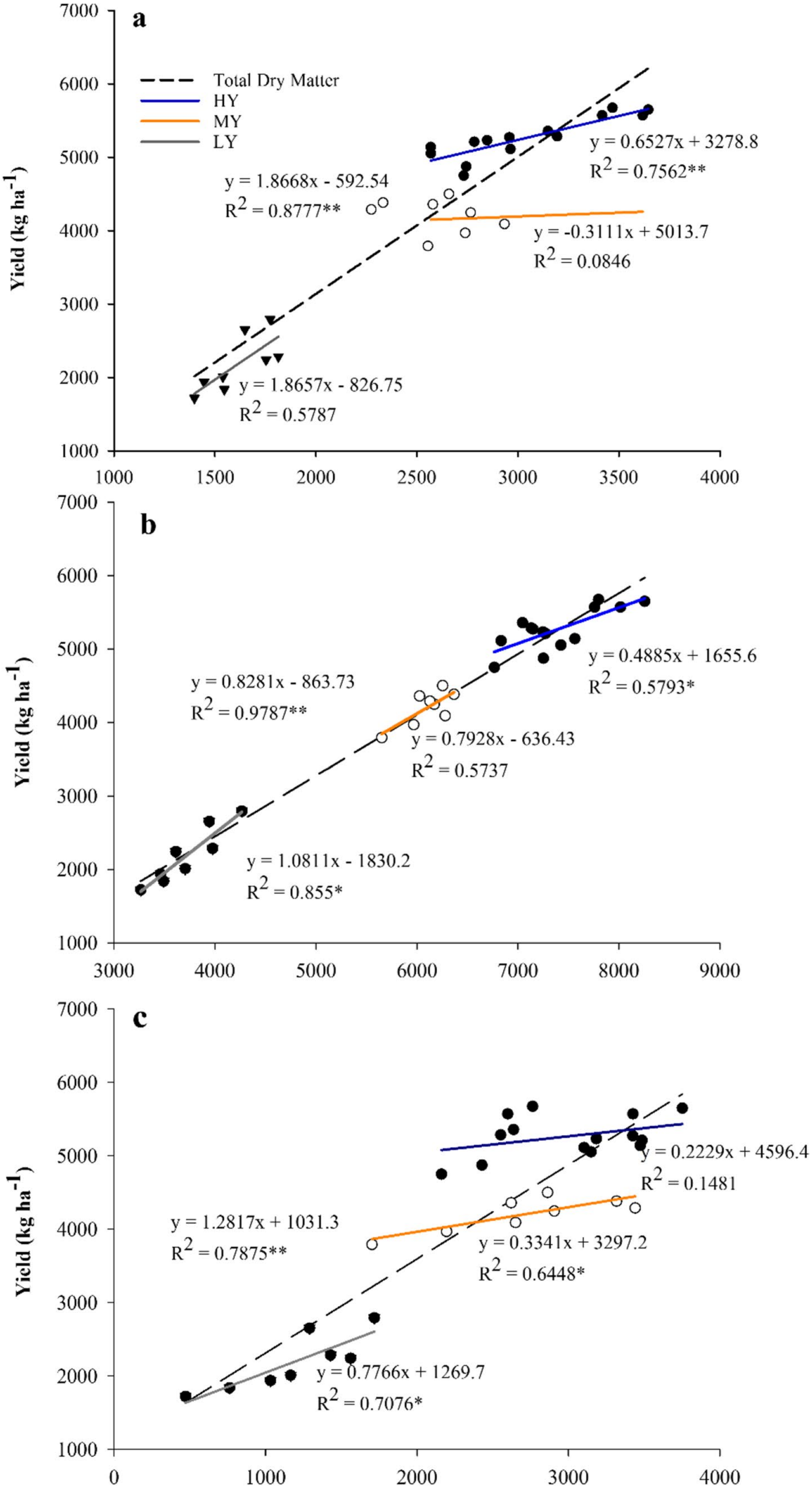
Table 3 Differences of dry matter accumulation in growth stages of wheat under different yield level

Yield level	SS-JS		JS-AS		AS-MS	
	Mean (kg·ha^{-1})	Ratio (%)	Mean (kg·ha^{-1})	Ratio (%)	Mean (kg·ha^{-1})	Ratio (%)
HY	3046.79 ± 8.27 a	22.63 ± 0.06 b	7394.06 ± 14.42 a	55.05 ± 0.11 b	3010.29 ± 7.28 a	22.32 ± 0.06 a
MY	2604.03 ± 26.77 b	22.89 ± 0.86 b	6104.72 ± 5.37 a	53.53 ± 0.00 c	2712.38 ± 14.83 a	23.59 ± 0.19 a
LY	1614.52 ± 1.33 c	24.92 ± 0.04 a	3714.45 ± 2.53 b	57.38 ± 0.11 a	1179.15 ± 50.12 b	17.70 ± 0.57 b

The different lowercase letters in the same column indicate significant differences at the level of LSD$_{0.05}$

HY, high yield level; *MY*, intermediate yield level; *LY*, low yield level; *SS-JS*, sowing stage–jointing stage; *JS-AS*, jointing stage–anthesis stage; *AS-MS*, anthesis stage–maturity stage

Fig. 2 Relationships between dry matter accumulation at different growth stages and yields respectively at different yield levels. HY, high yield level; MY, intermediate yield level; LY, low yield level; * and ** indicate differences at the 0.05 and 0.01 probability levels, respectively. The horizontal coordinates are the accumulation of dry matter (kg ha^{-1}) from sowing stage to jointing stage (**a**), from jointing stage to anthesis stage (**b**), and from anthesis stage to maturity stage (**c**)



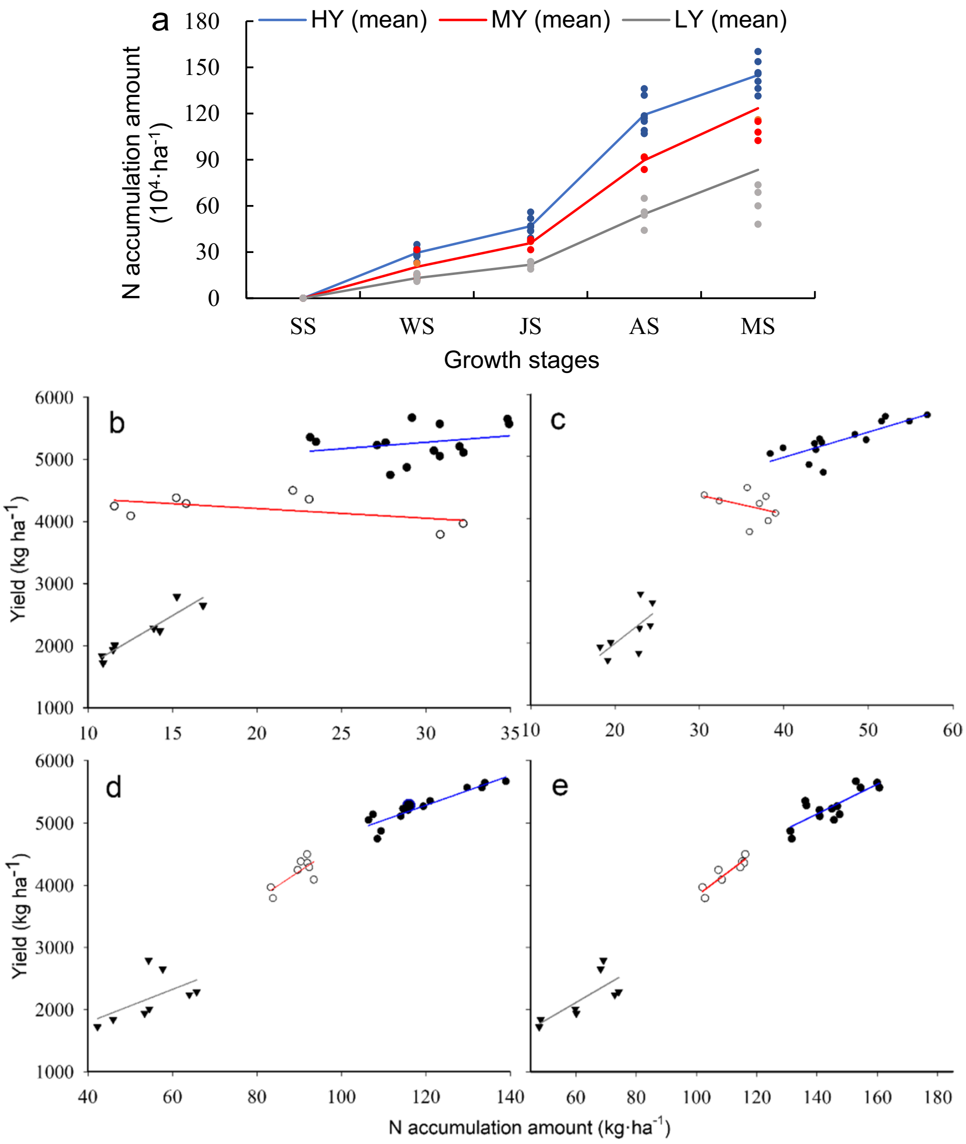


Fig. 3 N accumulation amount dynamics and relationships between N accumulation amount in growth periods and yield, respectively, at different yield levels. HY, high yield level; MY, intermediate yield level; LY, low yield level; SS, sowing stage; WS, wintering stage; JS, jointing stage; AS, anthesis stage; MS, maturity stage; * and ** indicate differences at the 0.05 and 0.01 probability levels, respectively. The vertical coordinates of (**c**) and (**e**) graphs are both yields. The horizontal coordinates of the (**b**)–(**e**) diagram are the nitrogen accumulation amount, which are wintering stage (**b**), jointing stage (**c**), anthesis stage (**d**), and maturing stage (**e**). The related equations can be found in the Supplementary information

3.5 Differences in Yield and Yield Components, NUE, N Harvest Index, and Partial Yield

The high yield level of wheat mainly appeared in wet years and normal years. The intermediate yield level was distributed in high precipitation years with low nitrogen application rate, and in dry years with high nitrogen application rate, whereas the low yield level was concentrated in dry years (Table 5). The N harvest index increased significantly with increasing yield, while NUE and partial productivity of N fertilizer increased first and then decreased. These data suggest that wheat yield and N use are regulated by precipitation

Table 4 Differences of pre-anthesis nitrogen (N) translocation and post-anthesis N accumulation at different wheat yield levels

Yield level	Pre-anthesis N translocation		Post-anthesis N accumulation	
	Amount (kg·ha^{-1})	Contribution to N in grains (%)	Amount (kg·ha^{-1})	Contribution to N in grains (%)
HY	89.28 ± 0.70 a	77.68 ± 0.85 b	25.78 ± 1.05 a	22.32 ± 0.85 a
MY	64.04 ± 0.22 b	75.72 ± 0.74 b	20.68 ± 0.75 b	24.28 ± 0.74 a
LY	37.43 ± 0.77 c	83.38 ± 1.83 a	7.84 ± 0.81 c	16.62 ± 1.83 b

The different lowercase letters in the same column indicate significant differences at the level of LSD$_{0.05}$

HY, high yield level; *MY*, intermediate yield level; *LY*, low yield level type (wet, normal, or dry) and N application. In wet and normal years, the yield could reach a high yield level when the nitrogen application rate was 150 kg ha^{-1} and 210 kg ha^{-1}. However, when the nitrogen application rate was 90 kg ha^{-1}, the yield in 2014–2015 was at a high yield level, while those in 2011–2012 and 2013–2014 were at intermediate yield levels. In addition, in 2015–2016 as a dry year, increasing nitrogen input could effectively improve the yield and make it reach the intermediate yield level. The yield in 2012–2013 was low, which was the same level as that of 2015–2016. It can be seen that the effect of nitrogen fertilizer on yield is different in different precipitation years. There was no significant change in the yield of increasing nitrogen fertilizer from 2012 to 2013, but the yield of increasing nitrogen fertilizer from 2015 to 2016 showed a leap between levels.

3.6 Correlation Analysis of Dry Matter on N Accumulation and Translocation, NUE, Yield, and Yield Components

The relationship between yield and its components differed with yield level (Table 6). The yield was correlated with spike number and 1000-kernel weight at high and low yield levels, while it correlated only with spike number at the intermediate yield level. Furthermore, yield components, dry matter, N accumulation, N translocation, and NUE were expressed differently at different yield levels (Table 7).

A high yield was achieved by increasing the spike number and 1000-kernel weight, which increased with the amount of pre-anthesis dry matter translocation, pre-anthesis N translocation, and post-anthesis N accumulation. Furthermore, yield increased with a greater spike number, which in turn increased with increasing dry matter translocation and accumulation at intermediate yield levels. Similarly, spike number and 1000-kernel weight increased yield at low yield levels because pre-anthesis dry matter translocation, pre-anthesis N translocation, and post-anthesis N accumulation increased those yield components.

4 Discussion

Previous studies have shown that nitrogen use efficiency (NUE) is related to yield (Loffler and Busch 1982); furthermore, differences in N accumulation at different growth stages and yield levels have also been demonstrated (Slaton et al. 2005). These findings are consistent with the experimental results described. In addition, we found that the amount of pre-anthesis N translocation into the developing grain contributed greatly to grain yield at different yield levels. With the increase in yield, the N harvest index increased significantly, whereas NUE and partial factor productivity of applied N first increased and then decreased. In addition, we also found that dry matter accumulation from jointing to flowering was the most correlated with grain yield. This indicates that the growth condition is the most important determinant of yield during the growing season. Dry matter production during this period may be affected by variety, nitrogen availability, water availability, or any other nutrient or environmental conditions. At a high yield level, the yield was related to dry matter accumulation over the period from sowing to anthesis and to N accumulation throughout the growth period. The yield can be increased by increasing spike number and 1000-kernel weight. In our experiment, the spike number was related to pre-anthesis N translocation, while 1000-kernel weight was related to the extent of pre-anthesis dry matter translocation, pre-anthesis N translocation, and post-anthesis N accumulation.

A previous study showed that increasing the productive tiller numbers increased plant activity and grain yield, thereby maximizing yield (Weiner et al. 2010). Here, we found that spike number and yield were significantly correlated at different yield levels, and that yield increased with increasing spike number, which was consistent with previous results (Cao et al. 2019). The study by Duan et al. (2018) in the 3H Plain (Huang-Huai-Hai Plain) showed that when the wheat yield was less than 7500 kg ha^{-1}, the increase in yield depended on the increase in spike number or grains per spike, with both affecting yield, but when yield exceeded 7500 kg ha^{-1}, the increase in yield depended mainly on spike number. However, here, we found that at different yield levels, spike number and 1000-kernel weight showed different correlations with yield, while yield showed no significant relationship with grains per spike. The reason for this finding may be that the water conditions at the two experimental sites are largely different. The pattern of precipitation distribution in the Loess Plateau is uneven, with little rain occurring during jointing through anthesis, which is not conducive to the formation of many grains per spike, whereby the effect of grains per spike on yield increase is much lower than that of the spike number and 1000-kernel weight. Moreover, in our experiment, the spike number was related to pre-anthesis N translocation, while 1000-kernel weight was related to the extent of pre-anthesis dry matter translocation, pre-anthesis N translocation, and post-anthesis N accumulation.

Many studies have shown that water stress reduces the ability of wheat to absorb nitrogen, affects the absorption and translocation of nitrogen, and then affects the yield (Hou et al. 2002). Although 2015–2016 was a dry year, yield increased significantly from the low-to-intermediate yield level with increasing N application. However, the increased N application in 2012–2013 did not achieve a significant yield increase. This might be explained by the fact that, although total precipitation and precipitation in the fallow and early growth periods did not differ significantly between the two cropping seasons, precipitation during

Table 5 Differences of wheat yield and its components, NHI, NUE, and PFPN, under different yield levels (2012 – 2016)

Yield level	Treatment	Spike number ($\times 10^4$ ha^{-1})	Grains per spike	Thousand kernel weight (g)	Grain yield (kg ha^{-1})	NHI (%)	NUE (kg·kg^{-1})	PFPN (kg·kg^{-1})
HY	2011–2012 N210	496.9 ± 11.6 c	30.7 ± 0.3 c	43.9 ± 0.1 a	5621.5 ± 51.5 a	76.8 ± 0.0 d	36.6 ± 0.3 b	26.8 ± 0.3 c
	2014–2015 N210	532.0 ± 4.0 a	31.1 ± 0.6 bc	41.9 ± 0.7 b	5609.8 ± 39.1 a	79.8 ± 0.0 b	35.0 ± 0.2 c	26.7 ± 0.2 c
	2011–2012 N150	485.7 ± 12.9 cd	31.5 ± 0.5 b	42.3 ± 0.3 b	5321.0 ± 35.4 b	77.2 ± 0.0 d	39.1 ± 0.3 a	35.5 ± 0.2 b
	2013–2014 N150	482.1 ± 7.7 cd	32.6 ± 0.4 a	41.7 ± 0.1 bc	5251.6 ± 20.6 b	78.7 ± 0.0 c	36.0 ± 0.1 b	35.0 ± 0.1 b
	2014–2015 N150	511.0 ± 5.0 b	30.4 ± 0.2 d	40.5 ± 0.2 c	5160.8 ± 49.3 c	81.8 ± 0.0 a	36.6 ± 0.4 b	34.4 ± 0.3 b
	2013–2014 N210	463.0 ± 1.9 d	31.7 ± 0.2 b	40.9 ± 0.3 c	5095.8 ± 44.3 c	79.9 ± 50.0 b	34.8 ± 0.3 c	24.3 ± 0.2 c
	2014–2015 N90	484.0 ± 9.0 cd	30.5 ± 0.2 cd	39.8 ± 0.1 d	4811.4 ± 61.9 d	81.7 ± 0.0 a	36.6 ± 0.5 b	53.5 ± 0.7 a
	Mean	493.5 ± 7.4 a	31.2 ± 0.2 a	41.6 ± 0.2 a	5267.4 ± 10.5 a	79.4 ± 0.0 a	36.4 ± 0.1 b	33.7 ± 0.1 a
MY	2011–2012 N90	459.4 ± 14.3 a	29.7 ± 0.6 c	40.4 ± 0.3 a	4429.5 ± 70.5 a	79.6 ± 0.0 a	38.2 ± 0.6 a	49.2 ± 0.8 a
	2013–2014 N90	456.1 ± 6.8 a	30.4 ± 0.3 ab	39.9 ± 0.5 a	4335.7 ± 46.4 a	75.1 ± 0.0 c	37.8 ± 0.4 b	48.2 ± 0.5 a
	2015–2016 N150	446.6 ± 10.8 a	30.1 ± 0.1 b	40.5 ± 0.6 a	4169.0 ± 78.1 b	73.9 ± 0.0 c	38.7 ± 0.7 a	27.8 ± 0.5 b
	2015–2016 N210	395.2 ± 13.2 b	31.0 ± 0.1 a	39.9 ± 0.4 a	3880.1 ± 88.3 c	78.8 ± 0.0 b	37.9 ± 0.9 b	18.5 ± 0.4 c
	Mean	439.3 ± 5.9 a	30.3 ± 0.2 a	40.2 ± 0.1 a	4203.6 ± 26.7 b	76.8 ± 0.0 b	38.1 ± 0.2 a	35.9 ± 0.4 a
LY	2015–2016 N90	328.8 ± 2.6 a	28.8 ± 0.6 c	39.6 ± 0.3 a	2723.3 ± 71.0 a	79.0 ± 0.0 a	39.6 ± 1.0 a	30.3 ± 0.8 a
	2012–2013 N150	264.3 ± 4.8 b	31.4 ± 1.3 a	37.5 ± 0.1 b	2262.7 ± 22.5 b	67.8 ± 0.0 c	30.8 ± 0.3 d	15.1 ± 0.2 b
	2012–2013 N210	255.3 ± 0.8 b	29.4 ± 0.9 b	36.8 ± 0.1 bc	1974.8 ± 35.9 bc	71.6 ± 0.0 b	32.9 ± 0.6 c	9.4 ± 0.2 c
	2012–2013 N90	231.3 ± 4.3 c	29.8 ± 2.0 ab	35.7 ± 0.5 c	1780.8 ± 59.2 c	70.8 ± 0.0 b	37.1 ± 1.2 b	19.8 ± 0.7 b
	Mean	269.88 ± 2 b	29.8 ± 0.3 a	37.4 ± 0.0 b	2185.4 ± 6.3 c	72.3 ± 0.0 c	35.1 ± 0.0 c	18.6 ± 0.0 b
ANOVA results								
Year (Y)		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Nitrogen (N)		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Y × N		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

The different lowercase letters in the same column indicate significant differences at the level of LSD$_{0.05}$

HY, high yield level; *MY*, intermediate yield level; *LY*, low yield level; *NHI*, nitrogen harvest index; *NUE*, nitrogen use efficiency; *PFPN*, partial factor productivity of applied N

the anthesis–maturity periods in 2015–2016 was nearly 50 mm higher than that recorded in 2012–2013, which greatly affected the 1000-grain weight. This is likely why the yields differed significantly between the two cropping campaigns. Furthermore, 2011–2012 and 2014–2015 were both wet years, but the yield with 90 kg ha^{-1} N application in 2011–2012 was within the intermediate yield level, the reason likely being that the precipitation in 2011–2012 occurred mainly during the fallow and the early growth period, while the precipitation in the later part of the growing period was relatively low. In addition, the low N dose applied clearly reduced grain numbers per spike and 1000-grain weights, and consequently, final yield was also reduced. Previous studies suggest that low soil nitrogen content is an important limiting factor for wheat production in the Loess Plateau. Increasing nitrogen application can effectively improve

Table 6 The path coefficient of grain yield (Y) and the influence factor of spike number (Y1) and grains per spike (Y2), and thousand kernel weight (Y3)

Yield level	Influence factor of Y on Y_n	Correlation coefficient	Direct path coefficient	Simulation equation
HY	Y1	0.553**	0.781	$Y=4.785*X1+165.149.9*X3-3956.947\ R^2=0.999$
	Y2	0.102		
	Y3	0.863**	0.389	
MY	Y1	0.886**	0.658	$Y=5.175*X1-152.116*X2+6537.549\ R^2=0.98$
	Y2	−0.775**	−0.393	
	Y3	0.169		
LY	Y1	0.960**	0.401	$Y=3.957*X1+59.565*X2+160.354*X3-6656.848\ R^2=0.97$
	Y2	−0.194	0.163	
	Y3	0.989**	0.647	

* and ** indicated the correlation levels $P<0.05$ and $P<0.01$, respectively

HY, high yield level; *MY*, intermediate yield level; *LY*, low yield level

Table 7 Correlation between yield components and transfer and accumulation of dry matter and nitrogen

Yield level	Yield composition	X1	X2	X3	X4	X5	Simulation equation
HY	Y1	−0.064	0.273	0.783**	−0.303	−0.058	$Y1=-0.02*X1+2.634*X3+289.434\ R^2=0.99$
	Y2	−0.251	0.369*	−0.293	0.306	−0.083	
	Y3	0.494*	−0.035	0.663**	−0.452*	0.207	$Y3=0.109*X3+31.815\ R^2=0.999$
MY	Y1	−0.659**	0.876**	0.479	0.444	0.201	$Y1=0.044*X2+321.427\ R^2=0.999$
	Y2	0.151	−0.521*	−0.776**	−0.322	−0.409	$Y2=0*X1-0.178*X3-0.401*X5+56.492\ R^2=0.97$
	Y3	−0.116	0.112	0.216	−0.168	0.198	
LY	Y1	0.088	0.787**	0.747**	0.917**	0.473	$Y1=9.599*X4+194.608\ R^2=0.999$
	Y2	−0.531*	0.122	0.076	−0.121	−0.712**	$Y2=-0.197*X5+36.741\ R^2=0.99$
	Y3	0.073	0.863**	0.813**	0.919**	0.416	$Y3=0.384*X4+34.392\ R^2=0.999$

* and ** indicated the correlation levels $P<0.05$ and $P<0.01$, respectively

HY, high yield level; *MY*, intermediate yield level; *LY*, low yield level; Y1, spike number; Y2, grains per spike; Y3, thousand kernel weight; X1, pre-anthesis dry matter translocation amount; X2, post-anthesis dry matter accumulation amount; X3, pre-anthesis N translocation amount; X4, post-anthesis N accumulation amount; X5, nitrogen use efficiency

wheat yields. Of course, the optimal amount of nitrogen application is determined by soil moisture (Guo et al. 2012). However, our research shows that appropriately increasing the amount of nitrogen fertilizer can improve the yield only when the precipitation at the later growth stage of wheat is guaranteed. Thus, the regulation of yield by nitrogen fertilizer mainly depends on the precipitation at the later growth stage. If there is not enough precipitation at the later growth stage, the soil water content will be low and the excessive nitrogen input will increase the number of ineffective tillers, resulting in plant lodging, and eventually, the yield will not increase but decrease (Charles et al. 2010). Although there was no significant difference between 2011–2012 and 2015–2016 in terms of total precipitation during the wheat growth period, there was a difference of nearly 310 mm in precipitation during the 2-year fallow period. At this time, precipitation significantly affected the emergence rate and spike number of wheats, therefore causing the difference in yield. Furthermore, although nearly 60–70% of the precipitation occurs in the fallow season, cool weather prevents a severe water deficit late during the reproductive stage. The soil moisture content at sowing in the Loess Plateau and other dryland areas is highly dependent on precipitation during the fallow season, which is of great significance to the early growth of wheat (Rossato et al. 2017). Therefore, water storage in the fallow season is more important for determining crop yield in the drylands of the Loess Plateau (Wang and Shangguan 2015; Sun et al. 2018). Furthermore, the distribution pattern of rainfall might be more important than total rainfall in determining crop yield in drylands, especially in soils with low water storage capacity, as previously proposed by Brunel et al. (2013). According to

Jan et al. (2016), higher wheat yields might be achieved by adjusting N fertilizer dosages in accordance with precipitation rates. We agree that precipitation in the fallow period is very important. The amount during this period basically determines the wheat yield, while the precipitation in the later growth period determines whether the yield can be improved. In other words, when there is sufficient precipitation in the fallow period, a good yield can be achieved without applying a large amount of nitrogen. When there is sufficient precipitation in the later growth period, an appropriate increase in nitrogen application can achieve a significant increase in yield. However, when there is insufficient precipitation in the late growth period, nitrogen input has no obvious effects on yield regulation. This result is different from our hypothesis.

5 Conclusions

In order to increase the dryland wheat yield, the amount of nitrogen application and precipitation should be considered at the same time. In a year with abundant precipitation, increasing the amount of nitrogen application can effectively improve the yield. In the dry year when the precipitation is concentrated in the later stage of growth, 150 kg ha^{-1} nitrogen fertilizer input also has an obvious yield increase effect. However, whether the yield-increasing mechanism of the two cases is the same needs further research.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42729-021-00671-1.

Funding This work was jointly supported by the Modern Agriculture Industry Technology System Construction (No. CARS-03-01-24), the National Key Research and Development Program of China (No. 2018YFD020040105), the National Natural Science Foundation of China (No. 31771727), the “Crop Ecology and Dry Cultivation Physiology Key Laboratory of Shanxi Province” (No. 201705D111007), the “1331” Engineering Key Innovation Cultivation Team-Organic Dry Cultivation and Cultivation Physiology Innovation Team (No. SXYBKY201733), the 2020 Graduate Education Innovation Plan Project (No. 2020SY206), the scientific and technological innovation project of Shanxi University (2019l0385), the science and technology innovation fund project of Shanxi Agricultural University (2019001), and the scientific research project of Shanxi excellent doctor working in Shanxi Province (sxybky2018044).

Declarations

Conflict of Interest The authors declare no competing interests.

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