Water and Nitrogen Coupling Effects on Grain Yield, Water and Nitrogen use Efficiency of Oilseed Flax in Semiarid Area of China

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Abstract

Irrigation and nitrogen management are essential for sustainable agricultural development in arid and semi-arid regions. Lower water availability and fertilizer utilization are two major factors of constrainting agricultural production in the semi-arid regions. Therefore, improving the utilization efficiency of water and fertilizer has become an important research goal. A two-year field experiment was laid out in a split-plot design with no irrigation (I_0), 1200 m^3 ha^{-1} (I_{1200}) and 1800 m^3 ha^{-1} (I_{1800}) as the main factor and 0 (N_0), 60 (N_{60}) and 120 (N_{120}) kg N ha^{-1} nitrogen rate as a sub-factor to investigate the effects of irrigation and nitrogen rates on precipitation storage efficiency (PSE), soil water storage, grain yield, and water and nitrogen use efficiency of oilseed flax in the Loess Plateau of China. The result showed that irrigation and nitrogen significantly increased PSE, soil water storage during the fallow period (ΔSWCf), dry matter accumulation and grain yeild of oilseed flax. However, the change of soil-water storage during the growing season (ΔSWCg) and the change of soil-water storage in the whole year (ΔSWCy) decreased. Soil water storage in irrigation supply treatment at after harvest in each growing season was higher than that in non-irrigation. PSE was highest under I1800N120 treatment. I1800 increased SWSs, SWSh and ETg at 2018 and improved above-ground biomass (anthesis and maturity stage), while decreased WUE and WUEI. Grain yield under 60 and 120 kg N ha^{-1} with 1800 m^3 ha^{-1} increased by 69.12, 68.07 (2017) and 22.77, 15.23% (2018), respectively, when compared to the I0N0 treatment. Considering flax grain yield, water and nitrogen productivity, 60 or 120 kg/ha N and irrigation of 1800 m^3/ha are recommended for water and nitrogen management of oilseed flax in Loess Plateau of China.

Introduction

Crop production is limited by irrigation water shortage, especially in the 40% of the world’s cropland under arid or semi-arid climatic conditions where irrigation is the only way to maintain stable food production [1]. Gansu province located in the arid and semi-arid regions of China. The effective precipitation is generally lowest during the growing season of crops, and the precipitation storage efficiency (PSE) is about 35–40% [2]. About half of total annual precipitation in this region focused on July to September, hence, the limited water resource in this region is inefficient in most cases [3]. Therefore, maximizing water productivity is a critical task in this region and will have significant impacts at local and regional levels. To cope with water scarcity, irrigation combined with nitrogen fertilizer is a commonly used water-saving cultivation technique in this area.

Irrigation is considered one of the key factor affecting crop water and nutrient uptake. Appropriate irrigation has been used by many researchers to promote crop growth, increase crop yield, improve water use efficiency and facilitate N uptake [4–6]. To facilitate N uptake, soil water availability in moist soil compartment should remain at a high water level with partial irrigation of root zone [7]. Irrigation should consider its side effects on increasing N emissions from paddy fields, which may also reduce N use efficiency [8]. Precipitation use efficiency (PUE) is the ratio of grain yield to annual precipitation [9], which can be used as an index to measure WUE [10]. Maximizing precipitation use for dryland agriculture is essentially about maximizing soil-plant-atmosphere persistence productivity [11].

Soil nutrient availability, along with water content, is another factor that affects the grain yield and crop quality. Nitrogen is an essential nutrient that affects crop productivity and water use efficiency (WUE) [12]. However, it has been reported that high N fertilization is not sufficient to maintain high grain yield and WUE in the long term, because soil water may be depleted under high N supply [13]. Moreover, crop response to nitrogen lies on soil water content, amount and frequency of rainfall during crop growing seasons, which is more than the amount and timing of nitrogen applications [14]. In addition, irrigation is the main factor of affecting nitrogen uptake, translocation, distribution and accumulation [15]. Understanding the mechanisms controlling water use and WUE under N fertilization is critical for efficient water use in semi-arid regions of the world, including the Loess Plateau of China.

Oilseed flax (*Linum usitatissimum* L.) is a fibrous and dicotyledonous plant of the *Linaceae* family with potential economic value, known as common flax or linseed [16], which has a long history of cultivation in agriculture and is grown throughout the world. With the booming economy and increasing demand for high quality food by the citizens around the world, there is a growing demand for food and industrial products [17]. The increasing demand for edible oil sources with significant amount of omega-3 fatty acids is leading to the consumption of oilseed as a functional food [18]. However, grain yield of oilseed flax is not only controlled by its genes but also influenced by environmental factors such as soil moisture, nutrients, climatic conditions and agronomic measures. Water and nitrogen are considered the most important and manageable factors.

Water and nitrogen (N) are the two most important inputs for high grain yield in oilseed flax production. The scarcity of water resources and low nitrogen utilization have limited the sustainable development of oilseed flax in Gansu. Grain yield and water use efficiency (WUE) of oilseed flax are mainly limited by soil water deficit during vegetative growth and grain filling due to high evaporation and erratic rainfall distribution. Therefore, effective water and nitrogen management is essential to improve water use efficiency, water productivity, nitrogen use efficiency and maintain grain yield. Balancing N and water remains a significant challenge as under- or over-supply can offset the benefits of reducing the overall production and nutrient gains [19]. However, the mechanism of irrigation-nitrogen coupling to improve grain yield and WUE in the semi-arid areas of China is still unclear. Therefore, this study aims to determine an optimal water and nitrogen fertilizer management strategy that can comprehensively improve grain yield, soil water storage (SWS), PSE, soil water balance, WUE and NUE of oilseed flax by establishing a quantitative relationship between water and fertilizer use and these parameters. This study aims to provide a scientific basis for the effective management of local irrigation and nitrogen application.

Materials And Methods

Experimental site

The field experiment was carried out in Dingxi Academy of Agricultural Science (34.26°N, 103.52°E, altitude 2050 m) Gansu Province, China, from April 2017 to August 2018. Mean annual rainfall was about 405.9 mm, annual temperature 8.8°C, annual sunshine duration 2161h. Before planting, several soil samples (0-30 cm) were collected to determine the basic nutrient contents. Soil samples were randomly collected from 5 sites before the study to measure soil organic matter, total nitrogen (N), total phosphorus, alkali-hydrolyzable N, available phosphorus, available potassium and pH, which were 10.51 g kg^{-1}, 1.00 g kg^{-1}, 0.85 g kg^{-1}, 47.91 mg kg^{-1}, 26.43 g kg^{-1}, 108.30 mg kg^{-1} and 8.13, respectively.

Experimental design

The field experiment was laid out in a split-plot design with irrigation as the main factor and nitrogen rate as a sub-factor. For each factor, treatments were randomized and replicated three times. The irrigation levels included: no irrigation (I_0), 1200 m^3 ha^{-1} (I_{1200}) and 1800 m^3 ha^{-1} (I_{1800}) while nitrogen rates were: no nitrogen (N_0), 60 kg N ha^{-1} (N_{60}) and 120 kg N ha^{-1} (N120). Urea (46% N) was applied as per treatment in a single application in the early growing season. Oilseed flax was planted on April 7 and harvested on August 8 in 2017, while in 2018, it was cultivated and harvested on April 5 and August 12, respectively. Each treatment received 90 kg P_2O_5 ha^{-1} yr^{-1}. The main plot was 6.8 m × 5.0 m while the sub-plot was 5.0 m × 2.0 m. Water was applied directly to the plots, with a pipe attached to a flow meter to measure the amount of water applied (Guo et al., 2014).

Measurement and calculation

The soil water content (SWC) in 0-160 cm layer was measured every 20 cm before sowing and after harvesting, and 5 points were randomly selected in each plot. Soil samples collected by drilling equipment are loaded into aluminum box, weighed by fresh weight, oven-dried at 105°C for 8-10 h, and then measured the dry weight. Soil water content (%) and soil water storage were calculated using the following formulas:

$$\mathrm{SWC}\ (\%) = (\mathrm{FW} - \mathrm{DW})/(\mathrm{DW} - \mathrm{AW}) \times 100 \quad (1)$$

where SWC is the soil water content (%), FW is fresh weight of soil sample with aluminum box, DW is dry weight of soil sample with aluminum box, and AW is the weight of aluminum box.

$$\mathrm{SWS}\ (\mathrm{mm}) = (\mathrm{SWC} \times b \times d) \times 100 \quad (2)$$

where SWS is the soil water storage (mm), b is soil bulk density in g/cm^3, and d is soil depth in cm. From each sampling time, the average soil water content at the 0-160 cm depth was used for statistical analysis.

$$\Delta \mathrm{SWC}_f = \mathrm{SWC}_{ph} - \mathrm{SWC}_s \quad (3)$$

ΔSWC_f is soil water storage during the fallow period (mm); SWC_{ph} is soil water content at previous harvest or the beginning of the fallow period (mm) and SWC_s is the soil water content at oilseed flax planting or the end of the fallow period (mm).

The precipitation storage efficiency (PSE) was calculated by:

$$\mathrm{PSE}\ (\%) = \Delta \mathrm{SWC}_f / R_f \times 100 \quad (4)$$

Where R_f is the rainfall during the fallow period (mm).

The ET_g (mm) was calculated by:

$$\mathrm{ETg} = \mathrm{SWC}_s + R_g - \mathrm{SWC}_h \quad (5)$$

Where Rg is the seasonal rainfall (mm), and SWCh is the soil water content at harvest (mm).

The change of soil-water storage (mm) was calculated by:

$$\Delta \mathrm{SWC} = P - \mathrm{ET} \quad (6)$$

Where P is the rainfall occurring during the given period (mm); ET is the amount of evapotranspiration (mm), and ΔSWC is the change of soil-water storage within the soil profile (mm).

Water use efficiency (WUE) was defined as follows [20–21]:

$$\mathrm{WUE} = Y/\mathrm{ET} \quad (7)$$

$$\mathrm{WUE}_I = Y/I \quad (8)$$

where Y ($kg\ ha^{-1}$) is the grain yield and ET (mm) is the crop ET (total water consumption) over the oil flax growing season, I is the irrigation amount.

2.6. Data analysis

The data were analyzed using the SPSS package (SPSS, 20.0 software, Inc., Chicago, IL) with replication as a random influence, and irrigation and N fertilizer rates as fixed effects. The significance between treatments was tested using Tukey's and LSD tests. All significant differences were declared at the 0.05 probability level.

Results

Weather conditions

There was a large variation in rainfall between the two years, with more than half of the annual rainfall from July to September (Fig. 1A), the maximum monthly mean rainfall occurred in July 2017 and August 2018, respectively. Compared with the long-term average of 377 mm (1981-2010), the annual rainfall was higher in 2017 (407.4 mm) and 2018 (481.1 mm). Compared with the yearly average fallow rainfall (99.1 mm), the fallow rainfall was higher in 2017 (109.9 mm) and 2018 (120.2 mm). The seasonal rainfall in 2017 was similar to the yearly average, but it was higher in 2018 (360.9 mm). The annual rainfall during the wetter growing season (2018) was higher by 23% than the long-term average (1981-2010). Minimum temperatures occurred in January each year during the growing season while maximum temperatures occurred at the young fruit stage in each growing season (Fig. 1B).

Soil water storage

There was no significant difference in soil water storage (SWS) among the N0, N60 and N120 treatments before sowing in 2017 (Figure 2a,c), but they were significantly varied by nitrogen (N) and irrigation treatments (Figure 2b,d) before sowing and after harvest in 2018. The SWS of treatment I0 was significantly lower than that of treatment I1200 and I1800 after harvest in 2017 (Figure 2c). The SWS of N60 treatment was significantly increased by 10.26% and 17.83%, respectively, compared to N0 and N120 treatments after harvest in 2018. In addition, SWS was increased with increas of irrigation rate. Compared with I0 treatment, SWS was increased by 14.32% and 19.23% in I1200 and I1800 treatments, respectively, before oilseed flax sowing. SWS was affected by interaction between irrigation and nitrogen levels, significantly, at the postharvest stage in 2018 (Figure 2d). There was highest SWS in I1800N60 treatment and lowest SWS in I0N120 treatment.

Evapotranspiration, soil water depletion and soil water balance

Precipitation storage efficiency (PSE) was significantly varied by irrigation and nitrogen levels (Figure 3). Compared with N0 treatment in 2017, the PSE in N60 and N120 treatment was increased by 12.85% and 26.86%, respectively. In 2018, PSE of different irrigation treatments was showed I1800>I0>I1200, while under different nitrogen treatments was showed N120>N60>N0. The I1800N120 treatment had the highest PSE, followed by the I1800N60, I0N60 and I1800N0 treatments. The PSE in I1800N120 treatment was increased by 13.55% compared to the I0N0 treatment in 2018.

The soil water components in the 0-160 cm soil depth was significantly influenced by irrigation and nitrogen levels (Table 1). The SWCs, SWCh, ΔSWCg, ETg and ΔSWCy were increased with the increasing of irrigation amount, and the ETf was reduced. Averaged across the 2 yrs., compared with the I0 treatment, the SWCs, SWCh, ETg, and ΔSWCy was increased by 9.36%, 17.02%, 56.46%, and 58.81% respectively, in I1800 treatment. However, compared with I0 treatment, the ETf of I1800 treatment was decreased by 45.05% in 2018. ΔSWCf, ETf, ΔSWCg, ETg, and ΔSWCy were significantly affected by nitrogen rate. Averaged across the 2 yrs., the SWCs, ΔSWCf and ETg in the N120 treatment was 4.43%, 16.42%, and 2.14%higher than that in N0 treatment, respectively. Conversely, the N120 treatment was decreased SWCh, ΔSWCg and ΔSWCy by 0.74%, 55.12% and 12.83%, respectively, compared with N0 treatment on an average of two years. The interaction effect of irrigation and nitrogen levels significantly affected SWCh, ETf, ΔSWCg, ETg and ΔSWCy in 0-160 cm soil depth (Table 1). Compared with the I0N0 treatment, the SWCs, SWCh, ΔSWCf, ETg and ΔSWCy was increased by 18.74%, 15.37%, 18.76%, 42.73% and 7.88%, respectively, under I1800N60 treatment in 2018.

Table 1

Effects of different irrigation levels and nitrogen levels on soil water balance components (soil-water storage at previous harvest - SWCph, soil-water storage at harvest - SWCh, soil-water storage at sowing - SWCs, the change in soil-water storage during the fallow period - ΔSWCf, the change in soil-water storage during the growing season - ΔSWCg, the change in soil-water storage during the whole year - ΔSWCy, the evapotranspiration during the fallow period - ETf, the evapotranspiration during the growing season - ETg) in the 0 - 160 cm soil depth at Dingxi station, China.

Growing seasons	I	N	SWCph	SWCs	SWCh	Fallow period		Growing period		ΔSWCy
			mm	mm	mm	ΔSWCf (mm)	ETf (mm)	ΔSWCg (mm)	ETg (mm)	(mm)
2017	I0	N0	202.81	234.66a	182.13c	31.85b	78.05a	-52.54d	350.04c	-20.68f
		N60		238.75a	188.20c	35.94ab	73.96a	-46.47c	343.97c	-14.61e
		N120		243.22a	195.13c	40.41a	69.49ab	-39.53c	337.03c	-7.68d
	I1200	N0		234.66	225.22ab	31.85	78.05	-13.54ab	431.04b	22.41b
		N60		238.75	229.94a	35.94	73.96	-8.82a	426.32b	27.13a
		N120		243.22	228.61a	40.41	69.49	-10.14a	427.64b	25.80a
	I1800	N0		234.66	217.46b	31.85	78.05	-25.76b	503.26a	14.65c
		N60		238.75	224.11ab	35.94	73.96	-19.11b	496.61a	21.30b
		N120		243.22	228.91a	40.41	69.49	-14.31ab	491.81a	26.10a
2018	I0	N0	182.13	219.54e	274.85d	37.41bc	103.47a	55.31b	242.19g	92.72d
		N60	188.20	229.54d	303.05c	41.34b	93.47b	73.51a	223.99h	114.85a
		N120	195.13	230.08d	257.19e	34.94c	92.93b	27.11d	270.39f	62.06g
	I1200	N0	225.22	255.06c	313.79b	29.84c	67.95c	58.73b	358.77e	88.57d
		N60	229.94	261.66c	313.44b	31.72c	61.35d	51.78b	365.72de	83.50e
		N120	228.61	259.70c	300.06c	31.08c	63.31cd	40.37c	377.13d	71.45f
	I1800	N0	217.46	258.39c	325.75a	40.93b	64.62cd	67.35a	410.15c	108.29b
		N60	224.11	270.16b	324.76a	46.05ab	52.85e	54.60b	422.90b	100.65c
		N120	228.91	281.20a	317.89 ab	52.29a	41.81e	36.69c	440.81a	88.98d
F-Values										
I			-	*	ns	*	*	*	**	**
N			-	ns	ns	*	**	*	*	**
I×N			-	ns	*	ns	*	*	*	**
Y			-	ns	**	ns	ns	**	**	**
Y×I			-	-	*	-	-	*	*	**
Y×N			-	ns	ns	ns	*	*	*	*
Y×I×N			-	-	ns	-	-	*	*	*

Growing seasons	I	N	SWCph	SWCs	SWCh	Fallow period		Growing period		ΔSWCy
			mm	mm	mm	ΔSWCf (mm)	ETf (mm)	ΔSWCg (mm)	ETg (mm)	(mm)

Note: I0, no irrigation; I1200, irrigation 1200 m^{3} ha^{-1}; I1800, irrigation 1800 m^{3} ha^{-1}; N0, no nitrogen; N60, 60 kg N ha^{-1}; N120, 120 kg N ha^{-1}. I, irrigation; N, nitrogen; Y, year. * means a significant difference at 0.05 probability level; ** means significant difference at 0.01 probability level; ns means no significant difference at 0.05 probability level. Mean values with different letters within column under the same growing season are significantly different from each other at 0.05 probabily level.

Biomass accumulation and grain yield The interaction of irrigation and nitrogen levels significantly affected the dry matter accumulation (DMA) of oilseed flax from budding stage to maturity (Figure 4). DMA increased linearly from seedling stage to maturity stage. The DMA under different irrigation treatments was showed that I1800> I1200> I0, while under different nitrogen levels was showed that N60> N120> N0 during the growth stage of oilseed flax. Compared to the I0N0 treatment, the I1800N60 treatment improved DMA of oilseed flax 36.96% and 38.68% at budding, 52.25% and 82.78% at anthesis, 50.07% and 37.39% at kernel stage, 79.73% and 77.58% at maturity in 2017 and 2018, respectively.

The interaction of irrigation and nitrogen significantly affected the number of effective capsules per plant (EC), number of seeds per pod (SN) and seed yield (Table 2). In 2017, EC varied from 17.9 to 25.6 per plant, SN per pod from 6.7 to 8.0 and grain yield from 913.8 to 1535.8 kg ha^{-1}, while in 2018, EC varied from from 9.1 to 13.8 per plant, SN per pod from 6.5 to 7.5 and grain yield from 1044.0 to 1203.0 kg ha^{-1}. EC, SN and grain yield in 2017 were increased by 45.0%, 2.2% and 13.7%, respectively, compared to 2018. Grain yield increased with increasing irrigation in both season. The N120 treatment had the highest grain yield in 2017, while the N60 treatment produced the optimum grain yield in 2018. The N0 treatment had the least grain yield in both seasons. Compared to the control (I0N0), the I1800N60 treatment increased EC (29.9%), SN (6.3%), and grain yield (40.9%) in 2017. However, 1000-grain weight was not significantly varied under different irrigation and nitrogen treatments in both seasons (Table 2).

Table 2

Effects of irrigation and nitrogen levels on yield and yield components of oilseed flax

Treatment		2017				2018			
		Effective capsule number plant^{-1}	**Grain number pod^{-1}**	**1000 grain weight (g)**	**Grain yield (kg ha^{-1})**	**Effective capsule number plant^{-1}**	**Grain number pod^{-1}**	**1000 grain weight (g)**	**Grain yield (kg ha^{-1})**
I0	N0	17.93d	7.40b	5.58b	913.79f	9.13f	7.10ab	7.88ab	1044.00c
	N60	19.67c	6.73e	5.77ab	1006.50e	12.27c	7.10ab	7.45b	1069.67c
	N120	22.33b	6.80 de	5.57 b	1224.61d	12.20c	7.30a	7.97a	1097.00c
I1$_2$00	N0	20.57c	7.27bc	5.40b	1339.17c	13.13b	6.53c	8.00a	1087.67c
	N60	22.17b	8.03a	6.28a	1424.71b	10.43e	7.10ab	7.53ab	1165.67 b
	N120	23.03b	7.00bcde	5.98ab	1467.07b	11.63d	7.53a	7.43b	1153.33b
I$_{18}$00	N0	16.87d	6.87cde	5.50b	1424.71 b	11.90cd	7.37a	7.75ab	1152.33b
	N60	25.57a	7.90a	5.83ab	1545.42a	13.77a	7.07abc	7.83ab	1281.67a
	N120	22.50b	7.20bcd	5.72ab	1535.77a	10.37e	6.67bc	7.88ab	1203.00ab
I		*	**	ns	***	*	*	ns	***
N		***	*	ns	**	*	*	ns	**
I×N		**	*	ns	*	***	*	ns	*

Note: I0, no irrigation; I1200, irrigation 1200 m^3 ha^{-1}; I1800, irrigation 1800 m^3 ha^{-1}; N0, no nitrogen; N60, 60 kg N ha^{-1}; N120, 120 kg N ha^{-1}. I, irrigation; N, nitrogen. * means a significant difference at 0.05 probability level; ** means significant difference at 0.01 probability level; ns means no significant difference at 0.05 probability level. Mean values with different letters within column are significantly different from each other at 0.05 probabily level .

HI, WUE, ANUE and NPFP

Water use efficiency (WUE), irrigation use efficiency (WUEI), agronomic nitrogen use efficiency (ANUE) and nitrogen partial factor productivity (NPFP) were significantly varied under the different interaction of irrigation and nitrogen levels (Table 3). The main effect of irrigation levels did not significantly affect ANUE and NPFP, while nitrogen levels had an insignificant effect on WUEI. The WUE varied from 4.52 to 6.12, WUEI from 7.92 to 12.23, ANUE from 0.93 to 2.59 and NPFP from12.80 to 25.76 in 2017, while WUE varied from 4.57 to 22.91, WUEI from 6.40 to 9.71, ANUE from 0.42 to 2.16 and NPFP from 9.14 to 21.36 in 2018. The content of WUEI, ANUE, and NPFP were increased by 19.44%, 44.68%, and 13.92% in 2017, respectively, compared to those in 2018. The WUE in 2018 was higher by 38.74% than in 2017. I0N120 and I0N60 treatments had the highest WUE in 2 growth seasons of oilseed flax. The highest WUEI was recorded under the I1200N120 treatment (12.23) in 2017 and under the I1200N60 treatment (9.71) in 2018. The I1800N60 treatment had the highest ANUE and NPFP values in both seasons, while the I1800N120 and I0N120 treatments had the lowest ANUE and NPFP values, respectively. Only the main effect of nitrogen levels significantly affected the harvest index (HI). HI varied from 0.36 to 0.59 in 2017 and 0.36 to 0.51 in 2018. HI followed the trend of N0>N120>N60. Compared to the N0 treatment, the N60 treatment reduced HI by 18.80% in 2017 and 21.21% in 2018, respecitivily.

Table 3
Effects of irrigation and nitrogen levels on harvest index (HI), water use efficiency (WUE), irrigation use efficiency (WUEI), nitrogen agronomy use efficiency (ANUE) and nitrogen partial factor productivity (NPFP) of oilseed flax.

Growing Seasons	Irrigation Rate	Nitrogen Rate	HI	WUE	WUEI	ANUE	NPFP
2017	I0	N0	0.49c	5.36cd	—	—	—
		N60	0.36d	6.12b	—	1.55c	16.78bc
		N120	0.51bc	7.77a	—	2.59a	10.21c
	I1200	N0	0.57ab	5.41bcd	11.16a		
		N60	0.48c	5.87bc	11.87a	1.43c	23.75a
		N120	0.49c	6.01bc	12.23a	1.07d	12.23c
	I1800	N0	0.59a	4.52e	7.92b	—	—
		N60	0.46c	5.01de	8.59b	2.01b	25.76a
		N120	0.51bc	5.06de	8.53b	0.93d	12.80c
2018	I0	N0	0.51a	16.09b	—	—	—
		N60	0.36b	22.91a	—	0.43c	17.83a
		N120	0.39ab	11.78c	—	0.44c	9.14b
	I1200	N0	0.40ab	5.99de	9.06a	—	—
		N60	0.37b	6.19d	9.71a	1.30b	19.43a
		N120	0.40ab	5.77de	9.61a	0.55c	9.61b
	I1800	N0	0.42ab	4.95f	6.40b	—	—
		N60	0.35b	5.22ef	7.12b	2.16a	21.36a
		N120	0.40ab	4.57f	6.68b	0.42c	10.03b
I			ns	**	**	ns	ns
N			**	**	ns	**	**
I×N			ns	**	*	*	*
Y			**	**	*	*	ns
Y×I			*	**	ns	ns	ns
Y×N			ns	**	ns	*	*
Y×I×N			ns	**	ns	ns	ns

Note: I0, no irrigation; I1200, irrigation 1200 m^3 ha^{-1}; I1800, irrigation 1800 m^3 ha^{-1}; N0, no nitrogen; N60, 60 kg N ha^{-1}; N120, 120 kg N ha^{-1}. I, irrigation; N, nitrogen; Y, year. * means a significant difference at 0.05 probability level; ** means significant difference at 0.01 probability level; ns means no significant difference at 0.05 probability level.

Correlation analysis

The relationship between grain yield and soil water balance components of oilseed flax was showed in Table 4. Grain yield showed positive and highly significant correlation with PSE (r = 0.856), SWCs (r = 0.935), Etg (r = 0.853) and SWCy (r = 0.935) in 2017; however, grain yield correlated negatively and non-significantly with ETf (r = -0.348), WUE (r = -0.322) and ANUE (r = -0.345). In 2018, grain yield showed positive and significant correlation with ANUE (r = 0.834); however, it was negatively correlated with ETf (r = 0.527), WUE (r = -0.535), HI (r = -0.515) and SWCh (r = -0.048).

Table 4
Correlation analysis between grain yeild and soil water balance components(precipitation storage efficiency - PSE, the soil water content at harvest - SWCh, the change in soil-water storage during the fallow season - SWCf, the amount of evapotranspiration at fallow season - ETf, the change in soil-water storage during the growing season - SWCg, the amount of evapotranspiration during the growing season - ETg, the change in soil-water storage during the whole year - ΔSWCy, harvest index – HI and water use efficiency - WUE) measured in 2017 and 2018 for oilseed flax grown in various irrigation and nitrogen levels systems at Dingxi station, China.

Year	PSE	SWCs	SWCh	SWCf	ETf	SWCg	ETg	ΔSWCy	HI	WUE	ANUE
2017	0.856**	0.348	0.935**	0.348	-0.348	0.443	0.853**	0.935**	0.394	-0.322	-0.345
2018	0.16	0.167	-0.048	0.214	-0.527	-0.001	0.493	0.287	-0.515	-0.535	0.834*

*, significant at *P* <0.05; **, significant at *P* <0.01.

Discussion

Soil water storage

Agro-ecosystem was fragile due to inadequate water resource in arid and semi-arid regions. Farmers often apply over-irrigation and nitrogen fertilizer to achieve high-yield production [22]. Consequently, a large amount of nitrogen fertilizer either remains in the soil profile or leaches into groundwater, which can lead to a battery of environmental problems. Therefore, water and nitrogen coupling plays an important role in the sustainable development of agriculture in the arid and semi-arid areas. Water and nitrogen were important inputs for agricultural performance of oilseed flax. The change of soil water storage was the balance of irrigation, precipitation, evaporation, percolation and root uptake [22], but most of the annual precipitation in the arid and semi-arid regions usually falls in autumn, and rainwater retention in autumn fallow was very important for crop production in the dryland [23]. Soil water storage during sowing is very importance for germination and seedling establishment [9]. This study found that nitrogen rates had no significant effect on soil water storage before sowing; however, irrigation 1200 m^3 ha^{-1} and 1800 m^3 ha^{-1} treatments significantly improved soil water storage before sowing compared to I0, which concurs with previous studies [24]. This was because irrigation directly increases soil water content [25], especially increases soil water storage under irrigation in dry periods compared to no irrigation. Our result is contradiction with that of Ren et al. (2019) [23], who reported that nitrogen significantly affects soil water storage. The discrepancy between the previous study and our study may be attributed to the use of plastic mulch.

Precipitation storage efficiency and soil water balance

Precipitation storage efficiency (PSE) is generally used to determine how much rainfall can be restored to the soil during the fallow period [20]. Shangguan (2002) [2] found that the PSE of Loess Plateau is about 30-35%. In this study, the value of PSE is 24.83 - 43.50%. Although there was abundant rainfall during fallow, the high evaporation loss from the soil surface could not store enough water for the growth of crops from seedling stage to maturity stage. Therefore, high evaporation during the fallow period and throughout the winter severely limited crop yield and water use efficiency [13]. The PSE initially increased and then decreased with the increase of N fertilizer rate under I0 and I1200 treatments. However, PSE increased with increasing N fertilizer rate under I1800 treatment in 2018, probably as a result of soil water limiting the promoting effect of nitrogen fertilizer on PSE. Under no or medium irrigation conditions, N120 reduced PSE, while under the conditions of high irrigation and high nitrogen, the coupling effect of irrigation and nitrogen was fully played out, promoting precipitation storage in the fallow period and improving PSE.

The ΔSWCf increased with increasing N fertilizer rate in 2017 and increased under high irrigation (I1800) in 2018, but first increased and then decreased with increasing N fertilizer rate under I0 and I1200 treatments. This was probably because N applications (N60) increased water uptake and resulted in severe soil water depletion during the growing season under I1200 treatment, while high irrigation (I1800) met crop requirements. The ΔSWC_f initially decreased and then increased with the increase of irrigation amount under the same nitrogen levels in 2018. In the arid and semi-arid regions, water for evapotranspiration (ET) comes partly from pre-sowing and partly from soil water storage of growing-season precipitation [20,26], in addition, partly from irrigation in the irrigated areas. Since ET during the fallow period (ETf) is simply a loss of the crop production system, ETg should generally be maximized and ETf minimized [20]. In this study, increasing nitrogen application and irrigation level resulted in lower lower ETf but higher ETg compared to N0 and I0 in 2018, suggesting that under the high irrigation and nitrogen treatments, more of the rainfall was used for ET and less was lost during the fallow (Table 1). Correlation analysis showed a significant positive correlation between pre-sowing SWS and grain yield, which could be attributed to precipitation and irrigation during the maize growing seasons, and wheat yield was significantly affected by precipitation [27]. In the present study, a significant positive relationship was found between grain yield and both PSE and ΔSWCy, confirming that grain yield of oilseed flax not only related to rainfall, but also to the change in soil water storage.

Biomass accumulation and grain yield

Aboveground biomass accumulation is the basis for yield formation [9]. Irrigation regime significantly affected the biomass yield and increased dry matter accumulation after anthesis compared with no irrigation, but over-irrigation significantly reduced the photosynthate and grain yield [28–29]. Nitrogen fertilizer application increased dry matter accumulation and nitrogen in rapeseed at different growth stages [30]; however, excessive N application reduced the dry biomass accumulation rate of plant [31]. Wang et al. (2018) [6] found that irrigation can promote plants' ability to absorb nutrients and fertilizer use efficiency. This study found that coupling of irrigation and nitrogen fertilizer management increased dry matter accumulation amount of oilseed flax, which is consistent with trevious studies [32–33]. In this study, biomass accumulation showed an obvious upward trend with the increase of water and nitrogen input, but once the water and nitrogen input exceeded a certain threshold, it resulted in a significant decrease, which was consistent with previous studies [34]. Treatment I1800 provided high quantity conditions for growth of oilseed flax, with the highest dry matter accumulation. With the increase of nitrogen application, the dry matter accumulation also increased significantly, but when nitrogen application reached the N120 level, dry matter accumulation began to decline, indicating that there was an upper limit of nitrogen requirement for oilseed flax growth. Only adequate water and nitrogen input resulted in high yield, which concurs with Li et al. (2019) [35].

Grain yield is strongly influenced by irrigation amount and nitrogen application rate as well as other agronomic measures [9,36–38]. The crop yields were significantly affected by irrigation frequency and nitrogen application rate, and grain yields were lowest in the non-irrigated and no-nitrogen treatment, and tended to increase with increasing irrigation frequency and nitrogen application rate [39–40]. In our study, within a certain range of water and nitrogen inputs, oilseed yield increased with increasing irrigation and nitrogen, but yield decreased when irrigation and nitrogen exceeded a certain threshold. Therefore, high crop yields could be obtained with adequate irrigation and nitrogen inputs, which was consistent with previous findings [41]. High biomass accumulation under I1800N60 improved the number of effective capsules per plant and the number of seeds per pod, which in turn increased grain yield (Figure 4 and Table 4).

Harvest index, waer use efficiency, irrigation water use efficiency, nitrogen agronomy utilization efficiency and nitrogen partial factor

productivity

Previous studies have showed that crop harvest index (HI) was susceptible to deficit irrigation in arid regions, and severe water stress dramatically reduced HI [42], in addition, nitrogen fertilizer had a significant effect on HI; however, the effect between irrigation and nitrogen did not affected HI [43]. In the current study, the interaction between irrigation and nitrogen did not significantly affect HI, however, nitrogen rate decreased HI under irrigation condition. There are two reasons for this phenomenon; on the one hand, irrigation and nitrogen increased the lodging of oilseed flax, which significantly affects grain yield and consequently decreased HI. On the other hand, irrigation and nitrogen application caused unfavorable-delayed senescence, which also affected the yield of oilseed flax and resulted in lower HI.

Improving water productivity in grain production is critical for maintaining food supply in regions with water scarcity [44], and appropriate irrigation and nitrogen application are helpful to improve water use efficiency [13]. Previous studies have showed that WUE was not affected by irrigation rate, but a decrease in nitrogen application rate resulted in a decrease in WUE at all irrigated treatments [45]. Our results showed that WUE decreased with increase of irrigation amount, which concurs with Zhai et al. (2017) [46]. The previous studies have shown that adequate N supply was useful to improve WUE [42]. In this study, nitrogen application was found to significantly affect WUE under no-irrigation level, but there was no significant difference under irrigation levels in 2017, which may be related to water pressure. Previous studies have found that moderate water deficit in a certain period is beneficial for improving WUE [47]. But WUE increased with the increase of nitrogen application under the same irrigation level in 2018, which was mainly because excessive water and nitrogen increased lodging, reduced grain yield and resulted in lower WUE. Researchers have proved that deficit irrigation has a positive impact on WUEI in arid regions [48], and our results also showed that I1200 increased by 40.89% (2017) and 40.36% (2018) compared to I1800.

Adequate amount of nitrogen fertilizer can achieve higher nitrogen use efficiency even at low irrigation level [49]. Agronomic use efficiency decreased with the increase of irrigation amount and nitrogen application rate, while partial productivity increased with the increase of irrigation amount, and decreased with the increase of nitrogen application rate [24]. In our study, irrigation or no-irrigation significantly affected the agronomic use efficiency of nitrogen, NAUE first increased and then decreased with the increase of nitrogen rate under irrigation, but increased with the increase of nitrogen rate under no irrigation. Nitrogen partial factor productivity (NPFP) is a comprehensive indicator of local nitrogen and soil nutrient levels. Our results showed that nitrogen had a highly significant effect on NPFP. The interaction of year and nitrogen, irrigation and nitrogen had a significant effect on NPFP (Table 3). The NPFP decreased with the increase of nitrogen rate at the same irrigation level. Numerous studies have showed that reducing nitrogen application can improve nitrogen fertilizer use efficiency, while excessive nitrogen application decreases nitrogen use efficiency 22. Some previous studies reported that grain yield is significantly related to N uptake and utilization [50], and NPFP is significantly and positively correlated with crop yield [51]. Our correlation analysis also revealed a significant or highly significant and positive correlation between grain yield and NAUE and NPFP in 2018, indicating that high yield and high nitrogen efficiency are possible under certain conditions.

Conclusions

As shown in this study, it was difficult to achieve maximum grain yield, water use efficiency and partial factor productivity simultaneously. Precipitation storage efficiency (PSE) varied from irrigation amount and nitrogen rates, irrigation and nitrogen application improved PSE. The change of soil water storage throughout the year (ΔSWCy) increased with the increase of irrigation volume at higher nitrogen level (N120). Irrigation increased the grain yield at the same nitrogen level, while high nitrogen application (N120) reduced the grain yield at high irrigation level (I1200). The treatment of I1200 produced the highest WUEI, while I1800N60 treatment produced the highest NPFP of oilseed flax. Grain yield positively correlated with PSE, NPFP, and NAUE, but negatively correlated with ETf. When only grain yield is considered, 1800 m^3/ha irrigation water is recommended. When only water use efficiency is considered, 1200 m^3/ha irrigation water is recommended for growing oilseed flax. The results of this study have great significance for the scientific management of irrigation and fertilization in oilseed flax fields in semi-arid area of China.

Declarations

Author contributions

Y.G., B. W. conceptualized the study, and J. N. Data were curated by B.Y., Y. W., H. W., J.M., K.Y. and Data were investigated by P. X., B. Z., and Z. C. The project was administered by J. Z., Y. G., and Y. X. The original draft was written by Z. C. The original draft was reviewed and edited by Z. C., and Y.G. All authors read and approved the manuscript.

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Competing interests

We declare that we have no commercial or associative interest that consttute a conflict of interest in relation to the submitted work. Meanwhile, the experimental research and field studies on L. *Linum usitatissimum* (either cultivated or wild) in present study, including the collection of plant material, were complied with crop science experiment guidelines of Gansu Agricultural University.

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Figures

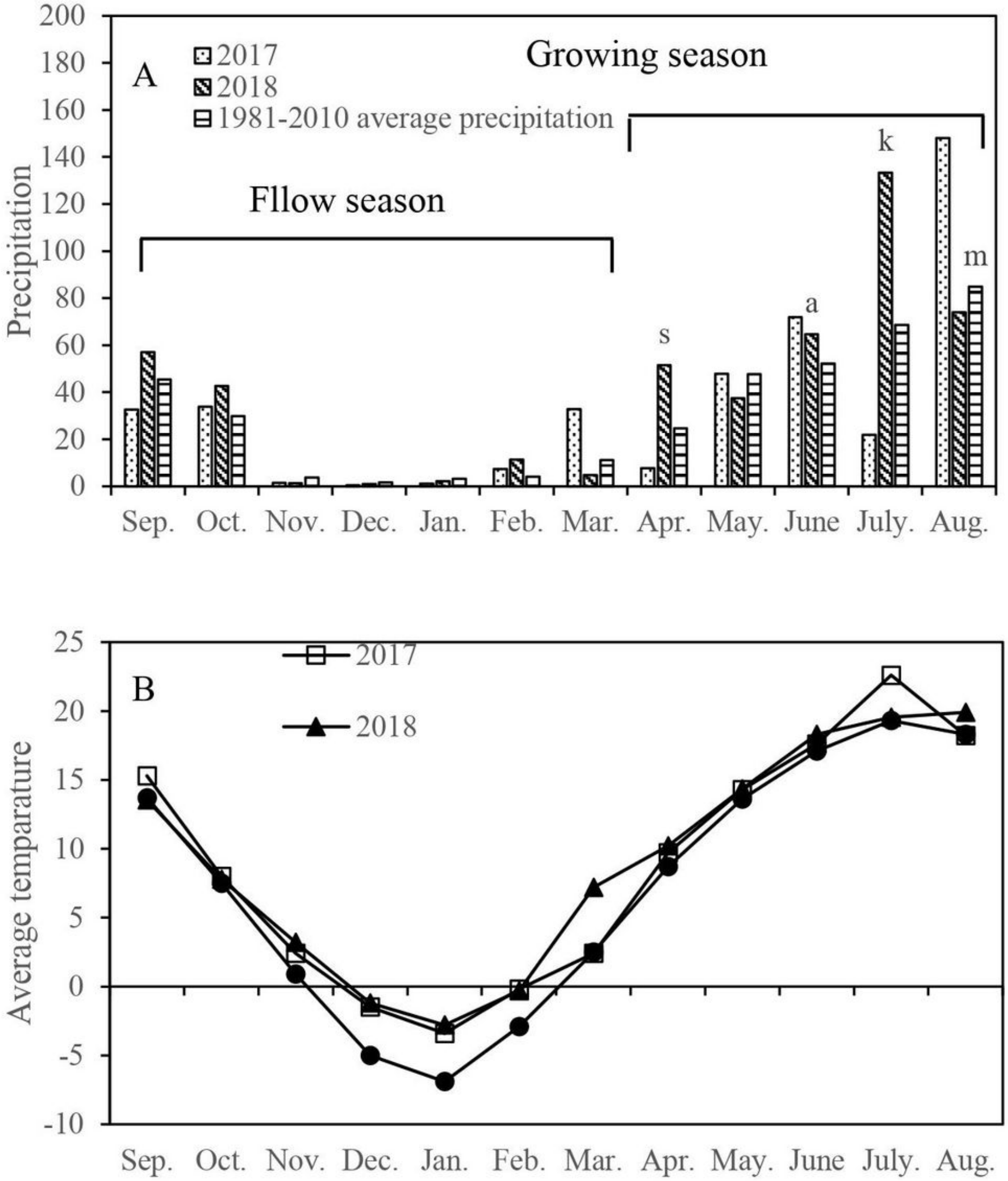

Figure 1

Monthly rainfall (A) and temperature (B) in 2017, 2018 and 1981-2010 at Dinxi station, China. The letters indicate sowing (s), anthesis (a), kernel (k) and maturity (m). Note: the growth of the oilseed flax was divided into five stages: Seedling, Budding, Anthesis, Kernel and Mature stages.

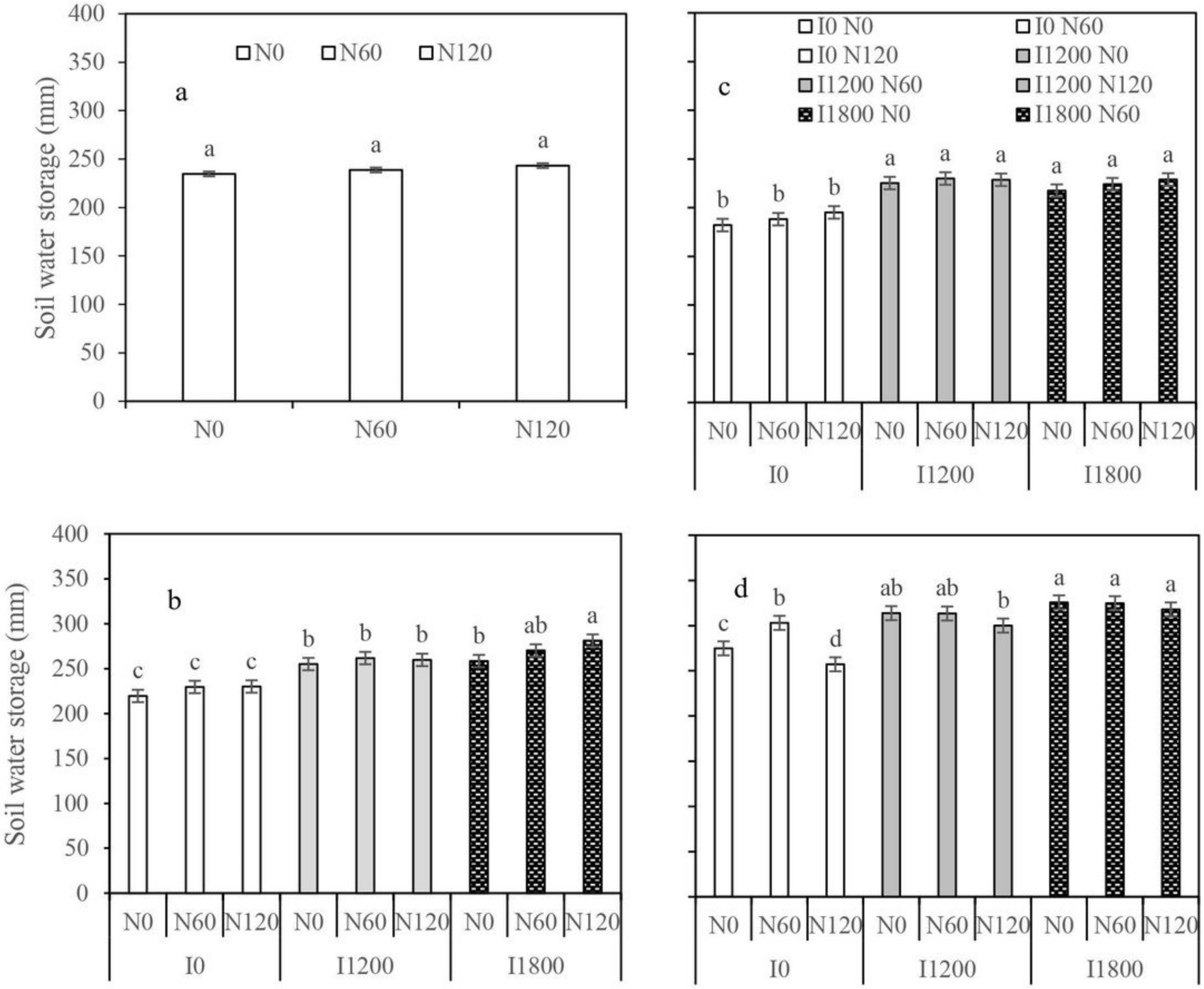

Figure 2

Effects of different irrigation levels (no irrigation (I0), 1200 m3 ha-1 (I1200) and 1800 m3 ha-1 (I2700)) and different nitrogen levels (no nitrogen (N0), 60 kg N ha-1 (N60) and 120 kg N ha-1 (N120)) on soil water storage in the 0 - 160 cm soil layer before sowing in 2017 (a) and 2018 (b), and after harvest of spring wheat in 2017 (c) and 2018 (d) at Dingxi station, China. Bars with different letters within the same growing season are significantly different at 0.05 p level.

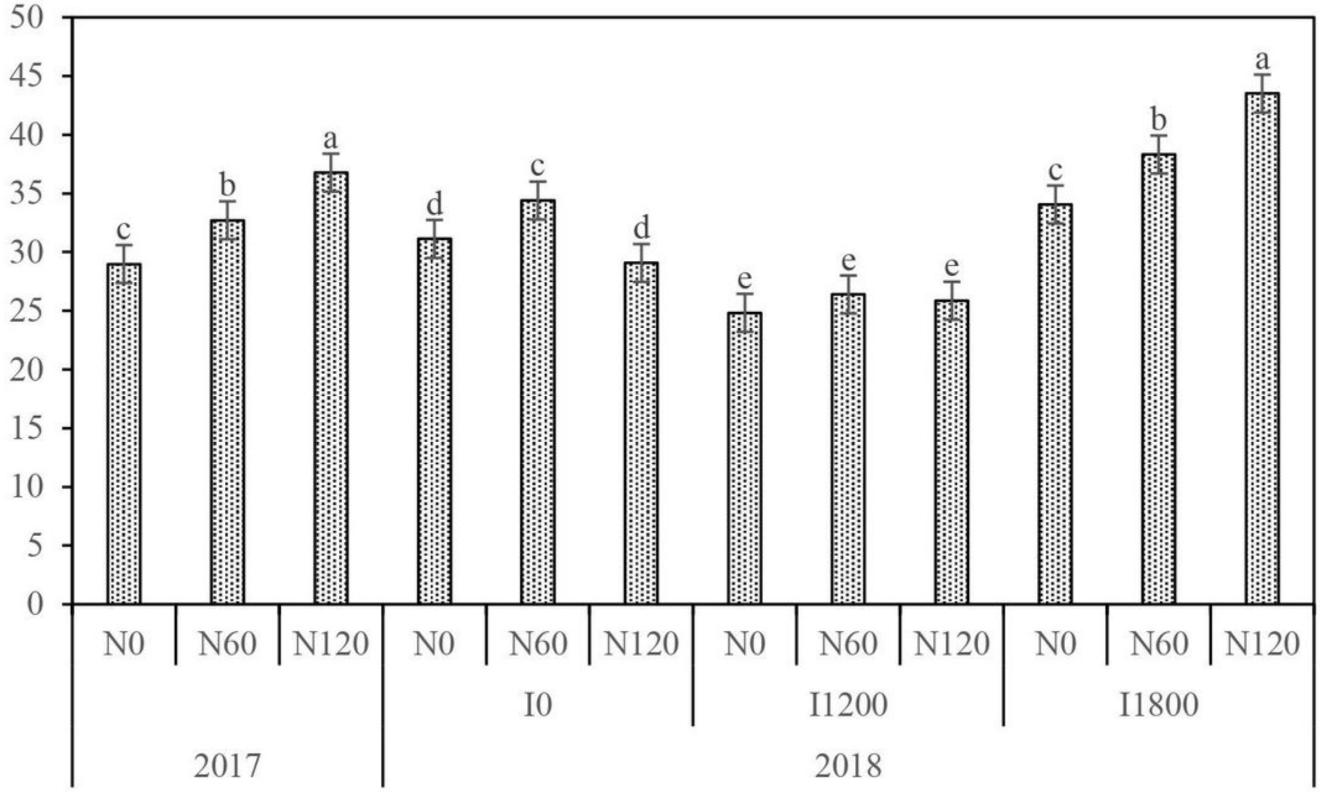

Figure 3

Effects of different irrigation levels and nitrogen levels on precipitation storage efficiency (PSE) during the summer fallow at Dingxi station, China. We only measured the soil moisture at the beginning of the fallow period so that we only calculated the PSE under different N rate in 2017. I0, no irrigation; I1200, irrigation 1200 m3 ha-1; I1800, irrigation 1800 m3 ha-1; N0, no nitrogen; N60, 60 kg N ha-1; N120, 120 kg N ha-1. Bars with different letters within the same growing season are significantly different from each other at 0.05 probability level.

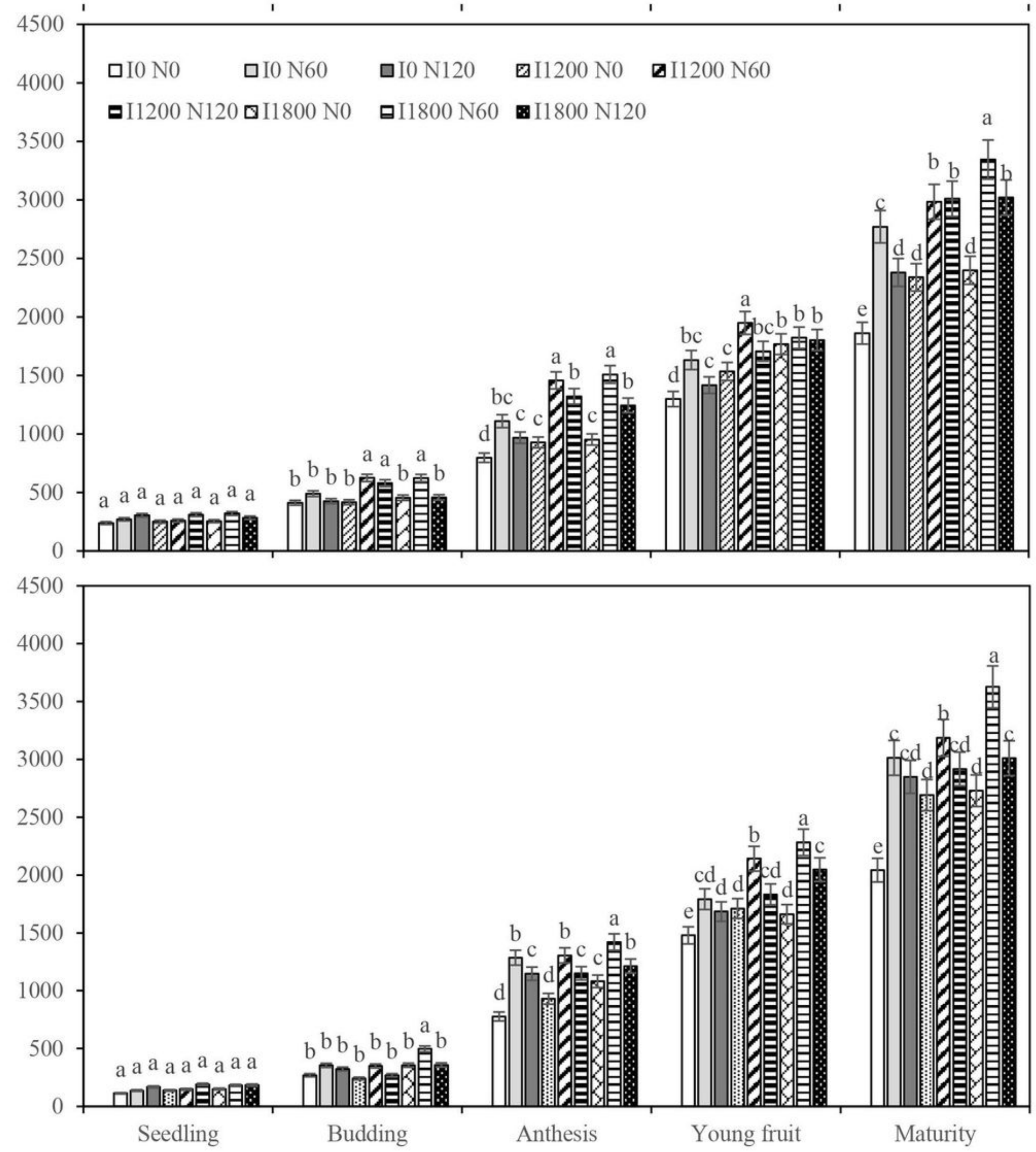

Figure 4

Effect of irrigation and nitrogen levels on dry matter accumulation of oilseed flax at different growth stages in 2017 (A) and 2018 (B). I0, no irrigation; I1200, irrigation 1200 m3 ha-1; I1800, irrigation 1800 m3 ha-1; N0, no nitrogen; N60, 60 kg N ha-1; N120, 120 kg N ha-1. Bars with different letters within the same growing are significantly different from each other at 0.05 probability level.