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Research paper

Optimization of water and fertilizer management improves yield, water, nitrogen, phosphorus and potassium uptake and use efficiency of cotton under drip fertigation

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ABSTRACT

As a fiber crop and oil crop, cotton plays an important role in the economic development of northwest China, but the lack of appropriate field water and fertilizer management strategies has restricted the harmonious development of cotton industry and environment. Field experiments were implemented to explore the coupling effects of various drip irrigation and fertilizer levels on the dry matter, yield, water and fertilizer use efficiency of cotton. The three drip irrigation levels included 1.0 ET_C (full irrigation), 0.8 ET_C (20% deficit) and 0.6 ET_C (40% deficit), where ET_C is the crop evapotranspiration. The five fertilizer (N-P-K) levels were F_1 (150–26.2–24.9 kg ha^{-1}), F_2 (200–34.9–33.2 kg ha^{-1}), F_3 (250–43.7–41.5 kg ha^{-1}), F_4 (300–52.4–49.8 kg ha^{-1}) and F_5 (350–61.1–58.1 kg ha^{-1}). The results revealed that the seed cotton yield and lint yield showed increasing trends as the irrigation water amount increased at the same fertilizer level during 2012–2014. When full irrigation (1.0 ET_C) was applied, the dry matter accumulation, seed cotton yield, N, P and K accumulation in plants and water productivity were the highest under F_4 (300–52.4–49.8 kg ha^{-1}) in 2012 and 2014. However, the lint yield was highest in 2012 and 2013 under F_3 (250–43.7–41.5 kg ha^{-1}). At the same irrigation level, N, P and K use efficiencies were higher at low fertilization rates than those at high fertilization rates in 2012 and 2013. Deficit irrigation and fertilization levels led to a severe decrease in cotton yield. N, P and K use efficiencies were low under F_4. Comprehensively considering cotton yield, N, P and K uptake and use efficiency, the application of irrigation amount of 1.0 ET_C and N-P-K rate of 250–43.7–41.5 kg ha^{-1} was the best drip fertigation strategy for cotton production in arid regions of northwest China.

1. Introduction

Cotton is an important economic crop, which plays an important part in the agricultural and industrial economic structure of China (Qian et al., 2014; Li et al., 2019). China's cotton production ranks first around the world, and the annual production of cotton lint has increased from 4.34 to 6.18 million tons between 1994 and 2014 (FAO, 2018). The Xinjiang Autonomous Region, located in northwest China is the main producing area of cotton in China as a result of abundant light and heat resources (Zhang et al., 2016a). However, the limited water resources in this region largely restrict the local agricultural development. Although drip irrigation under plastic mulching has been widely used in arid regions of China (Li et al., 2015b; Yan et al., 2019; Qi et al., 2020; Shi et al., 2020), local farmers still lack proper field water and fertilizer management strategies. The conventional excessive irrigation and fertilization can lead to low water and fertilizer use efficiency, waste of water and contamination of water resources (Wang et al., 2018; Wang et al., 2019).

Water is one of the important factors limiting cotton growth. Drought stress can thus significantly reduce the biological yield of cotton and hinder the absorption and accumulation of nitrogen, phosphorus and potassium (Hu et al., 2002). Many researchers have revealed that both deficit and excessive irrigation reduced seed cotton yields (DeTar, 2008;

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Ünlü et al., 2011; Papastylianou and Argyrokastritis, 2014). In addition, Zhang et al. (2016b) found that irrigation can significantly increase the nitrogen accumulation and nitrogen use efficiency, and the deficit irrigation (60% ET_C, where ET_C is the crop evapotranspiration) inhibited the absorption of nitrogen (N). However, some researchers believe that reasonable deficit irrigation can not only save water and keep reasonable proportions of crop vegetative and reproductive growth, but also promote root growth and improve root absorption in cotton (Du et al., 2007; Hassanli et al., 2009). In addition, irrigation method also has a great impact on the growth and development of cotton. Tang et al. (2005) suggested that the alternate drip irrigation could be applied in arid areas to save irrigation water. Rajak et al. (2006) found that drip irrigation lead to a higher cotton yield and water use efficiency compared with furrow irrigation. Wang et al. (2012a) also showed that drip irrigation significantly increased seed cotton yield, plant N uptake, and N use efficiency and decreased NO_3-N in the leakage water. Overall, cotton yield and fertilizer use efficiency can be enhanced by appropriate irrigation amounts and methods.

Reasonable fertilization can also increase cotton growth, yield and fiber quality (Wu et al., 2014; Geng et al., 2016). High yield of cotton is directly affected by the amount of nitrogen absorbed and the duration of absorption (Gong et al., 2015). When the application amount of nitrogen was 375 kg ha^{-1}, the highest fiber yield and agronomic N use efficiency were obtained by Chen et al. (2016). Applying N at the beginning of an irrigation cycle was useful for enhancing cotton yield and fertilizer use efficiency (Hou et al., 2009). The lack of N, P and K can significantly affect cotton growth. The fiber length and strength of cotton will be reduced when lack of N. K deficiency had adverse effects on reproductive growth and increased the soluble sugar to free amino acid ratio and C/N ratio (Read et al., 2006; Hu et al., 2017). Higher biomass, yield, nitrogen, phosphorus and potassium nutrient use efficiency can be obtained when using combined N, P and K fertilizer (Xin et al., 2010). In addition, other researchers have studied the effects of fertilizer ratio or added regulators on enhancing the fertilizer use efficiency of cotton. Yang et al. (2014) observed that applying plant growth regulators could improve the partial factor productivity and agronomic K use efficiency. In short, the reasonable application of N, P and K is beneficial to the growth of cotton and improves the fertilizer use efficiency.

In recent years, many researchers have investigated the influences of various irrigation and N application rates on cotton growth, yield, water productivity and nitrogen use efficiency (NUE) under drip fertigation conditions. It was found that cotton yield increased with the increasing nitrogen and irrigation amounts, but the WUE and NUE decreased significantly in high-water and high-N treatments (Aujla et al., 2005; Thind et al., 2008; Jayakumar et al., 2015). Janat (2008) reported that, relative to the maximum N rates applied in furrow irrigation, 100–150 kg ha^{-1} N was sufficient for lint yield, nitrogen uptake and recovery of cotton under drip irrigation. In addition, Wang et al. (2010) found that seed cotton yield first increased and then declined as the water and phosphorus (P) amount increased. Reasonable irrigation and N, P and K ratios can ensure crop yield, avoid both water and fertilizer waste, and reduce the environmental impact of excessive fertilizer application (Li et al., 2009). Improper drip fertigation was more likely to exacerbate salt loss or accumulation in the root zone compared with the conventional fertilization methods (Wu et al., 2014). Appropriate irrigation and fertilization can promote the coordinated growth of cotton root crowns and shape a reasonable canopy structure, which is conducive to the accumulation of above-ground biomass and lays a foundation for high yields (Deng et al., 2015).

It is clear from the above review that previous studies have focused largely on the effects of single irrigation and fertilization or the interacting effects of water and N on cotton growth and lint yield. Studies on the influences of various irrigation amounts as along with N, P and K rates and ratios on the dry matter accumulation, yield, nutrient absorption and fertilizer use efficiency of drip-fertigated cotton are still lacking. Therefore, the objectives of the present study were to (1) explore the coupling influences of various irrigation and fertilization levels on the dry matter accumulation and nutrient uptake of cotton, and (2) determine an appropriate irrigation and fertilization regime to maximize cotton yield and fertilizer use efficiency. This study is expected to provide scientific basis for optimal water and fertilization management of drip-fertigated cotton in arid regions.

2. Materials and methods

2.1. Experimental site description

Field experiments were carried out from 2012 to 2014 at the irrigation station of Xinjiang Academy of Land Reclamation Sciences (44°18′52″ N, 85°58′50″ E, altitude 412 m) in Shihezi, Xinjiang Autonomous Region, China. This area experiences a continental temperate climate. The long-term annual cumulative temperature is 3649 °C (>10 °C) and the average annual precipitation is only 207 mm. The study area has 168 frost-free days and 2770 h sunshine duration. The soil texture of 0–40 cm soil layer in the experimental area is sandy loam and the 40–100 cm soil is silty clay. Physical and chemical properties of the 0–40 cm soil layer are shown in Table 1. The previous crop in the experimental field was maize, and the same field was used for the 3-year experiment.

2.2. Experimental design and management

Field trials with three drip irrigation levels and five fertilizer levels were conducted over the span 2012–2014. The three irrigation levels included 1.0 ET_C (full irrigation), 0.8 ET_C (20% deficit) and 0.6 ET_C (40% deficit), where ET_C is the crop evapotranspiration. The five fertilizer (N–P–K) levels were F_1 (150–26.2–24.9 kg ha^{-1}), F_2 (200–34.9–33.2 kg ha^{-1}), F_3 (250–43.7–41.5 kg ha^{-1}), F_4 (300–52.4–49.8 kg ha^{-1}) and F_5 (350–61.1–58.1 kg ha^{-1}), with the N:P:K ratio of 1:0.175:0.166. The fertilization rates of F_1, F_2, F_4 and F_5 treatments were 60%, 80%, 120% and 140% of that of the local common fertilization rate F_3 (250–43.7–41.5 kg ha^{-1} N-P-K), respectively. The fifteen treatments were conducted with three replicates. Each experimental plot was 15 m long and 4.6 m wide with two sheets of plastic film. Split-plot design was used in this test. Fertilization was the main plots, and irrigation was the sub-plots. The five fertilization rates were placed in a randomized block design. A protective film was set between two plots.

The cotton cultivar Xinluzao 33 (*Gossypium hirsutum cv.*) was used in 2012 and 2013, while the variety MB799 was used in 2014. The planting system was one season per year. The land was prepared before planting, and the seeds were sown after laying drip irrigation tapes and white plastic film (0.006 mm thick and 2 m wide) with machine. Cotton was planted in a wide-narrow row planting mode. There were six cotton rows on each film, with the row spacing of 20–55–20–55–20 cm in 2012 and 2013 and 20–45–20–45–20 cm in 2014. The plant spacing was 10 cm in all three years. The cotton was sowed on 1st May in 2012, 27th April in 2013 and 18th April in 2014, respectively.

The irrigation method was surface drip irrigation and there were three irrigation tapes under each plastic film. The tape (16 mm in diameter) was placed in between two narrow rows. The discharge rate of drippers was 1.8 L h^{-1} and the dripper spacing was 30 cm. A differential pressure tank (13 L) was used for fertilization. Water meters were used to monitor the irrigation amount that was injected into each test plot. A fertilization tank was shared by three experimental plots with the same amount of fertilizer. Fertilizers forms of urea (46% N), ammonium dihydrogen phosphate (12.2% N, 11.8% P) and potassium chloride (39% K) were applied to each plot for eight times during each growing season. The amount of fertilizer applied each time was 12.5% of the total fertilizer amount of each treatment. The application rates were 12.5% at the seedling stage (12.5%), 25% at the bud stage (12.5% and 12.5%), 37.5% at the flower-boll development stage (12.5%, 12.5% and 12.5%),

Table 1
Physical and chemical properties of the 0–40 cm soil layer.

Soil layer (cm)	pH	Bulk density (g cm^{-3})	Field capacity (Volumetric water content %)	Organic matter (g kg^{-1})	Alkali-hydrolysable nitrogen (mg kg^{-1})	Available phosphorus (mg kg^{-1})	Available potassium (mg kg^{-1})
0–40	7.80	1.51	32.0	18.0	79.8	31.5	154

and 25% at the boll opening stage (12.5% and 12.5%), respectively. The fertilizers were stirred and completely dissolved in the water prior to irrigation. There was no irrigation before planting, and the cotton was drip irrigated after sowing for seedling emergence. Except for the irrigation after sowing, the fertilizer solution was applied into the field with irrigation.

Crop evapotranspiration (ETc) was determined by the following equations:

$$ET_C = E_P K_{CP} \quad (1)$$

$$K_{CP} = K_P K_C \quad (2)$$

where E_p is the evaporation observed by a 20-cm-diameter pan (mm), K_p is the pan coefficient and K_c is the crop coefficient. K_{cp} was defined according to Zhang et al. (2010), with the values of 0.2 at the budding stage, 0.4 at the flowering stage, 0.7 at the bell stage and 0.25 at the boll opening stage.

When there was rainfall, the following formula was used to correct the evaporation.

$$\Delta E_P = 0.4R / K_{cp} - 0.8R \quad (3)$$

where R is the rainfall amount (mm). The irrigation amounts under the three irrigation levels were 445, 368 and 291 mm in 2012, 392, 330 and 267 mm in 2013, and 395, 328 and 261 mm in 2014, respectively. The irrigation scheduling during 2012–2014 are illustrated in Table 2. The rainfall amount was 62 mm in 2012, 113 mm in 2013 and 102 mm in 2014, respectively.

2.3. Measurements and calculations

2.3.1. Dry matter, total N, P and K accumulation

During each growth period (the 50th, 61st, 73th, 85th, 124th and 150th days after sowing in 2012; the 45th, 66th, 77th, 89th, 101st, 116th, 135th and 140th days after sowing in 2013 and the 58th, 72nd, 86th, 103rd, 120th, 133rd and 145th days after sowing in 2014), four plants in each plot were cut from the base of the stem with scissors. The leaf area was obtained by measuring the length and width of each leaf on the plant using a tape. At harvest, the whole root systems were then dug out using the monolith method (Böhm, 1979). The dug holes were 0.2 m long, 0.1 m wide and 0.6 m deep. The soil layers were excavated every 10 cm. The excavated soils were rinsed in 0.25 mm gauze and the cotton roots were picked out (Xie and Tian, 2011). Different plant organs were dried in an oven for 30 min at 105 °C and then dried to a constant weight at 75 °C. The dried samples were pulverized and then sifted with a 0.5 mm sieve. The particulates were digested with a mixture of H_2SO_4–H_2O_2, and the digest was used to determine the nutrient contents. Total N and P were analyzed by a continuous flow analyzer (Auto Analyzer-III, Bran Luebbe, Germany), and total K was measured by atomic absorption spectrometry (Z-2000). The total N, P and K accumulation was calculated by multiplying the biomass and nutrient content.

2.3.2. Nutrient uptake in lint

The nutrient (N, P, K) uptake per 100 kg lint was determined by the following equation:

$$Y_{NU} = F_{N,P,K} / Y_L \times 100 \quad (4)$$

where Y_L is the lint yield. F_N, F_P and F_K are the total amounts of N, P and K accumulation (kg ha^{-1}) at harvest, respectively.

2.3.3. Seed cotton yield, lint yield and water productivity

Four 5 m-long rows of cotton were picked in the middle of plastic film by hand. The seed cotton was weighed, and lint percentage and lint yield was recorded after delinting.

Water productivity is the ratio of seed cotton yield to crop water consumption (ET).

$$ET = R + U + I - O - D - \Delta W \quad (5)$$

where R is the rainfall amount; U is the groundwater recharge; I is the irrigation amount; O is the runoff; D is the deep seepage; and ΔW is the change in soil moisture from the start to the finish of the test (Oweis et al., 2011; Zou et al., 2020). According to the actual conditions during the experiments, the amount of U, O and D were negligible.

2.3.4. Available P and K

Soil samples were taken before sowing. Twenty sampling points were taken in the test area by using the "Z" type method. Five soil layers were taken at each point: 0–20, 20–40, 40–60, 60–80 and 80–100 cm, respectively. The soil samples were air dried and then passed through a 2 mm sieve. Five grams of soil was weighed and extracted with 1 mol L^{-1} neutral NH_4OAc solution (soil/liquid ratio of 1:10), and the available potassium were measured by an Atomic absorption spectrophotometer

Table 2
Amounts of irrigation over the three growth seasons of cotton in 2012, 2013 and 2014.

Year/Treatment	Irrigation date (DAS)[a]									Total (mm)
	1	39	52	63	73	87	99	109	122	
2012										
1.0 ET_C	60	50	40	60	55	50	55	50	25	445
0.8 ET_C	60	40	32	48	44	40	44	40	20	368
0.6 ET_C	60	30	24	36	33	30	33	30	15	291
2013	1	49	60	73	83	93	102	111	120	
1.0 ET_C	60	50	30	50	60	42	45	40	15	392
0.8 ET_C	60	40	24	40	48	35	36	32	15	330
0.6 ET_C	60	30	18	30	36	27	27	24	15	267
2014	1	66	73	82	90	102	109	119	132	
1.0 ET_C	60	60	20	45	40	55	40	50	25	395
0.8 ET_C	60	48	16	36	32	44	32	40	20	328
0.6 ET_C	60	36	12	27	24	33	24	30	15	261

[a] DAS indicates day after sowing.

(AA370MC). Five grams of soil was weighed and extracted with 0.5 mol L^{-1} $NaHCO_3$ solution (soil/liquid ratio of 1:20), and the available phosphorus were measured by the continuous flow analyzer (Auto Analyzer-III, Bran Luebbe, Germany).

2.3.5. N, P and K use efficiency

N, P, and K use efficiency (yield kg kg^{-1} N P, K) were determined by the following equations:

$$NUE = Y_{SC}/F_N \quad (6)$$

$$PUE = Y_{SC}/F_P \quad (7)$$

$$KUE = Y_{SC}/F_K \quad (8)$$

where Y_{SC} is the seed cotton yield (kg ha^{-1}). F_N, F_P and F_K are the total amounts of N, P and K accumulation (kg ha^{-1}) at harvest, respectively (Li et al., 2011).

2.4. Data analysis

All data are the average of three replicates. Statistical Product and Service Solutions (SPSS) software was used to perform one-way analysis of variance. Significant differences were performed with the year, water level and fertilization level as the main effects, including two-, three-way interactions and means of fifteen treatments were compared by Duncan's multiple range tests at the probability level of $P = 0.05$. Origin 8.0 was used for plotting and curve fitting.

3. Results

3.1. Dry matter of different cotton organs and the root-to-shoot ratio at harvest

Higher reproductive organ biomass is the basis for higher yield. The effect of fertilization, year × water, year × fertilization, water × fertilization and year × water × fertilization on dry matter of stems and leaves wasn't significant ($P > 0.05$). However, the year, water, fertilization, year × water, year × fertilization, water × fertilization and year × water × fertilization showed significant ($P < 0.05$) effects on dry matter of roots and bolls (Table 3). The bolls at harvest accounted for the largest proportion of total dry matter, ranging from 53.3% to 66.7%. The roots accounted for the lowest proportion of total dry matter. Under the same fertilizer level, the cumulative amount of dry matter in bolls increased as the irrigation amount increased during the three years. When the same water amount was applied, the dry matter in bolls increased first and then decreased as the fertilizer amount increased. The drought resistance of cotton can be improved by properly increasing the amount of fertilizer under water deficit. When the irrigation level 1.0 ET_C and fertilizer level F_4 were applied, the total dry matter accumulation achieved the highest value in 2012 and 2014 (Table 3).

The root-to-shoot ratio is mainly used to characterize the distribution characteristics of photosynthetic products in plants, and is also a key parameter for measuring the plant nutrition index. The effects of year, fertilization and water × fertilization on the root-to-shoot ratio were significant ($P < 0.05$) (Table 3). When the irrigation levels 1.0 ET_C and 0.8 ET_C were applied, the root-to-shoot ratio in the fertilizer level F_1 was higher than that in the other four fertilizer levels. A low fertilizer amount can't improve the accumulation of dry matter in the shoots. Under the irrigation level 0.6 ET_C, F_4 decreased dry matter of root and increased dry matter accumulation in shoot. Thus, when the irrigation level 0.6 ET_C was applied, the root-to-shoot ratio in the fertilizer level F_4 was the lowest. Water and year × water × fertilization also had significant effect on the root-to-shoot ratio ($P < 0.05$). Under the fertilizer levels F_1 and F_2, the root-to-shoot ratio of the irrigation level 1.0 ET_C was lower than that of deficit irrigation levels. Under the low fertilization levels, deficit

Table 3
Effects of various irrigation and fertilization levels on dry matter of different cotton organs and root-to-shoot ratio at harvest in 2012, 2013 and 2014.

Irrigation	Fertilization	Roots (kg ha^{-1})			Stems (kg ha^{-1})			Leaves (kg ha^{-1})			Bolls (kg ha^{-1})			Root-to-shoot ratio (kg kg^{-1})		
levels	levels	2012	2013	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014	2012	2013	2014
1.0 ETc	F_1	1219a	1185a	883c	1956d	3285bcd	2421ghi	2049f	2369ab	1360g	8388e	8873cd	8983efg	0.098a	0.082bc	0.069cd
	F_2	1195ab	976defg	892c	2240bc	3413b	2515fghi	2159ef	1620ghi	1517ef	9373cd	9618ab	9743cde	0.087b	0.067gh	0.065e
	F_3	1205a	1102ab	858c	2511a	3077de	3186c	2451bcd	2293abc	1907c	9407cd	10082a	11928ab	0.084bc	0.071efgh	0.05h
	F_4	1149abc	910fgh	1065a	2627a	4060a	4033a	3101a	2190bcd	2075b	10094a	9436abc	12568a	0.073def	0.058i	0.057g
	F_5	1032de	1084bc	1077a	2600a	3193cd	3526b	2405cd	2461a	1742d	9913ab	9278bc	11220b	0.069ef	0.073defg	0.065e
0.8 ETc	F_1	1202ab	1094b	880c	1978d	3231bcd	2544fghi	2048f	2052cdef	1376fg	7562g	7270gh	8093hi	0.104a	0.087b	0.073b
	F_2	1171ab	1032bcd	896c	2265bc	3315bc	2543fghi	2207ef	2129bcde	1409efg	8908d	8287de	8627gh	0.088b	0.075cdef	0.071bc
	F_3	1113bcd	994cdef	975b	1975d	3328bc	2573fgh	2577b	2114bcde	1901c	8292e	8562de	9970cd	0.087b	0.071efgh	0.068de
	F_4	969e	997cdef	965b	2098cd	2943ef	3053cd	2287de	1866efg	2522a	10005ab	8338de	10347c	0.067ef	0.076cde	0.061f
	F_5	1071cd	885ghi	726e	2320b	3102de	2893de	2541bc	1986def	1765d	9529bc	7970ef	10386c	0.074de	0.068fgh	0.048h
0.6 ETc	F_1	964e	1063bcd	810d	1699e	2532h	2305i	1334i	1377i	1390efg	6187i	7020h	7617i	0.105a	0.097a	0.072bc
	F_2	945e	965efg	976b	1737e	2900ef	2488ghi	1419hi	1914ef	1529e	5902h	7388fgh	7589i	0.104a	0.079cd	0.084a
	F_3	771f	844hi	948b	1684e	2620gh	2337hi	1327i	1521i	1442efg	6797i	8178de	7960hi	0.079cd	0.068efgh	0.081a
	F_4	759f	802i	739e	1759e	2796fg	2739ef	1666g	1816fgh	1381fg	8125ef	7930efg	9463def	0.066f	0.064hi	0.054g
	F_5	820f	841hi	1035a	2092cd	2694gh	2597fg	1552gh	1581hi	1507ef	7655fg	6843h	8716fgh	0.073def	0.076cde	0.081a
Year		**			**			**			**			**		
Water		**			**			ns			**			**		
Fertilization		**			ns			ns			**			**		
Year × Water		**			ns			ns			**			**		
Year × Fertilization		**			ns			ns			**			**		
Water × Fertilization		**			ns			ns			**			**		
Year × Water × Fertilization		**			ns			ns			**			**		

Notes: Different letters mean the significant difference at $P < 0.05$. **means a remarkably significant difference ($P < 0.01$), and ns means no significant difference ($P > 0.05$).

irrigations had more negative effect on aboveground dry matter accumulation. Under the fertilizer levels F_3, F_4 and F_5, there was no significant difference in the root-to-shoot ratio between the irrigation levels 1.0 ET_C and 0.6 ET_C in 2012 and 2013. Low irrigation level 0.6 ET_C caused a similar degree of reduction in both aboveground and root dry matter (Table 3).

3.2. Nitrogen, phosphorus and potassium accumulation in different cotton organs and nutrient uptake in lint

At maturity, the total N, P and K accumulation of each treatment was 161–340 kg ha^{-1}, 42–77 kg ha^{-1} and 204–378 kg ha^{-1}, respectively. The N, P and K accumulation in the bolls accounted for the largest proportion of total N, P and K in the plant, ranging 54.9−71.6%, 56.1−72.4% and 55.3−71.8%, respectively (Fig. 1).

The effects of year, fertilization, year × fertilization, water × fertilization and year × water × fertilization on the total N accumulation were significant ($P < 0.05$) (Table 5). Compared with the treatment of low water and low fertilizer, increasing the amount of irrigation or fertilization was conducive to the nutrient uptake of cotton. Under the irrigation levels 1.0 ET_C and 0.8 ET_C, the total N accumulation in plants increased at first and then decreased with increasing fertilization rates. The total N accumulation in plants in the fertilizer level F_4 was significantly greater than that in the other four fertilizer levels in all three years. When 0.6 ET_C was applied, the total N accumulation increased as the fertilizer application rate increased in 2012 and 2014. The effects of water and year × water on the total N accumulation were also significant ($P < 0.05$). Under the same fertilizer level, the total N accumulation increased with increasing irrigation amount. The total N accumulation of 0.6 ET_C was significantly lower than that of 1.0 ET_C and 0.8 ET_C during 2012–2014 (Fig. 1a–c).

Water, fertilization, water × fertilization and year × water × fertilization had significant effects on the total P accumulation ($P < 0.05$) (Table 5). Under full irrigation (1.0 ET_C), there were no differences in total P accumulation between the fertilizer levels F_3, F_4 and F_5 in 2012, but total P accumulation was higher than that of the other two fertilizer levels. In 2013, the total P accumulation first increased and then decreased as the fertilization rate enhanced, and the total P

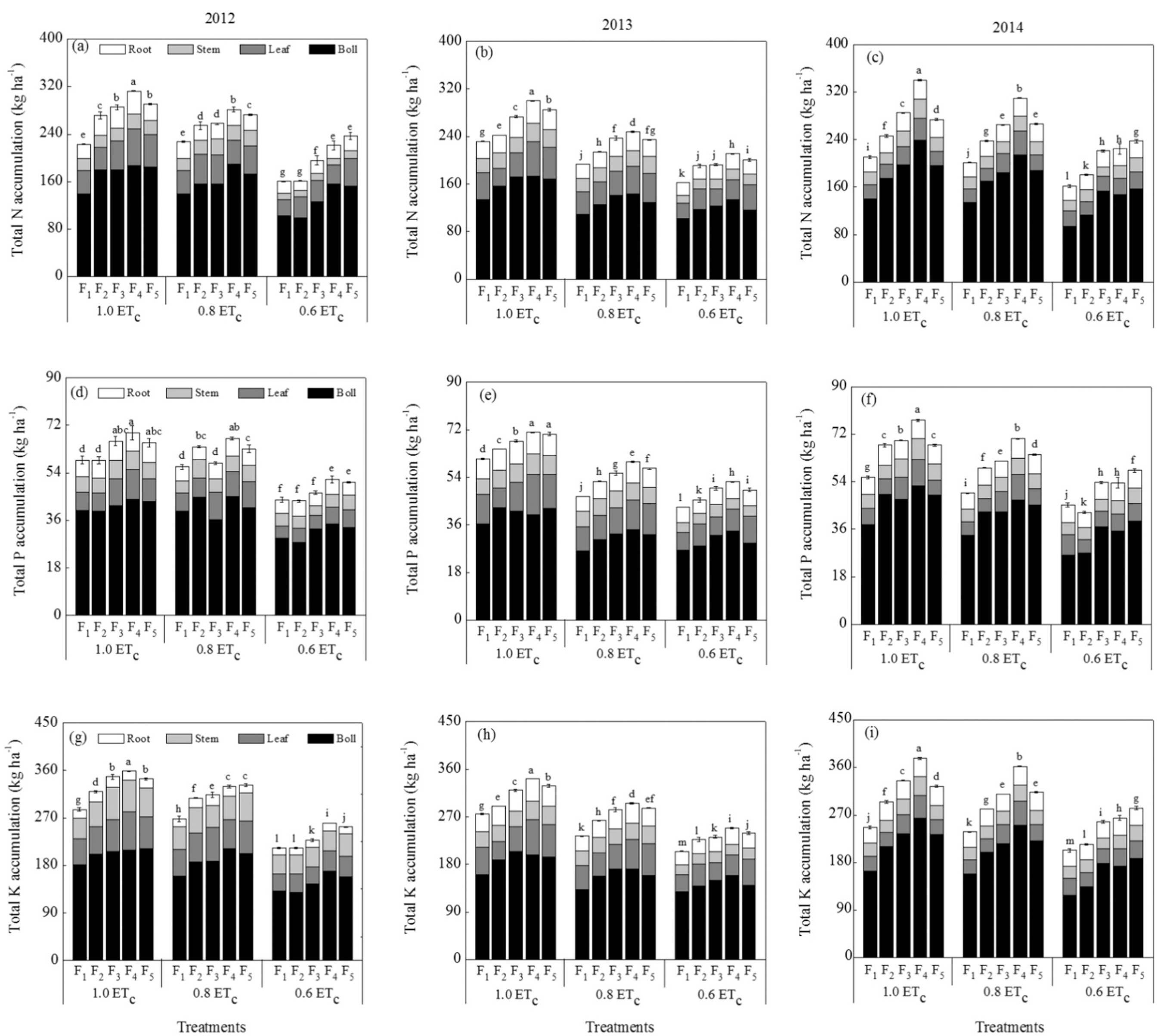

Fig. 1. Effects of various drip irrigation and fertilizer amounts on total nitrogen, phosphorus and potassium accumulation in different organs of cotton in 2012, 2013 and 2014. Different letters mean the significant difference at $P < 0.05$.

accumulation in plants in the fertilizer level F_4 was significantly greater than those in F_1, F_2, F_3 and F_5 under the same irrigation levels. When the irrigation levels 1.0 ET_C and 0.8 ET_C were applied, the total P accumulation in plants in the fertilizer level F_4 was highest in 2014. Total P accumulation decreased with declining irrigation amount in 2013 and 2014 (Fig. 1d–f).

The effects of water, fertilization, water × fertilization and year × water × fertilization on the total K accumulation were significant ($P < 0.05$) (Table 5). Under full irrigation 1.0 ET_C, the total K accumulation first increased and then decreased as the fertilization rate increased in all three years. The total K accumulation in plants in the fertilizer level F_4 was significantly greater than those in F_1, F_2, F_3 and F_5. This trend was the same when the moderate irrigation amount 0.8 ET_C was applied in 2013 and 2014. Total K accumulation in plants was enhanced by the increasing irrigation amount during 2012–2014. The total K accumulation in plants under full irrigation was significantly greater than that under the two deficit irrigation levels (Fig. 1g–i).

Understanding the proportion of nutrients absorbed by crops is important for guiding rational fertilization. The effects of year, fertilization, water, year × water, year × fertilization, water × fertilization and year × water × fertilization on the uptake of N, P and K per 100 kg lint were significant ($P < 0.05$) (Table 4). For producing 100 kg lint cotton, the required amounts of N, P and K were 8.77–14.98 kg, 2.29–3.45 kg and 11.33–17.19 kg, respectively, in 2012–2014 (Table 4). The uptake of N, P and K in 100 kg lint across all treatments ranged from 1:0.22–0.28:1.11–1.33 during the three years, with the average N:P:K ratio of 1:0.25:1.22. The proportion of N, P and K uptake in 100 kg lint was highest when the irrigation level 0.6 ET_C and fertilizer rate F_1 were applied (Table 4).

3.3. Seed cotton yield, lint yield and water productivity

Fertilization, water × fertilization and year × water × fertilization had significant effects on seed cotton yield ($P < 0.05$) (Table 5). Under a given designed irrigation level, seed cotton yield first increased with the increasing fertilization rate, but it then decreased when the fertilizer application rate was beyond a certain range. A quadratic negative correlation existed between fertilizer application and seed cotton yield (Fig. 2a–c). The effects of fertilization, water and year × water were significant ($P < 0.05$). The seed cotton yield was enhanced by the increase of water amount during 2012–2014. The seed cotton yield in the irrigation level 1.0 ET_C was significantly greater than that of the two deficit irrigation levels 0.8 ET_C and 0.6 ET_C. Compared to 1.0 ET_C, the average seed cotton yield of 0.8 ET_C and 0.6 ET_C was decreased by 4.1% and 25.1% in 2012, 6.9% and 22.2% in 2013, and 6.9% and 19.5% in 2014 (Fig. 2a–c), respectively.

The effects of year, water, fertilization year × water, year × fertilization, water × fertilization and year × water × fertilization on lint yield were significant during 2012–2014 ($P < 0.05$) (Table 5). The lint yield and WP first increased and then reduced with the increase of fertilization rate (Fig. 2d–i). When the fertilizer rate was F_3 (250–43.7–41.5 kg ha^{-1}), the lint yield and WP achieved the highest value in 2013. However, when the amount of fertilizer applied was F_4 (300–52.4–49.8 kg ha^{-1}), the greatest lint yield and WP were achieved in 2012 and 2014. The greater lint yield was found in treatments under full irrigation (1.0 ET_C). However, the WP of irrigation level 0.8 ET_C was higher than that of the other two irrigation levels 1.0 ET_C and 0.6 ET_C in 2012 and 2013.

3.4. N, P and K use efficiency

Fertilization, year × fertilization, water × fertilization and year × water × fertilization had significant ($P < 0.05$) effects on N use efficiency (Table 6). When the irrigation levels 1.0 ET_C and 0.8 ET_C were applied, the N use efficiency of fertilizer level F_1 was significantly greater than those of F_2, F_3, F_4 and F_5 in 2012. When the irrigation level 0.6 ET_C was applied, there was no difference in N use efficiency between the fertilizer levels F_1 and F_2, but the N use efficiency was greater than that of the other three fertilizer levels in 2012 (Table 6). The N use efficiency of fertilizer level F_1 was also significantly higher than that of F_3, F_4 and F_5 when the same irrigation amounts were applied in 2013. However, there was no difference in N use efficiency between the fertilizer levels F_1 and F_2 when the irrigation levels were 1.0 ET_C and 0.8 ET_C (Table 6). In 2014, the N use efficiency of treatment F_1 was greater than that of F_2, F_3, F_4 and F_5 under 1.0 ET_C, but the N use efficiency of F_5 was largest when the irrigation level 0.8 ET_C was used (Table 6). The maximum N use efficiency occurred when the irrigation level was 0.6 ET_C during 2012–2014. Although high irrigation amounts could obtain

Table 4
Uptake of nutrient in lint in 2012, 2013 and 2014.

Treatments		N uptake per 100 kg lint (kg (100 kg lint)$^{-1}$)			P uptake per 100 kg lint (kg (100 kg lint)$^{-1}$)			K uptake per 100 kg lint (kg (100 kg lint)$^{-1}$)		
		2012	2013	2014	2012	2013	2014	2012	2013	2014
1.0 ET_C	F_1	10.79f	11.06e	10.62gh	2.84cd	2.91c	2.81c	13.81f	13.12e	12.48gh
	F_2	12.84bc	11.28d	12.54a	2.77de	3.01b	3.45a	15.09c	13.51d	15.03a
	F_3	12.87bc	12.16c	10.79efg	2.98bc	3.01b	2.63ef	15.69b	14.25c	12.69g
	F_4	14.98a	13.85a	12.05b	3.31a	3.28a	2.74d	17.19a	15.80a	13.39de
	F_5	13.30b	13.32b	11.36d	2.99bc	3.29a	2.82c	15.75b	15.34b	13.47d
0.8 ET_C	F_1	12.05d	10.54g	11.03e	2.98bc	2.56f	2.72d	14.21e	12.75g	13.08f
	F_2	12.27d	10.03h	12.51a	3.08b	2.46g	3.12b	14.81cd	12.32h	14.80b
	F_3	12.04d	10.9ef	11.29d	2.69def	2.55f	2.63ef	14.62d	13.01e	13.21ef
	F_4	12.88bc	11.31d	11.77c	3.06b	2.73d	2.67de	15.08c	13.50d	13.77c
	F_5	12.77c	11.06e	10.72fg	2.95bc	2.70de	2.59f	15.54b	13.52d	12.63gh
0.6 ET_C	F_1	9.30h	9.13k	9.56i	2.53fgh	2.40h	2.67de	12.36h	11.54ij	12.05i
	F_2	8.77i	9.78i	10.43h	2.36h	2.33i	2.45g	11.57j	11.62i	12.41h
	F_3	10.32g	9.42j	11.67c	2.45gh	2.44gh	2.84c	11.87i	11.33j	13.60cd
	F_4	11.24e	10.83f	9.59i	2.62efg	2.69de	2.29h	13.23g	12.79fg	11.33j
	F_5	12.33d	10.89ef	10.92ef	2.72de	2.67e	2.68de	13.65f	12.97ef	13.03f
Year		**			**			**		
Water		**			**			**		
Fertilization		**			**			**		
Year × Water		**			**			**		
Year × Fertilization		**			**			**		
Water × Fertilization		**			**			**		
Year × Water × Fertilization		**			**			**		

Notes: Different letters mean the significant difference at $P < 0.05$. **means a remarkably significant difference ($P < 0.01$).

Table 5
Significance levels (*P* values) of the effects of irrigation and fertilization on the seed cotton yield, lint yield, WUE, total N, total P, and total K accumulation.

Treatment	Total N accumulation	Total P accumulation	Total K accumulation	Seed cotton yield	Lint yield	WP
Year	**	**	**	**	**	**
Water	**	**	**	**	**	**
Fertilization	**	**	**	**	**	**
Year × Water	**	**	**	**	**	**
Year × Fertilization	**	**	**	**	**	**
Water × Fertilization	**	**	**	**	**	**
Year × Water × Fertilization	**	**	**	**	**	**

Notes: **means a remarkably significant difference ($P < 0.01$).

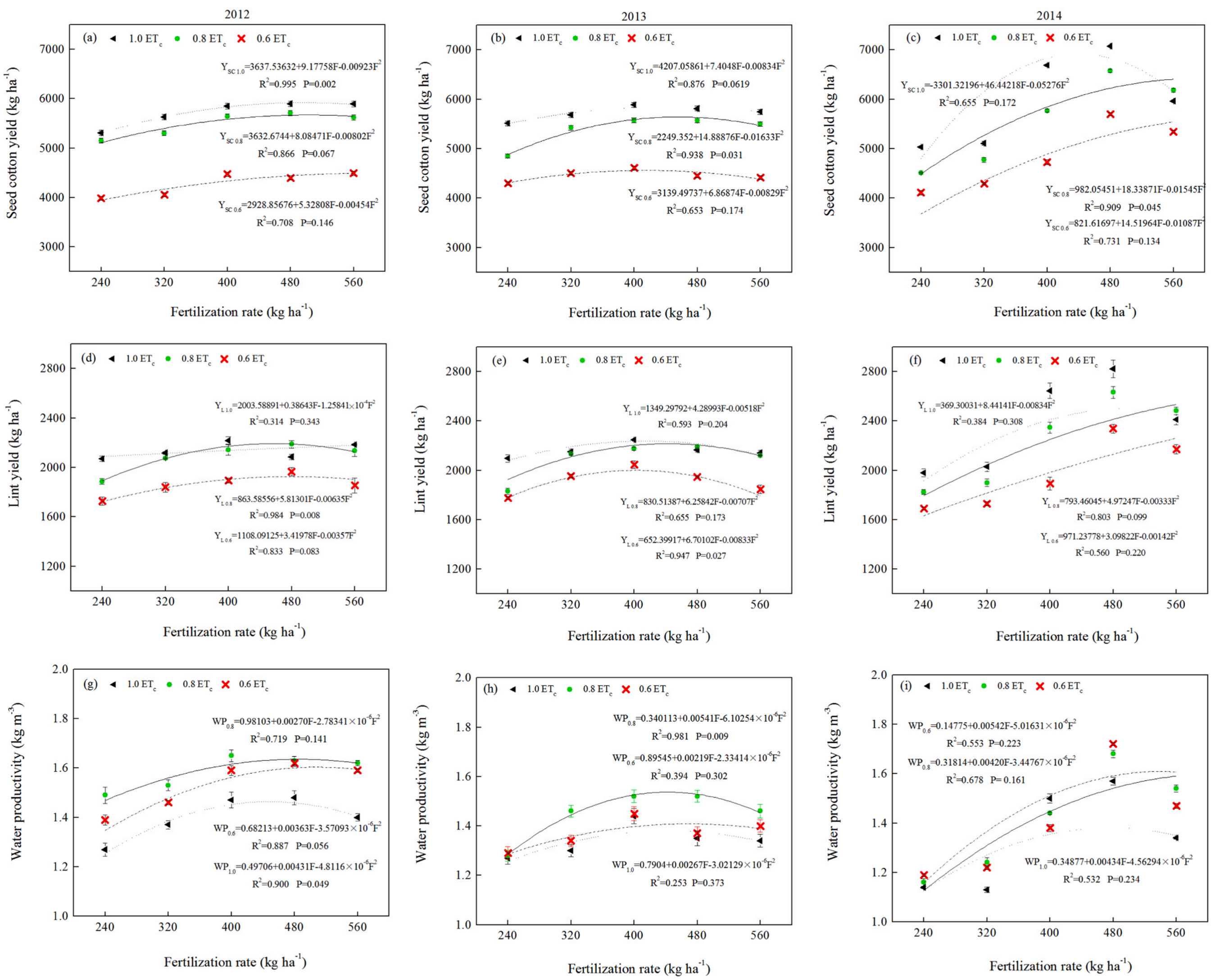

Fig. 2. Relationship between seed cotton yield (Y_{SC}), lint yield (Y_L), water productivity (WP) and applied total fertilization (F) rates under different irrigation levels in 2012, 2013 and 2014.

high seed cotton yield and total N accumulation, the N use efficiency was not high, which may be due to the accumulation of nitrogen mainly in the vegetative organs of cotton under high water conditions. Water and year × water also had significant ($P < 0.05$) effects on N use efficiency. Compared to 1.0 ET_C, the average N use efficiency of 0.8 ET_C and 0.6 ET_C was improved by 2% and 7.2% in 2012, 10.7% and 8.1% in 2013, and −1.8% and 7.1% in 2014, respectively.

The effects of fertilization, year × fertilization, water × fertilization and the three-way interaction on P use efficiency were significant ($P < 0.05$) (Table 6). When the irrigation level 1.0 ET_C was applied, the P use efficiency of fertilizer level F_2 was significantly greater than those of F_1, F_3, F_4 and F_5 in 2012. However, the P use efficiency of fertilizer level F_3 was greatest at the deficit irrigation levels (Table 6). In 2013, when the irrigation amount was 1.0 ET_C, the P use efficiency showed a decreasing trend as the fertilizer application rate increased. There was no difference in P use efficiency between the fertilizer levels F_1 and F_2 when the deficit irrigation levels were applied, but the P use efficiency of these two fertilization levels was significantly greater than that of the other three fertilizer levels (Table 6). However, the P use efficiency of fertilizer level F_2 was lowest under irrigation levels 1.0 ET_C and 0.8 ET_C

Table 6
Effects of various irrigation and fertilization levels on N, P and K use efficiency (NUE, PUE and KUE) in 2012, 2013 and 2014.

Irrigation	Fertilization	NUE (yield kg kg^{-1} N)			PUE (yield kg kg^{-1} P)			KUE (yield kg kg^{-1} K)		
levels	levels	2012	2013	2014	2012	2013	2014	2012	2013	2014
1.0 ET_c	F_1	23.75b	23.78c	23.93b	90.25cd	90.48e	90.46f	18.55bc	20.04b	20.37b
	F_2	20.71ef	23.44c	20.75g	95.93ab	87.96fg	75.33i	17.61def	19.58c	17.32i
	F_3	20.47ef	21.56ef	23.45c	88.51de	87.04g	96.11c	16.79gh	18.39f	19.95cd
	F_4	18.86g	19.37h	20.8g	85.38ef	81.84i	91.54ef	16.44h	16.97h	18.72ef
	F_5	20.29ef	20.15g	21.78e	90.12cd	81.59i	87.82g	17.12efgh	17.49g	18.37gh
0.8 ET_c	F_1	22.64c	25.12b	22.39d	91.54cd	103.66a	90.75ef	19.2b	20.78a	18.89e
	F_2	20.83e	25.35b	20.08h	82.94f	103.36a	80.62h	17.26defg	20.65a	16.98j
	F_3	21.85d	23.51c	21.78e	97.76a	100.36b	93.52d	17.99cd	19.7bc	18.62fg
	F_4	20.26ef	22.47d	21.25f	85.3ef	93.13d	93.53d	17.3defg	18.83de	18.15h
	F_5	20.57ef	23.44c	23.22c	89.16d	95.95c	96.33c	16.91fgh	19.19d	19.71d
0.6 ET_c	F_1	24.79a	26.49a	25.42a	91.11cd	100.56b	90.99ef	18.67bc	20.95a	20.19bc
	F_2	25.11a	23.57c	23.78b	93.48bc	99.06b	101.2b	19.03b	19.83bc	19.98c
	F_3	22.86c	23.92c	21.41f	96.22ab	92.44d	88.15g	19.89a	19.88bc	18.39gh
	F_4	19.88f	21.11f	25.43a	85.35ef	85.14h	106.5a	16.9fgh	17.87g	21.54a
	F_5	18.94g	21.97e	22.54d	89.14d	89.72ef	91.84e	17.74de	18.45ef	18.89e
Year		**			**			**		
Water		**			**			**		
Fertilization		**			**			**		
Year × Water		**			**			**		
Year × Fertilization		**			**			**		
Water × Fertilization		**			**			**		
Year × Water × Fertilization		**			**			**		

Notes: Different letters mean the significant difference at $P < 0.05$. **means a remarkably significant difference ($P < 0.01$).

in 2014 (Table 6). The effects of water and year × water on P use efficiency were significant ($P < 0.05$). Compared to 1.0 ET_C, the average P use efficiency of 0.8 ET_C and 0.6 ET_C was improved by −0.8% and 1.1% in 2012, 15.7% and 8.9% in 2013, and 3.1% and 8.5% in 2014, respectively.

Effects of fertilization and the interaction of year, water with fertilization on K use efficiency were significant ($P < 0.05$) (Table 6). When full irrigation (1.0 ET_C) and medium irrigation (0.8 ET_C) levels were applied, the K use efficiency of fertilizer level F_1 was significantly greater than those of F_2, F_3, F_4 and F_5 in 2012 (Table 6). In 2013, the K use efficiency of fertilizer level F_1 was also significantly higher than that of F_3, F_4 and F_5 under the same irrigation amounts, and the K use efficiency of fertilizer level F_4 was lowest (Table 6). In 2014, the trend of K use efficiency was the same as that of P use efficiency. Under the irrigation levels 1.0 ET_C and 0.8 ET_C, the K use efficiency of fertilizer level F_2 was significantly lower than those of F_1, F_3, F_4 and F_5 (Table 6). The maximum K use efficiency occurred at deficit irrigation levels during 2012–2014. The effects of water and year × water on K use efficiency were also significant ($P < 0.05$). Compared to 1.0 ET_C, the average K use efficiency of 0.8 ET_C and 0.6 ET_C was improved by 2.5% and 6.6% in 2012, 7.2% and 4.9% in 2013, and −2.5% and 4.5% in 2014, respectively.

3.5. *Correlation analysis of seed cotton yield, root-to-shoot ratio, and N, P and K accumulation*

Correlation analysis showed that highly positive correlation of total N, P and K accumulation, nutrient uptake in different organs with seed cotton yield ($P < 0.01$). Compared to the nutrient uptake in roots, leaves and stems, the nutrient uptake in bolls had the highest positive correlation coefficient with yield. However, the correlation between root-to-shoot ratio and seed cotton yield was significantly negative ($P < 0.01$) (Table 7). Higher N, P, and K absorption and nutrient uptake in reproductive organ can significantly increase cotton yield.

Table 7
Correlation analysis of seed cotton yield, root-to-shoot ratio, total N, P and K accumulation and nutrient uptake in different organs.

	Seed cotton yield	Root-to-shoot ratio	Total N accumulation	Total P accumulation	Total K accumulation	Nutrient uptake in bolls	Nutrient uptake in stems	Nutrient uptake in leaves	Nutrient uptake in roots
Seed cotton yield	1	−0.527**	0.903**	0.891**	0.911**	0.864**	0.407**	0.641**	0.607**
Root-to-shoot ratio		1	−0.512**	−0.515**	−0.448**	−0.559**	0.047	−0.048	−0.616**
Total N accumulation[a]			1	0.947**	0.987**	0.934**	0.532**	0.745**	0.515**
Total P accumulation				1	0.950**	0.918**	0.434**	0.662**	0.600**
Total K accumulation					1	0.924**	0.554**	0.783**	0.484**
Nutrient uptake in bolls[b]						1	0.219	0.563**	0.461**
Nutrient uptake in stems							1	0.768**	0.117
Nutrient uptake in leaves								1	0.079
Nutrient uptake in roots									1

** Means a remarkably significant difference ($P < 0.01$).
[a] The sum of N accumulation in different organs.
[b] The sum of N, P and K accumulation in bolls.

4. Discussion

4.1. Effects of irrigation and fertilizer management on dry matter accumulation

Dry matter was the basis of cotton yield, and a higher reproductive organ biomass could obtain a higher yield (Fang et al., 2009; Yang et al., 2011, 2013). Results showed that the dry matter of vegetative organs accounted for the smallest proportion in the total dry matter, and the proportion of reproductive organs was largest (Yan et al., 2009). But the dry matter of cotton is restricted by many factors, including the application of irrigation and fertilization. Yazar et al. (2002) reported that the largest cotton dry matter was gotten by the well-irrigated treatment. Yan et al. (2009) found both the water deficit and excess affected the accumulation and distribution of dry matter in different organs and different growth stages, the most appropriate irrigation amount was 360 mm. Shi et al. (2018) reported that under the same fertilization level, the dry matter of insufficient irrigation (280 mm) was less than conventional irrigation (380 mm), and the dry matter of medium to upper fertilization level (N 300 kg ha^{-1}) was higher when the same irrigation levels were applied. Our findings were consistent with previous studies. And we found the effect of fertilization, and water × fertilization on dry matter of stems and leaves wasn't significant ($P > 0.05$). However, the water, fertilization and the interaction of water with fertilization showed significant ($P < 0.05$) effects on dry matter of roots and bolls. The dry matter accumulation reduced with the decrease of irrigation amount, but it first increased and then decreased with increasing fertilization rates. Results showed that when water was sufficient, high fertilizer made the nutrient concentration of soil solution too high, which caused the senescence of root system and the decreased of nutrient absorption efficiency, finally led to the decline in biomass (Xie and Tian, 2011).

Yan et al. (2009) and Li and Zhang (2011) found the root-to-shoot ratio decreased with increasing irrigation amount. We found that no significant effect of water on the root-to-shoot ratio existed in 2012, while a significant effect existed in 2013 and 2014. The reason for this difference may be due to less rainfall in 2012 than in 2013 and 2014, and more evaporation in 2012 than in 2013 and 2014. The irrigation in 2012 was larger than in 2013 and 2014. The root-to-shoot ratio reflects the distribution and coordination of dry biomass in above-ground and underground. As the amount of irrigation increased, the distribution of increased photosynthates to the aboveground and underground parts was more uniform in 2012. However, as the amount of irrigation increased, more photosynthates were transported to the aboveground part in 2013 and 2014. Min et al. (2014) found that the application of nitrogen reduced the cotton root-to-shoot ratio compared to treatments without nitrogen fertilizer. We also found when the irrigation was applied at 1.0 ET_C and 0.8 ET_C, root-to-shoot ratio of fertilizer level F_1 was higher than that of the other four fertilizer levels. As the amount of fertilization increased, more photosynthesis products were transported to the reproductive organs.

4.2. Effects of irrigation and fertilizer management on N, P and K uptake

Nutrient absorption is the basis for the formation and accumulation of dry matter, and the accumulation of dry matter and nutrients is the prerequisite for the formation of yield. Studies have shown that a higher yield could be obtained by an adequate N, P and K acquisition (Xin et al., 2010; Khan et al., 2017). This study also found that the total N, P and K accumulation had a highly positive correlation with seed cotton yield. At maturity, with the senescence and shedding of leaves, N, P and K were transported to cotton bolls (Fang et al., 2009; Hu et al., 2010; Jiang et al., 2011). Yang et al. (2013) indicated that fertilizer ^{15}N was found in the greatest amounts in the reproductive part of all organs and the proportion of total N accumulated in plants enhanced with N application rates. Our findings were consistent with previous studies. Compared to the nutrient uptake in roots, leaves and stems, the nutrient uptake in bolls had a higher positive correlation with yield. Increasing the absorption of N, P and K, especially the nutrient uptake of reproductive organs, is conducive to the increase of yield.

Tariq et al. (2018) revealed that the K concentration in vegetative and boll components was enhanced as the K application rate increased. Li et al. (2018) found that the accumulation of N, P and K nutrients in cotton plants was increased gradually when more N was applied. We found the water, fertilization and the interaction of year, water with fertilization had significant ($P < 0.05$) effects on total N, total P and total K accumulation in plants. When full irrigation level (1.0 ET_C) was applied in 2012, 2013 and 2014, the value of total N, total P and total K accumulation in plants increased with the increase of fertilization rate within a certain fertilization threshold (F_1-F_4). But beyond this threshold, the total N, total P and total K accumulation decreased. The fertilizer accumulation in plants of fertilizer level F_4 was significantly greater than those in F_1, F_2, F_3 and F_5. The reason for this difference may be that when the amount of fertilizer was too high, the cotton field was too gloomy and the transmittance was poor, which affected the accumulation of nutrients in reproductive organs and led to yield reduction.

In agricultural production, the application of N, P and K in a certain proportion can not only balance the supply of nutrients, but also give full play to the role of various nutrient elements to increase yield and improve the fertilizer use efficiency. Finding out the proportion of nutrients absorbed by crops is of great significance for guiding rational fertilization. Mullins and Burmester (1990) pointed out that the N, P and K required was 19.9, 2.5 and 15.3 kg to produce 100 kg lint, respectively. However, Unruh and Silvertooth (1996) found that the requirements of N–P–K were 15–2.3–19 kg and 21–3.3–23 kg to produce 100 kg lint Upland cotton and Pima cotton, respectively. Fang et al. (2009) revealed that when the lint yield of hybrid cotton was 1778.23 kg ha^{-1}, the uptake amounts of N, P_2O_5 and K_2O were 242.92, 82.12 and 247.76 kg ha^{-1}, respectively, and the absorption ratios of N, P_2O_5 and K_2O were 1:0.34:1.02. Dong et al. (2010) determined that the values of N:P:K for producing 100 kg lint in low and high fertility fields were 1:0.365:0.728 and 1:0.364:0.884, respectively. We found that effects of water, fertilization and two-way interaction on the uptake of N, P and K in 100 kg lint were remarkably significant in 2012–2014. For producing 100 kg lint cotton, the required amounts of N, P and K were 8.77–14.98 kg, 2.29–3.45 kg and 11.33–17.19 kg, respectively, in 2012–2014. The uptake ratio of N, P and K in 100 kg lint ranged from 1:0.22–0.28:1.11–1.33 across all treatments during the three years, with the average N:P:K ratio of 1:0.25:1.22. This difference can be largely attributed to the difference in variety of cotton, soil texture, fertilization rates or irrigation amounts. The proportion of N, P and K uptake in 100 kg lint was highest when the irrigation level 0.6 ET_C and fertilizer rate F_1 were applied. The reasons for this result may be due to the fact that the ratio of nitrogen, phosphorus and potassium in this experiment was 1:0.175:0.166, where the amount of phosphorus applied was sufficient and the potassium content in the soil was very high (>150 mg kg^{-1}). Although the nitrogen application rate of fertilizer level F_1 was only 150 kg ha^{-1}, the crop may have ingested a large proportion of nitrogen from the soil.

4.3. Effects of irrigation and fertilizer levels on cotton yield and WP

Proper water and fertilizer inputs could result in a higher yield (Zheng et al., 2001; Wu et al., 2014). The effect of water was significant ($P < 0.05$). Increasing irrigation amount could enhance the seed cotton yield and lint yield in three years. The findings agree with previous studies which reported that yields were enhanced with increasing irrigation amount (Yang et al., 2015; Shareef et al., 2018).

Cotton yield showed an increasing trend with the increasing fertilizer application rate, but excessive fertilization did not increase yield (Li et al., 2010; Wang et al., 2012b). Similar conclusions were also obtained by us. Year, fertilization and year × water × fertilization showed significant ($P < 0.05$) effects on seed cotton yield. The yield first increased and then decreased with the increasing fertilization rate. The highest lint yield was obtained when the irrigation level was 1.0 ET_C and the fertilizer amount was F_3 in 2012 and 2013. When the irrigation at 1.0 ET_C level was applied, the seed cotton yield of F_4 was the maximum in 2012 and 2014. And there is no significant difference in seed cotton yield between F_3 and F_4 in 2012 and 2013. The reason for this difference in three years may be due to the different climates. During the cotton growing season, the precipitation was 62 mm in 2012, 113 mm in 2013 and 102 mm in 2014, respectively. The total precipitation was relatively small in 2012 and 2014, and most of the precipitation was ineffective (<5 mm), which affected the absorption of nutrients and the distribution of photosynthetic products in crops.

WP is negatively correlated with irrigation amounts, but positively correlated with fertilization amounts (Xing et al., 2015). Increasing the application of fertilizer was conducive to improving the WP of crops (Li et al., 2015a). Similar results were gained by us. In addition, we found there was a quadratic negative correlation between fertilizer application and WP, which was consistent with the findings of Liu et al. (2014) and Gu et al. (2017) for maize and winter rapeseed, respectively.

4.4. Effects of various irrigation and fertilizer amounts on N, P and K use efficiency

The rational application of N fertilizer is extremely important to improve yield and N use efficiency (Zhang et al., 2012). N, P and K use efficiency decreased as the amount of N, P and K applied increased, respectively (Hu et al., 2010; Li et al., 2010; Jiang et al., 2011; Wang et al., 2012b). When the application rates of phosphate and potassium fertilizer were the same, the application of nitrogen fertilizer can enhance the phosphorus and potassium use efficiency, but the nitrogen use efficiency decreased as the application of nitrogen increased (Li et al., 2018). We also came to a conclusion similar to previous studies. When the amount of irrigation was the same, N, P and K use efficiency of low fertilizer levels was higher than that of high fertilizer levels in 2012 and 2013. The highest N, P and K use efficiency occurred in the deficit irrigation levels in 2012–2014. The increased N, P and K accumulation in plants of full irrigation were mainly observed in vegetative organs compared to deficit irrigation levels. This result is similar to that of Shi et al. (2018) who reported that the N production efficiency of insufficient irrigation was greater than that of conventional irrigation when the fertilization levels were same.

We found the seed cotton yield, economic benefits and water use efficiency achieved $\geq$90% of their maximum values simultaneously when the irrigation interval was 362.3–462.5 mm and the fertilizer ($N–P_2O_5–K_2O$) interval was 212.5–85–42.5 to 367.5–147–73.5 kg ha^{-1} (Wang et al., 2018). In this study, comprehensively considering from the perspective of the seed cotton yield, lint yield, the N, P and K absorption and use efficiency as well as the environment, the irrigation level of 1.0 ET_C and $N–P_2O_5–K_2O$ rate of 250–43.7–41.5 kg ha^{-1} was the best drip fertigation strategy. This irrigation and fertilization level was included in the above interval.

5. Conclusions

The dry matter accumulation, seed cotton yield and lint yield showed an increasing trend with increasing irrigation amount under the same fertilizer level during 2012–2014. Although the highest WP, N, P and K use efficiency occurred at deficit irrigation levels, deficit irrigation resulted in a severe decrease in cotton yield. Total N, P and K accumulation had a highly positive correlation with seed cotton yield. Increasing the absorption of N, P and K, especially the nutrient uptake in reproductive organs, could enhance the seed cotton yield. Under full irrigation (1.0 ET_C), the total dry matter accumulation, seed cotton yield, N, P and K accumulation in plants in the fertilizer level F_4 (300–52.4–49.8 kg ha^{-1}) were significantly greater than those of the other four fertilizer levels during 2012 and 2014. However, when the irrigation amount was 1.0 ET_C and fertilizer amount was F_3 (250–43.7–41.5 kg ha^{-1}), the seed cotton yield and lint yield were highest in 2013. When the amount of irrigation was the same, the N, P and K use efficiencies of low fertilizer levels were higher than that of high fertilizer levels in 2012 and 2013. Comprehensively considering the cotton yield as well as the N, P and K absorption and use efficiency, the irrigation level of 1.0 ET_C and N-P-K rate of 250–43.7–41.5 kg ha^{-1} was the best drip fertigation strategy in northwestern China. The uptake ratio of N, P and K in 100 kg lint was about 1:0.25:1.22, which is of great significance for guiding rational fertilization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Aujla, M.S., Thind, H.S., Buttar, G.S., 2005. Cotton yield and water use efficiency at various levels of water and N through drip irrigation under two methods of planting. Agric. Water Manag. 71, 167–179.
Böhm, W., 1979. Methods of Studying Root Systems. Springer-Verlag, New York.
Chen, B., Yang, H., Song, W., Liu, C., Xu, J., Zhao, W., Zhou, Z., 2016. Effect of N fertilization rate on soil alkalihydrolyzable N, subtending leaf N concentration, fiber yield, and quality of cotton. Crop J. 4 (4), 323–330.
Deng, Z., Zhai, G., Zong, J., Lv, M., Li, Y., Feng, J., Cai, J., Zhang, W., 2015. Effects of water and nitrogen regulation on root and shoot growth characteristics and yield of cotton in arid area. Soils Fertil. Sci. China 6, 57–64.
DeTar, W.R., 2008. Yield and growth characteristics for cotton under various irrigation regimes on sandy soil. Agric. Water Manag. 95 (1), 69–76.
Dong, H., Kong, X., Li, W., Wei, T., Zhang, D., 2010. Effects of plant density and nitrogen and potassium fertilization on cotton yield and uptake of major nutrients in two fields with varying fertility. Field Crops Res. 119, 106–113.
Du, T., Kang, S., Wang, Z., Wang, F., Yang, X., Su, X., 2007. Responses of cotton growth, yield, and water use efficiency to alternate furrow irrigation. Acta Agron. Sin. 33 (12), 1982–1990 (in Chinese with English abstract).
Fang, W., Li, L., Xie, D., Ma, Z., Zhang, D., Du, Y., 2009. Comparison of dry matter accumulation and N, P, K uptake and distribution in different organs and yield of hybrid cotton and conventional cotton varieties. Plant Nutr. Fertil. Sci. 15 (6), 1401–1406 (in Chinese with English abstract).
FAO, 2018. FAOSTAT Online Database. Food and Agriculture Organization of the United Nations. http://faostat3.fao.org/browse/Q/QC/E.
Geng, J., Ma, Q., Chen, J., Zhang, M., Li, C., Yang, Y., Yang, X., Zhang, W., Liu, Z., 2016. Effects of polymer coated urea and sulfur fertilization on yield, nitrogen use efficiency and leaf senescence of cotton. Field Crops Res. 187, 87–95.
Gong, S., Yang, T., Chen, B., Ma, X., Niu, X., Lou, S., 2015. Regulation of nitrogen fertilizer management of cotton yield and nutrient uptake under the machine pick cotton pattern. Chin. Agric. Sci. Bull. 12, 145–151 (in Chinese with English abstract).
Gu, X., Li, Y., Du, Y., 2017. Optimized nitrogen fertilizer application improves yield, water and nitrogen use efficiencies of winter rapeseed cultivated under continuous ridges with film mulching. Ind. Crops Prod. 109, 233–240.
Hassanli, A.M., Ebrahimizadeh, M.A., Beecham, S., 2009. The effects of irrigation methods with effluent and irrigation scheduling on water use efficiency and corn yields in an arid region. Agric. Water Manag. 96, 93–99.
Hou, Z., Chen, W., Li, X., Xiu, L., Wu, L., 2009. Effects of salinity and fertigation practice on cotton yield and ^{15}N recovery. Agric. Water Manag. 96 (10), 1483–1489.
Hu, W., Coomer, T.D., Loka, D.A., Oosterhuis, D.M., Zhou, Z., 2017. Potassium deficiency affects the carbon-nitrogen balance in cotton leaves. Plant Physiol. Biochem. 115, 408–417.
Hu, M., Tian, C., Ma, Y., 2002. The effects of water and fertilizer on cotton growth, nutrition absorption and water utilization. Agric. Res. Arid Areas 20 (3), 35–37 (in Chinese with English abstract).
Hu, G., Zhang, Y., Hu, W., Li, Q., Tang, M., Qi, G., 2010. Effects of phosphate fertilizer application on P absorption, utilization and yield of cotton. Soils Fertil. Sci. China 4, 27–31 (in Chinese with English abstract).
Janat, M., 2008. Response of cotton to irrigation methods and nitrogen fertilization: yield components, water-use efficiency, nitrogen uptake, and recovery. Commun. Soil Sci. Plant Anal. 39 (15–16), 2282–2302.

Jayakumar, M., Surendran, U., Manickasundaram, P., 2015. Drip fertigation program on growth, crop productivity, water, and fertilizer-use efficiency of Bt cotton in semi-arid tropical region of India. Commun. Soil Sci. Plant Anal. 46 (3), 293–304.
Jiang, C., Xia, Y., Chen, F., Lu, J., Wang, Y., 2011. Plant growth, yield components, economic responses, and soil indigenous K uptake of two cotton genotypes with different K-efficiencies. J. Integr. Agric. 10 (5), 705–713.
Khan, A., Wang, L., Ali, S., Tung, S.A., Hafeez, A., Yang, G., 2017. Optimal planting density and sowing date can improve cotton yield by maintaining reproductive organ biomass and enhancing potassium uptake. Field Crops Res. 214, 164–174.
Liu, C., Zhou, L., Jia, J., Wang, L., Si, J., Li, X., Pan, C., Siddique, K., Li, F., 2014. Maize yield and water balance is affected by nitrogen application in a film-mulching ridge-furrow system in a semiarid region of China. Eur. J. Agron. 52, 103–111.
Li, H., Cong, R., Ren, T., Li, X., Ma, C., Zheng, L., Zhang, Z., Lu, J., 2015a. Yield response to N fertilizer and optimum N rate of winter oilseed rape under different soil indigenous N supplies. Field Crops Res. 181, 52–59.
Li, M., Du, Y., Zhang, F., Bai, Y., Fan, J., Zhang, F., Chen, S., 2019. Simulation of cotton growth and soil water content under film-mulched drip irrigation using modified CSM-CROPGRO-cotton model. Agric. Water Manag. 218, 124–138.
Li, L., Fang, W., Xie, D., Ma, Z., Du, Y., Zhang, D., 2010. Effect of nitrogen application rate on dry matter accumulation and N, P, K uptake, distribution and utilization in different organs of hybrid cotton under high-yield cultivated condition. Cotton Sci. 22 (4), 347–353 (in Chinese with English abstract).
Li, F., Guo, L., Li, J., Xiao, C., 2018. Effects of nitrogen application rate on N P K uptake , distribution and utilization of direct seeding cotton after rape harvest. Acta Agric. Boreal. -Sin. 33 (3), 196–202 (in Chinese with English abstract).
Li, R., Li, Y., He, J., Li, G., Hao, X., Wang, F., 2011. Effect of nitrogen application rate on nitrogen utilization and grain yield of winter wheat. J. Triticeae Crops 31 (2), 270–275 (in Chinese with English abstract).
Li, X., Song, C., Wang, R., Wang, S., Li, Z., Gao, J., 2009. Effects of nitrogen, phosphorus and potassium at different proportion on biological traits and yield of cotton. Shandong Agric. Sci. 4 (68–70), 73 (in Chinese with English abstract).
Li, Z., Wang, H., Zhang, F., Wu, L., Wang, Z., Zhou, J., 2015b. Effects of water-fertilizer coupling on field cotton growth and yield under fertigation in Xinjiang. J. Drain. Irrig. Mach. Eng. 33 (12), 1069–1077 (in Chinese with English abstract).
Li, P., Zhang, F., 2011. Effect of root zone water and nitrogen regulation on cotton population physiological indices under different furrow irrigation patterns. Trans. Chin. Soc. Agric. Eng. 27 (2), 38–45 (in Chinese with English abstract).
Min, W., Guo, H., Zhou, G., Zhang, W., Ma, L., Ye, J., Hou, Z., 2014. Root distribution and growth of cotton as affected by drip irrigation with saline water. Field Crops Res. 169, 1–10.
Mullins, G.L., Burmester, C.H., 1990. Dry matter, nitrogen, phosphorus, and potassium accumulation by four cotton varieties. Agron. J. 4, 729–736.
Oweis, T.Y., Farahani, H.J., Hachum, A.Y., 2011. Evapotranspiration and water use of full and deficit irrigated cotton in the Mediterranean environment in northern Syria. Agric. Water Manag. 98 (8), 1239–1248.
Papastylianou, P.T., Argyrokastritis, I.G., 2014. Effect of limited drip irrigation regime on yield, yield components, and fiber quality of cotton under Mediterranean conditions. Agric. Water Manag. 142, 127–134.
Qi, M., Zhang, Y., Wang, W., Wang, C., Wu, Z., Wang, J., 2020. Effect of mulched drip irrigation on water and heat transfer and crop water consumption in maize field. J. Drain. Irrig. Mach. Eng. 38 (7), 731–737.
Qian, J., Li, N., Guo, J., 2014. Measurement and analysis on contribution rate of input factors in China's cotton yield increase. J. Agric. Sci. Technol. 16 (2), 160–165 (in Chinese with English abstract).
Rajak, D., Manjunatha, M.V., Rajkumar, G.R., Hebbara, M., Minhas, P.S., 2006. Comparative effects of drip and furrow irrigation on the yield and water productivity of cotton (*Gossypium hirsutum,* L.) in a saline and waterlogged vertisol. Agric. Water Manag. 83 (1–2), 30–36.
Read, J.J., Reddy, K.R., Jenkins, J.N., 2006. Yield and fiber quality of upland cotton as influenced by nitrogen and potassium nutrition. Eur. J. Agron. 24 (3), 282–290.
Shareef, M., Gui, D., Zeng, F., Waqas, M., Zhang, B., Iqbal, H., 2018. Water productivity, growth, and physiological assessment of deficit irrigated cotton on hyperarid desert-oases in northwest China. Agric. Water Manag. 206, 1–10.
Shi, P., Liu, H., He, X., Li, H., Li, K., 2020. Experiments on drainage rule and soil desalination effect under mulched subsurface pipe drainage. J. Drain. Irrig. Mach. Eng. 38 (7), 726–730.
Shi, H., Zhang, J., Yan, Q., Li, Q., Li, J., 2018. Compensation effects of nitrogen fertilizer on yield and quality of cotton under insufficient irrigation. Plant Nutr. Fertil. Sci. 24 (1), 134–145 (in Chinese with English abstract).
Tang, L., Li, Y., Zhang, J., 2005. Physiological and yield responses of cotton under partial root-zone irrigation. Field Crops Res. 94 (2–3), 214–223.
Tariq, M., Afzal, M.N., Muhammad, D., Ahmad, S., Shahzad, A.N., Kiran, A., Wakeel, A., 2018. Relationship of tissue potassium content with yield and fiber quality components of *Bt* cotton as influenced by potassium application methods. Field Crops Res. 229, 37–43.
Thind, H.S., Aujla, M.S., Buttar, G.S., 2008. Response of cotton to various levels of nitrogen and water applied to normal and paired sown cotton under drip irrigation in relation to check-basin. Agric. Water Manag. 95, 25–34.
Ünlü, M., Kanber, R., Koç, D.L., Tekin, S., Kapur, B., 2011. Effects of deficit irrigation on the yield and yield components of drip irrigated cotton in a Mediterranean environment. Agric. Water Manag. 98 (4), 597–605.
Unruh, B.L., Silvertooth, J.C., 1996. Comparisons between an Upland and a Pima cotton cultivar: II. Nutrient uptake and partitioning. Agron. J. 88 (4), 589–595.
Wang, H., Cui, J., Hou, Z., Yang, X., Luo, L., Lv, X., 2010. Effects of water and phosphorus on yield and water use efficiency of cotton with drip irrigation under mulch. J. Shihezi Univ. 28 (5), 551–554 (in Chinese with English abstract).
Wang, H., Wang, X., Bi, L., Wang, Y., Fan, J., Zhang, F., Hou, X., Cheng, M., Wu, L., Xiang, Y., 2019. Multi-objective optimization of water and fertilizer management for potato production in sandy areas of northern China based on TOPSIS. Field Crops Res. 240, 55–68.
Wang, X., Wei, C., Zhang, J., Dong, P., Wang, J., Zhu, Q., Wang, J., 2012a. Effects of irrigation mode and N application rate on cotton field fertilizer N use efficiency and N losses. J. Appl. Ecol. 23 (10), 2751–2758 (in Chinese with English abstract).
Wang, X., Wei, C., Zhang, J., Dong, P., Wang, J., Zhu, Q., Wang, J., 2012b. Effects of irrigation methods and N application level on cotton growth and nitrogen use efficiency. Cotton Sci. 24 (6), 554–561 (in Chinese with English abstract).
Wang, H., Wu, L., Cheng, M., Fan, J., Zhang, F., Zou, Y., Chau, H.W., Gao, Z., Wang, X., 2018. Coupling effects of water and fertilizer on yield, water and fertilizer use efficiency of drip-fertigated cotton in northern Xinjiang, China. Field Crops Res. 219, 169–179.
Wu, L., Zhang, F., Zhou, H., Suo, Y., Xue, F., Zhou, J., Liang, F., 2014. Effect of drip irrigation and fertilizer application on water use efficiency and cotton yield in North of Xinjiang. Trans. Chin. Soc. Agric. Eng. 30 (20), 137–146 (in Chinese with English abstract).
Xie, Z., Tian, C., 2011. Coupling effects of water and nitrogen on dry matter accumulation, nitrogen uptake and water-nitrogen use efficiency of cotton under mulched drip irrigation. Plant Nutr. Fertil. Sci. 17 (1), 160–165 (in Chinese with English abstract).
Xing, Y., Zhang, F., Zhang, Y., Li, J., Qiang, S., Wu, L., 2015. Effects of irrigation and fertilizer coupling on greenhouse tomato yield, quality, water and nitrogen utilization under fertigation. Sci. Agric. Sin. 48 (4), 713–726 (in Chinese with English abstract).
Xin, C., Dong, H., Luo, Z., Tang, W., Zhang, D., Li, W., Kong, X., 2010. Effects of N, P, and K fertilizer application on cotton growing in saline soil in Yellow River Delta. Acta Agron. Sin. 36 (10), 1698–1706.
Yang, G., Chu, K., Tang, H., Nie, Y., Zhang, X., 2013. Fertilizer ^{15}N accumulation, recovery and distribution in cotton plant as affected by N rate and split. J. Integr. Agric. 12 (6), 999–1007.
Yang, F., Du, M., Tian, X., Eneji, A.E., Duan, L., Li, Z., 2014. Plant growth regulation enhanced potassium uptake and use efficiency in cotton. Field Crops Res. 163, 109–118.
Yang, C., Luo, Y., Sun, L., Wu, N., 2015. Effect of deficit irrigation on the growth, water use characteristics and yield of cotton in arid northwest China. Pedosphere 25 (6), 910–924.
Yang, G., Tang, H., Nie, Y., Zhang, X., 2011. Responses of cotton growth, yield, and biomass to nitrogen split application ratio. Eur. J. Agron. 35 (3), 164–170.
Yan, S., Wu, Y., Fan, J., Zhang, F., Qiang, S., Zheng, J., Xiang, Y., Guo, J., Zou, H., 2019. Effects of water and fertilizer management on grain filling characteristics, grain weight and productivity of drip-fertigated winter wheat. Agric. Water Manag. 213, 983–995.
Yan, Y., Zhao, C., Sheng, Y., Li, J., Peng, D., Li, Z., Feng, S., 2009. Effects of drip irrigation under mulching on cotton root and shoot biomass and yield. Chin. J. Appl. Ecol. 20 (4), 970–976.
Yazar, A., Sezen, S.M., Sesveren, S., 2002. LEPA and trickle irrigation of cotton in the Southeast Anatolia project (GAP) area in Turkey. Agric. Water Manag. 54 (3), 189–203.
Zhang, J., Duan, A., Shen, X., Yang, G., Song, J., Liu, X., 2010. Design and experiment of scheduling irrigation device based on pan evaporation for drip-irrigated cotton under plastic mulch. Trans. Chin. Soc. Agric. Mach. 41 (9), 56–60 (in Chinese with English abstract).
Zhang, D., Li, W., Xin, C., Tang, W., Eneji, A.E., Dong, H., 2012. Lint yield and nitrogen use efficiency of field-grown cotton vary with soil salinity and nitrogen application rate. Field Crops Res. 138 (3), 63–70.
Zhang, D., Luo, Z., Liu, S., Li, W., Tang, W., Dong, H., 2016a. Effects of deficit irrigation and plant density on the growth, yield and fiber quality of irrigated cotton. Field Crops Res. 197, 1–9.
Zhang, Y., Zhang, F., Wu, L., 2016b. Coupling water and fertilizer effects on cotton yield, nitrogen accumulation and nitrogen use efficiency. Water Sav. Irrig. 12, 20–26.
Zheng, Z., Ma, F., Mu, Z., Li, J., Yang, H., 2001. Effects of factors of water and fertilizers under mulch drip irrigation on cotton canopy structure and yield. Agric. Res. Arid Areas 19 (2), 42–47.
Zou, H., Fan, J., Zhang, F., Xiang, Y., Wu, L., Yan, S., 2020. Optimization of drip irrigation and fertilization regimes for high grain yield, crop water productivity and economic benefits of spring maize in Northwest China. Agric. Water Manag. 230, 105986.