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Water–Nitrogen Coupling and Multi-Objective Optimization of Cotton under Mulched Drip Irrigation in Arid Northwest China

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Abstract: Cotton is the most important cash crop in Xinjiang but low utilization rate of water and fertilizer is restricting healthy development of this industry. At present, there is a lack of water and nitrogen management optimization methods based on multi-objectives of cotton water use efficiency (WUE), nitrogen use efficiency (NUE), yield, and income. A continuous field experiment was conducted during 2017–2018 to study the effects of water–nitrogen coupling on cotton growth, WUE, NUE, nitrogen partial factor productivity, yield, quality, and economic benefits under drip irrigation in northern Xinjiang. Using multiple regression and spatial analyses, the water and nitrogen management strategy for multi-objective optimization was determined. Three irrigation levels were used—low (I_1), medium (I_2), and full (I_3)—Representing 75%, 87.5%, and 100% of cotton water demand, respectively. The three nitrogen application levels were low (N_1, 210 kg/ha), medium (N_2, 280 kg/ha), and high (N_3, 350 kg/ha), representing 75%, 100%, and 125% of the local nitrogen application, respectively. Among all treatments, the leaf area index, boll weight, dry matter quantity and yield reached respective maxima of 4.43 m^2/m^2, 4.73 g, 16,623 kg/ha, and 6333 kg/ha for the I_3N_2 treatment. Cotton fiber quality was the best for I_3 irrigation, but too little or too much nitrogen reduced fiber quality. The economic benefit under I_3 irrigation was 1.93–4.81 times that for I_1. For a single optimization objective, WUE reached a maximum of 1.78 kg/ha·mm for irrigation of 415.80 mm and nitrogen application of 295.71 kg/ha; corresponding single maxima follow: NUE of 37.65% for 418.27 mm and 278.57 kg/ha; yield of 6416.42 kg/ha for 470.12 mm and 304.29 kg/ha; and economic benefit of 15,338.55 RMB/ha for 470.12 mm and 307.14 kg/ha. Multiple regression and spatial analysis showed that for irrigation of 430.71–440.12 mm and nitrogen application of 270.95–318.45 kg/ha, the WUE, NUE, yield, and economic benefits of cotton simultaneously exceeded 90% of their maxima, which was an efficient and reasonable water and nitrogen management mode in this location. The results provide a scientific basis for effective integrated management of water and fertilizer in drip irrigation cotton fields in northern Xinjiang.

Keywords: water–nitrogen coupling; water and nitrogen use efficiency; yield; fiber quality; economic benefit

1. Introduction

Xinjiang's abundant light and heat resources provide high-quality conditions for cotton growth. Cotton has become the most important economic crop in Xinjiang. Its planting area and total output account for 35% and 41% of the country's totals, respectively [1]. However, Xinjiang is located in the inland arid area of Northwest China and there is little effective rainfall during the crop growing season. The contradiction between supply and demand of water resources and cotton production is becoming increasingly prominent [2]. Nitrogen is the most important nutrient element in cotton growth. As an important component of nucleic acids and proteins, nitrogen application can significantly regulate cotton yield. Excessive nitrogen application not only brings a series of problems, such as waste of resources and uncoordinated growth of cotton, it also causes soil salinization in serious cases, which ultimately leads to the decline of quality and yield, and low economic benefit of cotton fields. At present, saline cultivated land in Xinjiang represents 31.10% of the total cultivated area, and the physical and chemical conditions of soil are not ideal [3]. Therefore, for cotton production in Xinjiang, how to supply water and nitrogen reasonably and efficiently and improve the efficiency of their utilization has become a key technical factor to promote protection of soil and water resources and achieve high quality and yield of cotton in this region.

In recent years, the integrated technology of water and fertilizer for drip irrigation under mulch has developed rapidly, and the coupling effect of crop water and nitrogen under drip irrigation has been studied, achieving useful results. Xie et al. found that insufficient water or high nitrogen supply limited the accumulation of cotton dry matter, leading to early decline of cotton and so lower yield [4]. Wang et al. found that water–nitrogen interaction significantly affected net photosynthetic rate, transpiration rate, and stomatal conductance of cotton at all growth stages. The optimum irrigation nitrogen rate for cotton in mild saline-alkali soil was 3740 m^3/ha and 754 kg/ha [5]. Singh et al. showed that for irrigation amount of 0.8–1.0 ET_c (ET_c is the evapotranspiration required for cotton from planting to harvest under sufficient water supply), the yield of cotton increased with the increase of nitrogen application, and the suitable amount of nitrogen application was 200 kg/ha [6]. Deng et al. found that when the irrigation amount was 3900 m^3/ha and nitrogen application rate was 300 kg/ha, the number of effective bolls and boll weight of cotton increased significantly, yield reached 6992 kg/ha and water use efficiency (WUE) and nitrogen use efficiency (NUE) were 1.45 kg/m^3 and 45.9% [3], respectively. Wang et al. showed that under full irrigation, leaf area index (LAI), seed cotton yield, and economic benefits were improved with increased irrigation amount. Low irrigation was not conducive to effectiveness of fertilizers, and WUE was at its minimum [7]. Zhou et al. found that for mature apples, controlling soil moisture to 65%–75% of field capacity and nitrogen application to 20 g/tree was the best combination of water and fertilizer conservation [8].

Although there are many studies on the water–nitrogen coupling effect in drip irrigation crops, most results show that the best combination of water and nitrogen for the study area comes from the established water and nitrogen treatment. However, due to limited numbers of experimental treatments, the suitable combination of water and nitrogen input is often outside the established treatments, and any single treatment cannot take into account the multiple objectives of improving quality, yield, and WUE and NUE. Hou et al. conducted a quadratic regression analysis of irrigation and fertilizer application; spatial analysis showed that for irrigation of 725–825 mm and nitrogen application of 273.6–355.6 kg/ha, grape yield, quality, and economic benefits could be simultaneously achieved [9]. Lin et al. established a functional relationship between water and nitrogen input and jujube yield, fruit quality, and economic benefit in an extremely arid area using quadratic regression. Through spatial analysis, the multi-objective of suitable water and nitrogen interval for comprehensive yield, fruit quality, and economic benefit was obtained [10]. However, there is still a shortage of water and nitrogen management methods for cotton based on multi-objective optimization such as WUE, NUE, yield, and income.

Aiming at comprehensive improvement of WUE, NUE, yield, and economic benefit of cotton, the effect of water and nitrogen regulation on cotton growth and production in northern Xinjiang was studied using the integrated technology of drip irrigation under mulch. The quantitative relationship between water and nitrogen input and WUE, NUE, yield, and economic benefit was established, and the appropriate water and nitrogen management strategy was sought. The results will provide a theoretical basis for effective water and fertilizer management in cotton fields under mulch drip irrigation in northern Xinjiang.

2. Materials and Methods

2.1. Experimental Site

The experimental area is located in Shihezi Irrigation District, Xinjiang, China (84°43′–86°35′ E, 43°21′–45°20′ N) and is a typical temperate inland arid area. The irrigated area is located in the center of the Economic Zone on the northern slope of Tianshan Mountains in Xinjiang and on the southern margin of Junggar Basin with a total area of 1326.15 km^2. Annual average temperature is 7.5–8.2 °C, annual precipitation is 180–270 mm, annual evaporation is 1723–2260 mm, annual sunshine duration is 2318–2770 h, and the annual frost-free period is 147–191 days. Soil physical properties of the 0–60 cm tillage layer in the experimental area are shown in Table 1, and soil fertility level of this layer is shown in Table 2.

Table 1. General situation of soil physical properties in experimental area.

Soil Depth (cm)	Soil Texture	Particle Mass Fraction (%)			Soil Bulk Density (g/cm^3)	Field Water Holding Capacity (%)	Saturated Water Content (%)
		Sand	Silt	Clay			
0–10	Sandy loam	55.24	40.64	4.12	1.34	27.04	44.07
10–20	Sandy loam	57.69	38.02	4.29	1.47	29.74	45.30
20–30	Sandy loam	57.60	37.76	4.64	1.47	28.78	45.67
30–40	Sandy loam	61.92	33.78	4.30	1.51	27.82	48.20
40–50	Sandy loam	70.46	24.93	4.61	1.57	30.60	49.30
50–60	Sandy loam	72.93	22.41	4.66	1.59	28.59	49.30

Table 2. General situation of soil fertility level in experimental area (0–60 cm depth).

Organic Matter (g/kg)	Total Nitrogen Content (%)	Total Phosphorus Content (%)	Alkaline Hydrolyzed Nitrogen (mg/kg)	Available Phosphorus (mg/kg)	Available Potassium (mg/kg)
18.70	0.87	0.23	67.53	33.29	186.12

2.2. Field Experiment Design

The field experiment was conducted in the cotton growing seasons of 2017 and 2018. Three irrigation levels were set—low (I_1), medium (I_2), and full (I_3) irrigation, accounting for 75%, 87.5%, and 100% of ET_c, respectively. The three nitrogen application levels were low (N_1, 210 kg/ha), medium (N_2, 280 kg/ha), and high (N_3, 350 kg/ha) nitrogen, accounting for 75%, 100%, and 125% of the local nitrogen application respectively. The nitrogen fertilizer applied was urea (nitrogen content 46.7%). The experiment adopted a completely randomized block design, with nine treatments and three replications per treatment making a total of 27 field experimental plots.

The cotton varieties selected in the experiment were "Chuangza 100" (CZ-100), and the cotton planting pattern was six rows of plants with three irrigation tubes mulched with one plastic film of 1.8 m (Figure 1). Each plot was 6 m long and 4.4 m wide, with a planting density of 480 plants per plot. Single-wing labyrinth drip irrigation tape was used for irrigation. The diameter of drip irrigation tape was 16 mm, the distance between drip emitters was 0.3 m, and average flow rate of drip emitters was 3.2 L/h. Water meters, ball valves, and fertilizer cans were installed at the beginning of each experimental plot to quantitatively control irrigation and fertilization. Cotton was sown on 22 April 2017 and 25 April 2018, respectively. At the same time, according to the corresponding level of nitrogen application, 30% of nitrogen (10% ^{15}N-urea + 20% conventional urea, nitrogen content of 46.7%.), 100 kg/ha of phosphorus (P_2O_5), and 100 kg/ha of potassium (K_2O) fertilizer were applied in the field as base fertilizer at one time. The remaining 70% of nitrogen fertilizer was applied in the field with water nine times in different growth stages of cotton. The ^{15}N-urea was purchased from Shanghai Research Institute of Chemical Industry, and its abundance was 5.16%.

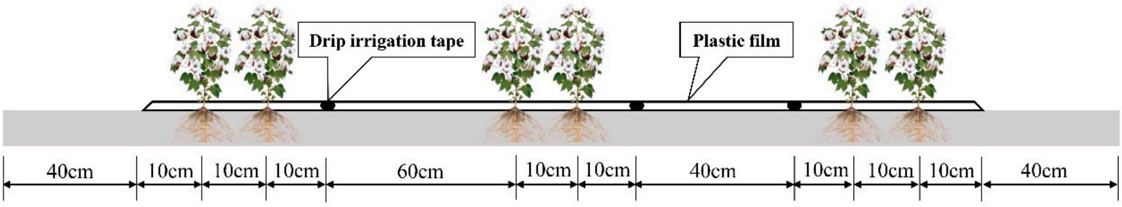

Figure 1. Planting pattern and drip irrigation system layout.

In the field experiment, cotton water demand was calculated by reference crop evapotranspiration and cotton crop coefficient method. The calculation formulas were as follows:

$$ET_c = K_c \times ET_0 \tag{1}$$

where, ET_c is water demand of crops in a certain period (mm), K_c is the crop coefficient corresponding to the growth period and ET_0 is the reference crop evapotranspiration for the corresponding period (mm). In this experiment, the K_c values of seedling, bud, boll, and boll opening stages of cotton were 0.35, 0.76, 1.18, and 0.6, respectively [11].

Reference crop evapotranspiration (ET_0) was calculated by Penman–Monteith formula recommended by FAO [12]:

$$ET_0 = \frac{0.408\Delta \times (R_n - G) + \gamma \times \frac{900}{T+273} \times V_2 \times (P_a - P_b)}{\Delta + \gamma \times (1 + 0.3V_2)} \tag{2}$$

where, R_n is ground net radiation evaporation equivalent (MJ/m^2/day), G is soil heat flux (MJ/m^2/day), γ is a thermometer constant (kPa/°C), T is average temperature (°C), V_2 is wind speed 2 m above the ground (m/s), P_a is saturated vapor pressure (kPa), P_b is the actual vapor pressure (kPa), and Δ is the slope of the temperature-saturated vapor pressure curve (kPa/°C). The parameters in the formula were provided by the Shihezi Meteorological Bureau.

The specific irrigation and nitrogen application settings in the field experiment are shown in Table 3.

2.3. Monitoring Indicators

2.3.1. LAI

At different growth stages, five cotton plants were randomly selected in each experimental plot to measure the length (L) and width (W) of each leaf with a tape measure. The calculation formula of cotton LAI follows [13]:

$$LAI = \lambda \sum \frac{LW}{A} \tag{3}$$

where, λ is the shape coefficient of cotton leaves (in this experiment, λ = 1.0 [14]), L is blade length (m), W is blade width (m), and A is area of land occupied by a single cotton plant (m^2).

2.3.2. Dry Matter Quantity of Cotton

At different growth stages, five cotton plants were randomly selected in each experimental plot, and the plants were separated indoors into roots, stems, leaves, buds, and bolls. The samples were placed in an oven at 105 °C for 30 min, then dried to constant weight at 75 °C, and the dry matter quantity of samples weighed and recorded [15]. Cotton dry matter per hectare = average dry matter of five cotton plants × planting density per hectare.

Table 3. Irrigation and nitrogen application table for field trials.

Irrigation Times	Irrigation Date	Growth Period	ET_0 (mm)	K_c	Irrigation Amount (mm)			Nitrogen Application Rate (kg/ha)		
					I_3	I_2	I_1	N_3	N_2	N_1
2017										
1	4.22	Sowing			60	53	45	105	84	63
2	5.15	Seedling	97	0.35	34	30	26	10.5	8.4	6.3
3	6.7	Seedling	86	0.35	30	26	23	10.5	8.4	6.3
4	6.12	Seedling	117	0.35	41	36	30	10.5	8.4	6.3
5	6.19	Bud stage	72	0.76	55	48	40	24.5	19.6	14.7
6	7.2	Bud stage	75	0.76	57	50	43	24.5	19.6	14.7
7	7.17	flowering and boll-setting period	49	1.18	58	51	44	52.5	42	31.5
8	7.31	flowering and boll-setting period	53	1.18	62	54	47	52.5	42	31.5
9	8.10	flowering and boll-setting period	41	1.18	48	41	36	52.5	42	31.5
10	8.30	Boll opening stage	55	0.6	33	29	25	7	5.6	4.2
Total					478	418	359	350	280	210
2018										
1	4.25	Sowing			60	53	45	105	84	63
2	5.14	Seedling	86	0.35	30	26	23	10.5	8.4	6.3
3	6.4	Seedling	91	0.35	32	28	24	10.5	8.4	6.3
4	6.10	Seedling	123	0.35	43	38	32	10.5	8.4	6.3
5	6.19	Bud stage	79	0.76	60	52	45	24.5	19.6	14.7
6	7.1	Bud stage	72	0.76	55	48	40	24.5	19.6	14.7
7	7.15	flowering and boll-setting period	49	1.18	58	50	44	52.5	42	31.5
8	7.31	flowering and boll-setting period	51	1.18	60	53	45	52.5	42	31.5
9	8.11	flowering and boll-setting period	42	1.18	50	44	38	52.5	42	31.5
10	8.31	Boll opening stage	53	0.6	32	28	24	7	5.6	4.2
Total					480	420	360	350	280	210

2.3.3. Boll Weight and Seed Cotton Yield

Boll weight: During the boll opening stage, 30, 40, and 30 cotton bolls were collected in the upper, middle, and lower parts of each experimental plot. After drying, each boll was weighed and average weight of 100 cotton bolls was taken as the single boll weight.

Yield: During the boll opening stage, the area of length × width = 1.5 m × 4.4 m was selected in each experimental plot, and the cotton plant number and boll number in each area were counted. Cotton yield per area = cotton plant number × boll number × single boll weight. This was converted to yield per hectare [16].

2.3.4. Cotton Fiber Quality

During the boll opening period, 20 g cotton samples were randomly picked in each experimental plot, and the cotton fiber micronaire value, fiber length, uniformity index, fracture specific strength, and elongation were determined by the Cotton Quality Inspection Center of the Ministry of Agriculture (Urumqi, Xinjiang, China). The cotton fiber detector HVI 1000M 700 was used for testing, and the cotton fiber calibrator HVICC was used for calibration (U.S. Department of Agriculture) [17,18].

2.3.5. WUE

$$WUE = Y/ET \tag{4}$$

In the formula, Y is seed cotton yield (kg/ha) and ET is actual water consumption of crops (mm) [3].

$$ET = P + I - \Delta W \tag{5}$$

In the formula, P is precipitation during growth period (mm), I is irrigation amount (mm), and ΔW is the change of soil water storage before sowing and after harvesting (mm) [19]. Before sowing and after harvesting cotton, three locations in each plot were selected to drill soil (0–200 cm) once every 10 cm. The soil moisture content was measured by drying method, and the soil water storage before sowing and after harvesting was calculated [20].

2.3.6. NUE

The ^{15}N isotope tracer method was used to calculate NUE [21] with the following formula:

$$\text{Nitrogen uptake by organs} = \text{Dry weight of organs} \times \text{Total nitrogen content in organs} \tag{6}$$

$$\text{Nitrogen uptake by crops} = \text{Nitrogen uptake of aboveground parts} + \text{Root nitrogen uptake} \tag{7}$$

$$^{15}\text{N atom percentage excess} = {}^{15}\text{N abundance of samples or } {}^{15}\text{N-urea} - {}^{15}\text{N natural abundance} \tag{8}$$

$$\text{Ndff} = {}^{15}\text{N atom percentage excess of organs}/{}^{15}\text{N atom percentage excess of } {}^{15}\text{N-urea} \tag{9}$$

$$^{15}\text{N-urea nitrogen uptake by organs} = \text{Nitrogen uptake by organs} \times \text{Ndff of organs} \tag{10}$$

$$^{15}\text{N-urea nitrogen uptake by crops} = {}^{15}\text{N-urea nitrogen of aboveground parts} + {}^{15}\text{N-urea nitrogen uptake of root} \tag{11}$$

$$\text{NUE} = {}^{15}\text{N-urea nitrogen uptake by crops}/{}^{15}\text{N-urea nitrogen application rate} \times 100\% \tag{12}$$

In the formulas, the total nitrogen content of the sample was determined by Kjeldahl method [22] and ^{15}N abundance was determined by stable isotope mass spectrometer MAT-253 (provided by Institute of Geography and Resources, Chinese Academy of Sciences, Beijing).

2.3.7. Nitrogen Partial Factor Productivity (N_{PFP})

$$N_{PFP} = Y/N_T \quad (13)$$

In the formula, Y is seed cotton yield (kg/ha) and N_T is the total amount of nitrogen applied (kg/ha) [20].

2.3.8. Economic Benefit

$$E = G - W - F - K \quad (14)$$

In the formula, E is economic benefit, G is gross profit, W is the cost of irrigation, F is the cost of fertilization, and K is the cost of machinery and materials (all in RMB/ha) [23].

2.4. Data Processing

The value of each indicator is the average of the data for 2017 and 2018, and the data for each year is the average of three replicates per process. The DPS data processing system (Manufacturer: Zhejiang University, Hangzhou, China) was used for variance analysis (Duncan's new repolarization method), and MATLAB 2017 (Manufacturer: The company of MathWorks, Natick, Massachusetts, USA) and Origin 2017 (Manufacturer: the company of OriginLab, Northampton, Massachusetts, USA) were used for multiple regression, extremum solution, and drawing graphics.

3. Results

3.1. LAI, Boll Weight, Dry Matter Quantity and Yield

Irrigation and nitrogen application significant affected LAI ($p < 0.01$), but water–nitrogen coupling had less effect on LAI ($p < 0.05$). When cotton was under the same irrigation level, LAI initially increased and then decreased with increased nitrogen level. At the same nitrogen application level, LAI increased with the increase of irrigation level. The LAI under full irrigation (I_3) was significantly higher than for medium (I_2) and low irrigation (I_1). The LAI under medium nitrogen (N_2) was significantly higher than for low (N_1) and high nitrogen (N_3). The LAI did not differ significantly among I_1N_2, I_2N_1 and I_2N_3 treatments. There was no significant difference in LAI between I_2N_2 and I_3N_3, and between I_2N_3 and I_3N_1 treatments (Table 4).

Table 4. Effects of water–nitrogen coupling on LAI, boll weight, dry matter quantity, and yield of cotton.

Irrigation Level	Nitrogen Level	LAI	Boll Weight (g)	Dry Matter Quantity (kg/ha)	Yield (kg/ha)
I_1	N_1	2.46 f	4.44 d	10,980 f	4757 h
	N_2	3.34 d	4.54 c	12,584 e	5235 f
	N_3	2.72 e	4.52 c	11,308 f	4979 g
I_2	N_1	3.42 d	4.63 bc	13,268 de	5607 e
	N_2	4.09 b	4.67 b	14,552 c	6164 b
	N_3	3.49 cd	4.66 b	14,105 cd	5954 c
I_3	N_1	3.63 c	4.65 b	13,770 cd	5795 d
	N_2	4.43 a	4.73 a	16,623 a	6333 a
	N_3	4.07 b	4.72 a	15,667 b	6276 a
Significance Test p Value					
I		0.0004 **	0.0003 **	0.0020 **	0.0001 **
N		0.0020 **	0.0117 *	0.0237 *	0.0019 **
I × N		0.0471 *	0.9994 ^{ns}	0.0726 ^{ns}	0.0013 **

Note: The values of each monitoring indicator in the table are average data for 2017 and 2018. According to Duncan's new repolarization method, * means significant difference ($p < 0.05$), ** means extremely significant difference ($p < 0.01$), and ns means no significant difference ($p > 0.05$); different lower-case letters in the same column represent significant differences ($p < 0.05$). Same below.

The effect of irrigation on boll weight and dry matter quantity was greater than that of nitrogen ($p < 0.01$). There was no significant effect of water–nitrogen coupling on boll weight and dry matter quantity ($p > 0.05$). At the same nitrogen level, boll weight and dry matter quantity increased with the increase of irrigation level; at the same irrigation level, boll weight and dry matter quantity initially increased and then decreased with increased nitrogen level. The boll weight and dry matter quantity were significantly higher for I_3 than for I_2 and I_1, and significantly higher for N_2 than for N_1 and N_3. The dry matter quantity did not significantly differ among the I_2N_2, I_2N_3, and I_3N_1, between I_2N_1 and I_1N_2, or between I_1N_1 and I_1N_3 treatments (Table 4).

Irrigation, nitrogen application and water–nitrogen coupling all had extremely significant effects on yield ($p < 0.01$). At the same irrigation level, yield initially increased and then decreased with increased nitrogen level; at the same nitrogen level, yield increased with the increase in irrigation level. The yield under I_3 was significantly higher than for I_1 and I_2, and it was significantly higher for N_2 compared with N_1 and N_3. There was no significant difference in yield between I_3N_2 and I_3N_3 treatments (Table 4).

3.2. Cotton Fiber Quality

Irrigation, nitrogen application and water–nitrogen coupling had extremely significant effects on micronaire value ($p < 0.01$). For the same irrigation level, micronaire value increased with the increase of nitrogen level. For the same nitrogen level, micronaire value decreased with the increase of irrigation level. The micronaire value was significantly higher for I_1 than for I_2 and I_3, and significantly higher for N_3 than for N_1 and N_2 (Table 5).

Table 5. Effect of water–nitrogen coupling on cotton fiber quality.

Irrigation Level	Nitrogen Level	Micronaire Value	Fiber Length (mm)	Uniformity Index (%)	Fracture Specific Strength (cN/tex)	Elongation (%)
I_1	N_1	4.45 e	27.42 g	80.40 d	26.90 d	6.25 f
	N_2	4.99 b	29.37 cd	80.77 cd	25.84 f	6.40 e
	N_3	5.42 a	27.35 g	82.06 a	29.41 a	7.01 b
I_2	N_1	4.24 g	28.41 f	81.12b cd	26.86 d	6.24 f
	N_2	4.63 d	29.28 de	81.89 ab	27.72 b	6.17 g
	N_3	4.89 c	29.06 e	81.70 ab	26.57 e	6.71 d
I_3	N_1	3.42 i	29.58 c	81.45 abc	27.77 b	7.33 a
	N_2	4.07 h	30.63 a	80.78 cd	27.28c	6.82 c
	N_3	4.35 f	30.26 b	81.39 abc	26.06 f	6.39 e
Significance Test p Value						
I		0.0006 **	0.0170 ^{ns}	0.5772 ^{ns}	0.9490 ^{ns}	0.5107 ^{ns}
N		0.0011 **	0.0788 ^{ns}	0.3410 ^{ns}	0.9468 ^{ns}	0.8217 ^{ns}
I × N		0.0001 **	0.0001 **	0.0040 **	0.0001 **	0.0001 **

Irrigation had a significant effect on fiber length ($p < 0.05$), but nitrogen application did not ($p > 0.05$). Water–nitrogen coupling had a very significant effect on fiber length ($p < 0.01$). For the same irrigation level, fiber length initially increased, and then decreased with increased nitrogen level. For the same nitrogen level, fiber length increased with the increase of irrigation level. The fiber length was significantly larger for I_3 than for I_1 and I_2. There were no significant differences in fiber length between I_1N_2 and I_3N_1, between I_2N_2 and I_2N_3, and between I_1N_1 and I_1N_3 treatments (Table 5).

Irrigation and nitrogen application had no significant effect on uniformity index, fracture specific strength, and elongation ($p > 0.05$), while there was no significant change in uniformity index, fracture specific strength, and elongation between different irrigation levels and different nitrogen application levels. Water–nitrogen coupling had very significant effects on uniformity index, fracture specific strength, and elongation ($p < 0.01$). Uniformity index and fracture specific strength were both greatest for the I_1N_3 treatment with 82.06% and 29.41 cN/TEX, respectively, and elongation was greatest for the I_3N_1 treatment at 7.33% (Table 5).

3.3. WUE, NUE, and N_{PFP}

Irrigation had a significant effect on WUE ($p < 0.05$), and nitrogen application and water–nitrogen coupling had a very significant effect on WUE ($p < 0.01$). For the same irrigation level, WUE initially increased and then decreased with increasing nitrogen level. For the same nitrogen level, WUE initially increased and then decreased with increasing irrigation level. The WUE was significantly higher for I_2 than for I_1 and I_3, and significantly higher for N_2 than for N_1 and N_3. There was no significant difference in WUE between I_1N_2 and I_2N_3, and between I_1N_3 and I_2N_1 treatments (Table 6).

Table 6. Effect of water–nitrogen coupling on water use efficiency (WUE), nitrogen use efficiency (NUE), and N_{PFP}.

Irrigation Level	Nitrogen Level	WUE (kg/ha·mm)	NUE (%)	N_{PFP} (kg/kg)
I_1	N_1	1.48 e	25.79 de	22.64 b
	N_2	1.70 b	28.88 c	18.68 c
	N_3	1.57 d	26.25 d	14.21 e
I_2	N_1	1.58 d	36.48 a	26.68 a
	N_2	1.75 a	36.62 a	22.00 b
	N_3	1.70 b	35.56 b	17.00 d
I_3	N_1	1.40 f	25.36 e	27.57 a
	N_2	1.64 c	28.49 c	22.60 b
	N_3	1.58 d	25.56 de	17.92 cd
Significance Test *p* Value				
I		0.0116 *	0.0003 **	0.0004 **
N		0.0025 **	0.0586 ns	0.0001 **
I × N		0.0052 **	0.0001 **	0.4057 ns

Irrigation and water–nitrogen coupling significantly affected NUE ($p < 0.01$), but nitrogen application did not ($p > 0.05$). For the same irrigation level, NUE initially increased and then decreased with increasing nitrogen level. For the same nitrogen level, NUE initially increased and then decreased with increasing irrigation level. The NUE was significantly higher for I_2 than for I_1 and I_3. There was no significant difference in NUE between I_2N_1 and I_2N_2, between I_1N_2 and I_3N_2, and among I_1N_1, I_1N_3, I_3N_1, and I_3N_3 treatments (Table 6).

Irrigation and nitrogen application had significant effects on N_{PFP} ($p < 0.01$), but water–nitrogen coupling did not ($p > 0.05$). For the same irrigation level, N_{PFP} decreased with increasing nitrogen level. For the same nitrogen level, N_{PFP} increased with the increase in irrigation level. The N_{PFP} was significantly greater for I_3 than for I_1 and I_2 and was significantly higher for N_1 than for N_2 and N_3. There was no significant difference in N_{PFP} between I_2N_1 and I_3N_1, between I_1N_2 and I_3N_3, between I_3N_3 and I_2N_3, and among I_1N_1, I_2N_2, and I_3N_1 treatments (Table 6).

3.4. Economic Benefits

In this study, the gross profit of I_1N_1 was the lowest with 38,059 RMB/ha, and I_3N_2 treatment was highest with 50,661 RMB/ha. Compared with the minimum gross profit, the maximum gross profit increased by 33.11%. The economic benefit was lowest for the I_1N_1 treatment, with only 3059 RMB/ha, and that for the I_3N_3 treatment was highest, with 14,704 RMB/ha. Compared with the lowest economic benefit, the highest economic benefit increased by 380.68%. The results showed that water and nitrogen inputs were closely related to the gross profit and economic benefit of the cotton field. When the inputs of water and nitrogen were inappropriate, gross profit and economic benefit of the cotton field were greatly reduced (Table 7).

Table 7. Effect of water–nitrogen coupling on economic benefits.

Irrigation Level	Nitrogen Level	Irrigation Cost (RMB/ha)	Fertilizer Cost (RMB/ha)	Gross Profit (RMB/ha)	Economic Benefit (RMB/ha)
I_1	N_1	1440	2925	38,059	3059
	N_2	1440	3600	41,877	5877
	N_3	1440	4275	39,828	4328
I_2	N_1	1680	2925	44,855	9855
	N_2	1680	3600	49,312	13,312
	N_3	1680	4275	47,629	12,129
I_3	N_1	1920	2925	46,357	11,357
	N_2	1920	3600	50,661	14,661
	N_3	1920	4275	50,204	14,704

For the same irrigation level, the economic benefit initially increased and then decreased with increasing nitrogen level. Excessive nitrogen application did not lead to a continuous increase in economic benefit. For the same nitrogen level, the economic benefit obviously increased with increasing irrigation level. In this experiment, irrigation accounted for a very small proportion of the management and maintenance costs of cotton fields. When the irrigation level was reduced, although irrigation cost could be reduced, the economic benefits of cotton fields were also greatly reduced. Therefore, in production practice, cotton farmers are more willing to increase the amount of irrigation to obtain high economic benefits.

3.5. Multi-Objective Optimization (WUE, NUE, Yield, and Economic Benefits)

In actual production, cotton farmers are most concerned with the yield and economic benefits of cotton fields, but researchers pay more attention to WUE and NUE, because they are important indicators reflecting the local cotton planting technology level. Therefore, in this study, irrigation and nitrogen application were selected as independent variables, and WUE, NUE, yield, and economic benefits were dependent variables. Four binary quadratic regression equations were established (Table 8). The R^2 of each regression equation exceeded 0.95 with $p < 0.01$. Thus, the equations had good reliability and described the mathematical relationship between dependent and independent variables.

Table 8. Regression equations between water and nitrogen inputs and WUE, NUE, yield, and economic benefits.

η	Regression Equation	R^2	p
WUE/η_1	$\eta_1 = -3.17905 \times 10^{-5} I^2 + 5.43374 \times 10^{-6} IN - 2.9393 \times 10^{-5} N^2 + 0.02478I + 0.01512N - 5.59765$	0.966	< 0.01
NUE/η_2	$\eta_2 = -0.00266I^2 - 15.1982 \times 10^{-6} IN - 4.41978 \times 10^{-4} N^2 + 2.22667I + 0.25326N - 463.62331$	0.973	< 0.01
Yield/η_3	$\eta_3 = -0.09722I^2 + 0.01552IN - 0.0713N^2 + 86.75318I + 35.9177N - 19430.08497$	0.996	< 0.01
Economic Benefits/η_4	$\eta_4 = -0.77773I^2 + 0.12418IN - 0.41732N^2 + 694.02543I + 198.05588N - 178440.6798$	0.996	< 0.01

When irrigation amount was 415.80 mm and nitrogen application was 295.71 kg/ha, WUE reached its maximum of 1.78 kg/ha·mm. When irrigation was 418.27 mm and nitrogen application was 278.57 kg/ha, NUE reached a maximum of 37.65%. When irrigation was 470.12 mm and nitrogen application was 304.29 kg/ha, yield reached its maximum of 6416.42 kg/ha. When irrigation was 470.12 mm and nitrogen application was 307.14 kg/ha, the maximum economic benefit was 15,338.55 RMB/ha. When WUE and NUE reached their maxima, the amounts of irrigation and nitrogen application were similar. When the yield and economic benefits reached their maxima, the amounts of irrigation and nitrogen application were similar. However, under any single combination of irrigation and nitrogen application, WUE, NUE, yield, and economic benefits cannot all reach their maxima (Table 9).

Table 9. Maximum value solution of WUE, NUE, yield, and economic benefits.

η	η_{max}	I (mm)	N
WUE/η_1	1.78	415.80	295.71
NUE/η_2	37.65	418.27	278.57
Yield/η_3	6416.42	470.12	304.29
Economic Benefits/η_4	15,338.55	470.12	307.14

The WUE, NUE, yield, and economic benefits were taken as optimization objectives, and three optimization gradients of 85%η_{max}, 90%η_{max}, and 95%η_{max} were set in advance. The purpose was to find the appropriate irrigation and nitrogen application intervals such that the above four optimization objectives could simultaneously reach 85%, 90%, and 95% of their respective maxima.

Since the unit dimensions of WUE, NUE, yield, and economic benefits are not uniform, the η value of each optimization objective was normalized to be within zero and one. In Table 8, the binary quadratic regression equations of the four optimization objectives correspond to four three-dimensional curved surfaces respectively, and four contour maps were obtained by projecting the four curved surfaces into two-dimensional planes using spatial analysis (Figure 2). The area surrounded by three white lines in each map represents the corresponding irrigation and nitrogen application interval for which each optimization objective reached 85%, 90%, and 95% of its maximum value respectively. Preliminary results showed that when each optimization objective simultaneously reached 85% and more than 90% of its maximum value, there was an overlapping area between irrigation and nitrogen application. When each optimization objective simultaneously exceeded 95% of its maximum, it was not yet possible to determine whether there was an overlap between irrigation and nitrogen application. (Figure 2).

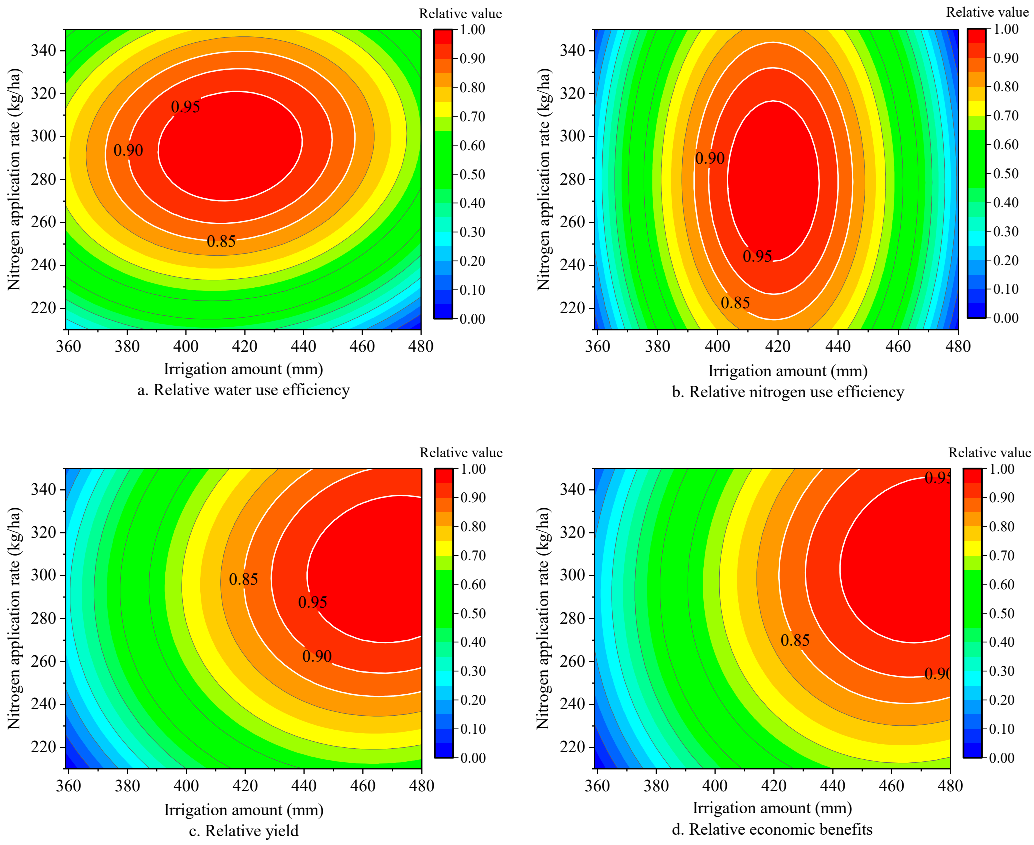

Figure 2. Relationships between water and nitrogen inputs and the relative value of each optimization index. (**a**) Relative water use efficiency; (**b**) Relative nitrogen use efficiency; (**c**) Relative yield; (**d**) Relative economic benefits.

In order to obtain an accurate irrigation and nitrogen application interval, contour lines representing the maximum values of 85%, 90%, and 95% of each optimization objective were extracted (Figure 3). The gray-filled area in the figure is the irrigation and nitrogen application interval that met the preset optimization objective. When the irrigation interval was 421.66–444.83 mm and the nitrogen application interval was 257.92–336.06 kg/ha, the WUE, NUE, yield, and economic benefits simultaneously exceeded 85% of their maxima (Figure 3a). When the irrigation interval was 430.71–440.12 mm and nitrogen application interval was 270.95–318.45 kg/ha, the WUE, NUE, yield, and economic benefits simultaneously exceeded 90% of their maxima (Figure 3b). There was no irrigation and nitrogen application interval for which WUE, NUE, yield, and economic benefits simultaneously exceeded 95% of their maxima (Figure 3c). Therefore, this study showed that when irrigation interval was 430.71–440.12 mm and nitrogen application interval was 270.95–318.45 kg/ha, which was an efficient and reasonable water and nitrogen management mode in the study area. For these intervals, the WUE, NUE, yield, and economic benefits simultaneously exceeded 90% of their maxima.

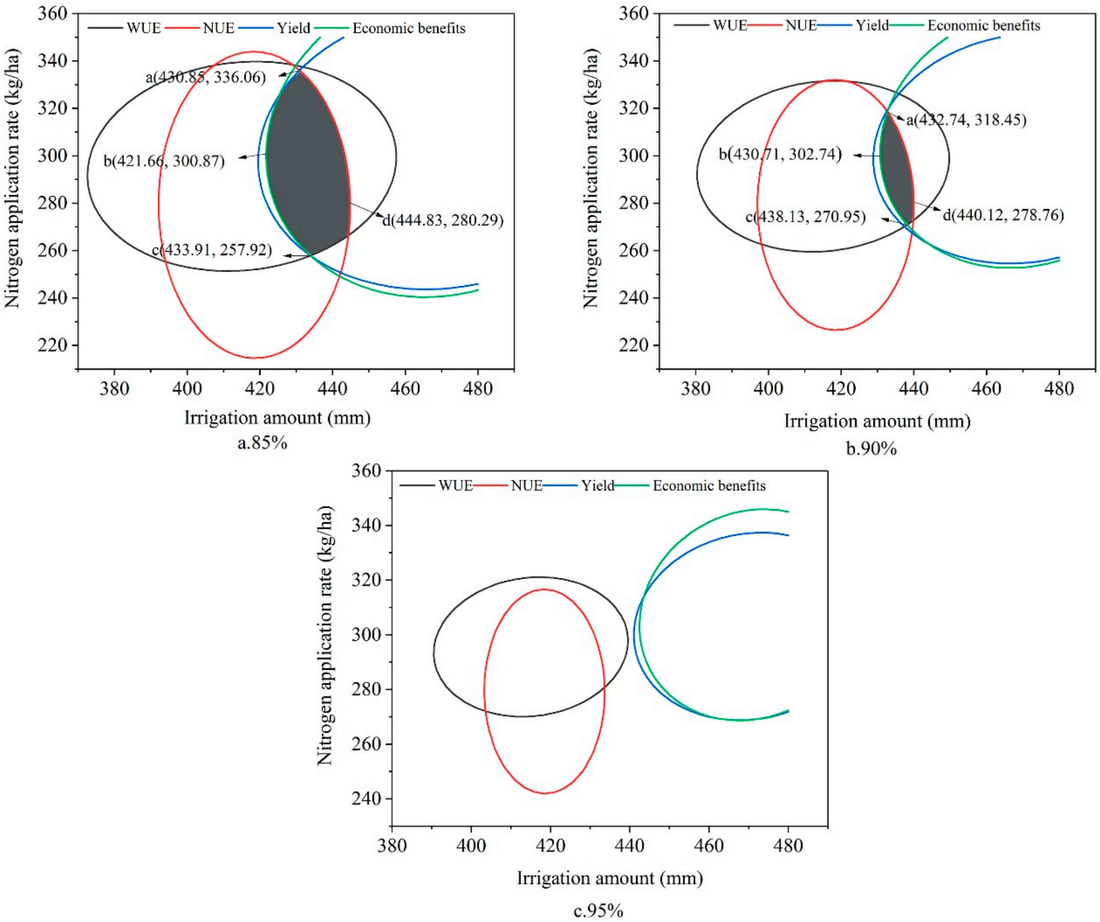

Figure 3. Finding the optimum input interval of water and nitrogen. (**a**) 85% Irrigating amount (mm); (**b**) 90% Irrigating amount (mm); (**c**) 95% Irrigating amount (mm).

4. Discussion

4.1. Effects of Irrigation and Nitrogen Application on Cotton Growth

The LAI is an important indicator reflecting the growth status of a plant population, and its size is directly related to the final yield. With an increased amount of irrigation, the LAI of crops showed an increasing trend [24]. Jia et al. showed that the peak LAI of cotton was within 4.3–4.6 m^2/m^2 [25]. Under drip irrigation, the maximum LAI of cotton could reach 4.7 m^2/m^2 [26]. Using a digital image method to estimate cotton LAI showed its maximum value to be 5 m^2/m^2 [27]. The results of this experiment are basically consistent with previous studies. Different levels of irrigation and nitrogen application had obvious effects on LAI during the whole growth period of cotton. The LAI increased significantly with the increase in irrigation level, but excessive nitrogen application did not benefit growth of cotton leaves, and LAI decreased significantly. The LAI was greatest for the I_3N_2 treatment, with 4.43 m^2/m^2. The results showed that appropriate application of nitrogen could improve photosynthetic capacity of leaves, prolong the time of efficient use of light energy, improve photosynthetic performance of cotton population, and ensure that more photosynthates were formed in the later growth stage of cotton [5].

Previous studies have shown that the boll weight of cotton differs depending on location [3], with boll weight in southern Xinjiang reaching 4.61 g and that in eastern China reaching 5.1 g [28]. In our experimental area of the north of Xinjiang, the boll weight of cotton was within 4.44–4.74 g. Irrigation had a very significant effect on cotton boll weight, but nitrogen application had little effect. Under I_3 irrigation, cotton boll weight was the greatest. There was no significant difference in boll weight among the experimental treatments. There are two reasons for this situation. On the one hand, compared with southern Xinjiang and Eastern China, the frost-free period in northern Xinjiang is shorter. From the peak boll stage to the early boll opening stage, the temperature decreased, and boll weight was negatively affected. On the other hand, the characteristics of the cotton varieties differ among studies, and the gene expression of boll weight varies greatly among varieties [29]. Therefore, the boll weight of cotton is affected by water, nitrogen, region, and genotype.

4.2. Effects of Irrigation and Nitrogen Application on Cotton Yield and Fiber Quality

There is a close relationship between dry matter quantity and yield, and irrigation and nitrogen application have a significant regulatory effect on this [30,31]. Wu et al. showed that cotton dry matter quantity and yield showed an obvious increasing trend with the increase of water and nitrogen input, but once water and nitrogen input exceeded a certain threshold, a significant yield reduction resulted [16]. Similar conclusions were drawn in this study. Irrigation had a significant effect on dry matter quantity and yield. The I_3 irrigation provided high quantity conditions for cotton growth, with the highest dry matter quantity and yield. Reducing the irrigation level significantly reduced dry matter quantity and yield. With the increase of nitrogen application, the dry matter quantity and yield also increased significantly but, when nitrogen application reached the N_3 level, the dry matter quantity and yield began to decline, indicating that there was an upper limit to demand for nitrogen in cotton growth. Only reasonable water and nitrogen input resulted in high yield.

Micronaire value is a comprehensive index reflecting the fineness and maturity of cotton fibers and is one of the important internal quality indicators of cotton fibers. The results of this experiment are consistent with previous findings [5,32]. The results showed that the cotton fiber quality was best under I_3 irrigation followed by I_2, and worst was for I_1. Water, nitrogen, and water–nitrogen coupling were the main factors affecting the micronaire value of cotton. Irrigation and nitrogen application had no significant effect on cotton fiber length, uniformity index, fracture specific strength, and elongation, but the water–nitrogen coupling had a very significant impact on the above indicators. Too much or too little water and nitrogen use reduced cotton carbon and nitrogen metabolism processes, leading to premature aging or late maturity of cotton, and to the decline of cotton fiber quality. Therefore, there is an appropriate amount of water and nitrogen to optimize fiber quality.

4.3. Effects of Irrigation and Nitrogen Application on WUE, NUE, and Economic Benefit of Cotton

Appropriate water and nitrogen input improved WUE of cotton, and WUE decreased when nitrogen application decreased [33]. Other studies showed no effect on WUE by irrigation [34]. The results of our experiment were slightly different—irrigation, nitrogen application, and water–nitrogen coupling significantly affected WUE. The WUE of cotton for I_2 irrigation was significantly higher than for I_1 and I_3. The WUE of cotton was higher for N_2 than for levels N_1 and N_3. Too little or too much water and nitrogen input was not conducive to improving WUE. In this experiment, NUE and WUE of cotton both showed similar changes. Irrigation and water–nitrogen coupling had a significant effect on NUE, but nitrogen application did not. At the same nitrogen level, NUE initially increased and then decreased with increasing irrigation level, and I_2 irrigation was the most beneficial to the effect of nitrogen fertilizer, consistent with the conclusion of Tao et al. [35]. Irrigation and nitrogen application had significant effects on cotton N_{PFP}, but water–nitrogen coupling did not. The N_{PFP} for I_3 irrigation was significantly greater than for I_1 and I_2. At the same irrigation level, N_{PFP} decreased significantly with increasing nitrogen level. Although N_{PFP} for N_1 level was the highest for the same irrigation level, WUE and NUE did not meet production requirements. Use of N_2 and N_3 levels were most beneficial to improving WUE and NUE, consistent with previous results [4].

The results showed that water and nitrogen inputs represented a small proportion of the total investment cost of the cotton field. Excessive nitrogen application did not increase economic benefits, but reducing irrigation level led to significant economic losses, consistent with conclusions of Wang et al. [7]. The economic benefit of I_3 irrigation was 1.93–4.81 times that of I_1. Therefore, in areas with abundant water resources, full irrigation should be advocated according to crop type. However, for arid and water-deficient areas, it is necessary to determine water and nitrogen management strategies that balance economic benefits with water and fertilizer saving.

5. Conclusions

Based on two consecutive years of cotton field experiments, combined with multiple regression and spatial analysis, the quantitative relationship between water and nitrogen input and WUE, NUE, yield, and economic benefits of cotton was established. The conclusions were as follows: The efficient and reasonable water and nitrogen management model in the study area was 430.71–440.12 mm for irrigation and 270.95–318.45 kg/ha for nitrogen application. At these levels, cotton WUE, NUE, yield, and economic benefits could simultaneously exceed 90% of their maxima. These results provide a scientific basis for the effective integrated management of water and fertilizer in cotton fields under mulch drip irrigation in northern Xinjiang.

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