

## Article

# Comparison of Efficiency-Enhanced Management and Conventional Management of Irrigation and Nitrogen Fertilization in Cotton Fields of Northwestern China

Ping Wang<sup>1</sup>, Zhenyong Zhao<sup>1,2</sup>, Lei Wang<sup>1,2</sup>  and Changyan Tian<sup>1,2,\*</sup>

<sup>1</sup> State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China; wangping@ms.xjb.ac.cn (P.W.); zhaozy@ms.xjb.ac.cn (Z.Z.); egiwang@ms.xjb.ac.cn (L.W.)

<sup>2</sup> University of Chinese Academy of Sciences, Beijing 100049, China

\* Correspondence: tianchy@ms.xjb.ac.cn; Tel.: +86-991-7823189

**Abstract:** Excessive application of nitrogen fertilizers and improper methods of irrigation under conventional management are common problems in the cotton fields of northwestern China. Efficiency-enhanced management, based on the water and nitrogen dynamics and crop requirements, has been used as a valuable strategy in different crops. The present study aimed to compare efficiency-enhanced management and conventional management of irrigation and nitrogen fertilization in the cotton fields at the Junggar Basin (Shihezi) and Tarim Basin (Cele) of northwestern China. Compared with conventional management, efficiency-enhanced management reduced the amount of N fertilizer by 41% in Cele and 44% in Shihezi, and the irrigation quantity by 35% in Cele and 24% in Shihezi. However, the cotton yield under efficiency-enhanced management was similar to that found under conventional management at both the experimental sites. The efficiency-enhanced management increased the water-use efficiency (WUE) and reduced the residual soil mineralizable N ( $N_{\min}$ ) and apparent N losses. This study indicated that efficiency-enhanced management can significantly enhance the utilization efficiency of irrigation water and N fertilizers for cotton production in the fields of northwestern China.

**Keywords:** cotton; efficiency-enhanced management; nitrogen; irrigation; nitrogen balance; WUE



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## 1. Introduction

Xinjiang is one of the largest and high-yielding areas of cotton in China. The shortage of water due to the region's arid nature and climate change have become increasingly serious [1]. A large amount of arable land has been abandoned due to lack of water. Currently, increased water input and nutrient input are the two major approaches used to obtain higher yield. Drip irrigation is the primary irrigation system used to combat the water crisis, while flood irrigation is still prevalent in farmers' small-scale cotton fields in southern Xinjiang. However, extensive irrigation, especially flood irrigation, decreases water-use efficiency (WUE). Another major approach used in this area to promote cotton production is nitrogen (N) fertilization. The recommended N fertilizer rate in Xinjiang ( $240 \text{ kg ha}^{-1}$ ) [2] is double the average used in the USA ( $105 \text{ kg N ha}^{-1}$ ) [3]. The excessive use of N fertilizers reduces the N recovery [4,5] without any change in yield [6,7]. Moreover, excessive urea use and heavy irrigation by cotton farmers can easily lead to nitrate leaching losses [8,9]. Therefore, there is an urgent need to develop an efficiency-enhanced production strategy, including efficiency-enhanced irrigation and efficiency-enhanced N fertilization, for the high-yield cotton system in Xinjiang.

Several studies have analyzed the effects of different N fertilization methods on factors, such as crop N uptake [10–12], yield [13,14], crop N status [15–17], and fertilizer effect models [18–20]. Researchers have also evaluated the effects of reasonable irrigation

measures, including reasonable irrigation index [21], reasonable irrigation schedules and methods [22,23], and coupling water and fertilizer [7,24] on cotton. These earlier findings provided a scientific basis for water and N management to promote cotton production in Xinjiang. However, no research has focused on water and N dynamics in the soil-plant system during the cotton-growing season. An understanding of the water and N status will further modify the management measures and provide an ideal situation.

The methods-based approach on soil nitrate-N tests have been used as a valuable tool for determining proper N fertilizer rates for different crops [25–27]. The previous researchers hypothesized that the efficiency of N fertilization could be enhanced by synchronizing fertilizer application with the plant requirement. Therefore, the synchronization of soil N supply (mineralizable N in root layer), N fertilizer application rates, and crop's N demand should improve N-use efficiency and reduce fertilizer N losses.

Thus, the present study compared efficiency-enhanced management and conventional management of irrigation and N fertilization in the cotton fields of northwestern China. Under efficiency-enhanced management, water and N fertilizers were applied in the Xinjiang cotton fields by assessing the soil water and N dynamics in the cotton root layer. The study analyzed and compared the effects of efficiency-enhanced water and nitrogen management strategy on cotton dry matter and yield, water-use efficiency (WUE), and N balance with the traditional management strategy. In the efficiency-enhanced N management strategy, cotton N demand (dependent on cotton target yield) and soil available N content (soil  $N_{\min}$  test) before irrigation were tested to synchronize soil N supply ( $N_{\min}$  in root layer), fertilizer N application, and cotton N demand. Meanwhile, soil moisture before irrigation was monitored, and the plant-available soil water (PASW) was maintained between 45% and 90% in the efficiency-enhanced irrigation strategy.

## 2. Materials and Methods

### 2.1. Site Description

The field experiments were conducted in the high-yielding cotton belt of southern and northern Xinjiang. One field experiment was conducted in Cele County (80°13' E, 35°17' N), located at the south edge of the Tarim Basin. During the growing seasons, the mean maximum and mean minimum temperatures were 34 °C and 14 °C, respectively. The relative humidity ranged from 18% to 68%, and the total amount of precipitation was 55.3 mm. The second field experiment was conducted in Shihezi County (86°02' E, 44°18' N), located at the south edge of the Junggar Basin. During the growing seasons, the mean maximum and mean minimum temperatures were 35 °C and 17 °C, respectively. The relative humidity ranged from 17% to 77%, and the total amount of precipitation was 77.1 mm. The physical and chemical properties of the soils (0–30 cm) of the two experimental sites before sowing are shown in Table 1.

**Table 1.** Physical and chemical properties of the 0–30 cm soil layer of the experimental sites in Xinjiang.

Characteristics	Cele	Shihezi
Soil texture	Fine Sand	Sandy Loam
Bulk density ( $\text{g cm}^{-3}$ )	1.38	1.32
pH (1:5)	8.10	7.94
Organic matter (O.M, $\text{g kg}^{-1}$ )	3.07	10.81
Total nitrogen (N, $\text{g kg}^{-1}$ )	0.36	0.78
$N_{\min}$ ( $\text{NO}_3^- - \text{N} + \text{NH}_4^+ - \text{N}$ , $\text{mg kg}^{-1}$ )	9.29	22.40
Available phosphorus (Olsen-P, $\text{mg kg}^{-1}$ )	25.21	30.06
Available potassium (K, $\text{mg kg}^{-1}$ )	153.10	188.57

### 2.2. Experimental Design

The cotton (*Gossypium hirsutum*) cultivars Xinluzao12 and Xinluzao45 were used for the experiments in Cele and Shihezi, respectively. The cotton seeds were sown on 12 April in Cele and 21 April in Shihezi at a row spacing of 40 cm and a pot distance of 12.5 cm.

Approximately 273,000 plants per hectare were maintained in Cele and 200,000 plants per hectare in Shihezi.

Irrigation and N fertilization were the two treatment factors of this experiment. Two methods of irrigation were employed: conventional irrigation and efficiency-enhanced irrigation. Under the conventional irrigation, flood irrigation was completed five times during the growth period, with 660 mm of (cumulative) irrigation water in Cele, while drip irrigation was done seven times during the growth period, with 525 mm (cumulative) of irrigation water in Shihezi. These methods represented the common irrigation practice in the areas of the experimental county. Under the efficiency-enhanced irrigation, the timing and quantity of irrigation were determined after monitoring the soil water status in the root layer using the time-domain reflectometry (TDR) probes. The PASW was maintained between 45% and 90% in both sites. Meanwhile, three N fertilization treatments were employed: None-N fertilization (NonN), conventional fertilization (ConN), and efficiency-enhanced N fertilization (EEN). Under None-N treatment used as a control, no N fertilizer was applied during the entire growing season. Under ConN, 123 kg ha<sup>-1</sup> N (urea) was applied as base fertilizer (incorporated after broadcasting), and 309 kg ha<sup>-1</sup> N (urea) was used as topdressing (irrigation after broadcasted) at budding, early flowering, and peak flowering stages separately in Cele. This method represented the farmer's practice in the areas of the experimental site. In the Shihezi site, 345 kg ha<sup>-1</sup> of fertilizer was applied in total; N fertilizer (urea) was split-applied together with irrigation water via the surface drip system seven times (34.5, 34.5, 34.5, 69, 69, 69, and 34.5 kg N ha<sup>-1</sup>) during the growing season. Under efficiency-enhanced N fertilization, N fertilization was determined based on the plant N demand at different growth stages. Before each irrigation, soil N<sub>min</sub> was analyzed. Next, the rate of N fertilizer was determined based on the N<sub>min</sub> target value and the measured N<sub>min</sub> value. The steps followed in efficiency-enhanced N fertilization were as follows: the targets yield was determined based on the average yield of the test site over the past five years. In this study, both the experiment sites' target lint yield was 2250 kg ha<sup>-1</sup>; next, the N demand of cotton at different growth stages under the target yield was estimated as reported earlier [28]; the soil N<sub>min</sub> target value of the growth stage was determined by multiplying the N demand of cotton at a specific growth stage with the factor 1.15 as follows:

$$\text{Soil } N_{\min} \text{ target value (kg N ha}^{-1}\text{)} = \text{N demand (kg N ha}^{-1}\text{)} \times 1.15 \quad (1)$$

Finally, the rate of N fertilizer at a particular stage of growth was determined by subtracting the measured soil N<sub>min</sub> at the beginning of that growth stage from the N<sub>min</sub> target value as follows:

$$\text{N fertilizer rate (kg N ha}^{-1}\text{)} = \text{Soil } N_{\min} \text{ target value of the stage (kg N ha}^{-1}\text{)} - N_{\min} \text{ at the beginning of that growth stage (kg N ha}^{-1}\text{)} \quad (2)$$

The experiment was conducted in a randomized complete block design with three replicates; the area of each replicate plot was 8 × 8 m. The details on N fertilization and irrigation amount were shown in Tables 2 and 3. All plots were fertilized with 65.5 kg P ha<sup>-1</sup> (triple superphosphate) and 75 kg K ha<sup>-1</sup> (potassium sulfate) as a base fertilizer before sowing.

**Table 2.** Irrigation amount (mm) under different irrigation managements of two experimental sites.

Treatments	Basal	Topdressing							Total
		1st	2nd	3rd	4th	5th	6th	7th	
Cele									
ConI	0	135	135	0	135	0	135	120	660
EEl	0	71	55	68	68	58	52	55	427 ( $\pm 31$ )
Shihezi									
ConI	0	75	75	75	75	75	75	75	525
EEl	0	65	52	64	67	50	62	39	399 ( $\pm 26$ )

“ConI” and “EEl” represent conventional irrigation and efficiency-enhanced irrigation, respectively.

**Table 3.** Nitrogen rates ( $\text{kg ha}^{-1}$ ) under different nitrogen fertilization managements of two experimental sites.

Treatments	Basal	Topdressing							Total
		1st	2nd	3rd	4th	5th	6th	7th	
Cele									
ConI	NonN	0	0	0	0	0	0	0	0
	ConN	123	0	69	0	135	0	105	0
	EEN	30	0	36	0	57	0	103	55
EEl	NonN	0	0	0	0	0	0	0	0
	ConN	123	0	69	0	135	0	105	0
	EEN	30	0	36	50	87	0	53	0
Shihezi									
ConI	NonN	0	0	0	0	0	0	0	0
	ConN	0	34.5	34.5	34.5	69	69	69	34.5
	EEN	0	0	26	35	56	43	40	17
EEl	NonN	0	0	0	0	0	0	0	0
	ConN	0	34.5	34.5	34.5	69	69	69	34.5
	EEN	0	0	33	29	38	34	35	22

“NonN”, “ConN”, and “EEN” represent none nitrogen (N) fertilization, conventional N fertilization, and efficiency-enhanced N fertilization, respectively. “ConI” and “EEl” represent conventional irrigation and efficiency-enhanced irrigation, respectively.

### 2.3. Measurement of Plant and Soil Parameters

#### 2.3.1. Plant Dry Matter Accumulation and Nitrogen Content

Sampling was initiated approximately 30 days after plant emergence. The entire plant was sampled periodically (every 14 days) throughout the growing season. Ten plants were sampled per plot at a time. A border of 140 cm was allowed for each sampling area in the front, back, and sides. Harvested plants were immediately separated into leaves, stems, and fruiting forms. No attempt was made to collect the shed leaves and fruits. Mature bolls were divided into lint, seeds, and burs. The bur fraction included squares, flowers, immature bolls, and burs from mature bolls. Plant parts were dried at 60 °C, weighed, and ground to a fine powder, then passed through a 40 mm stainless steel sieve.

Approximately 0.3 g of each plant part (except for the lint) was weighed and added into a digestion solution (sulfuric acid,  $\text{H}_2\text{SO}_4$ ; potassium sulfate,  $\text{K}_2\text{SO}_4$ ; and mercuric sulfate,  $\text{HgSO}_4$ ), and the sample mixture was digested for 1 h at 160 °C on a preheated block digester to allow the water to evaporate. Then, the temperature was increased to 380 °C, and the sample was maintained at this temperature for another 2.5 h. The tubes were then allowed to cool, and the samples were diluted to 25 mL with ammonia-free water. The N content of the digest was measured using an Autoanalyzer (Bran Luebbe GmbH, Norderstedt, Germany).

### 2.3.2. Seed Cotton Yield

Seed cotton yield was determined at maturity by manually picking the seed cotton from each plot's yield-counting (unsampled) area.

### 2.3.3. Soil Mineral Nitrogen Content

Soil samples were collected to determine the mineral N content ( $N_{\min}$ ) throughout the growing season. Approximately 60 cm deep soil cores were collected from each plot and separated into 0–30 cm and 30–60 cm parts. Meanwhile, the 60–120 cm soil samples were collected before sowing and after harvest to evaluate the possibility of nitrate ( $\text{NO}_3^-$ ) leaching in the deeper soil. Soil samples were sieved, mixed, and extracted with a  $0.01 \text{ mol L}^{-1}$  calcium chloride ( $\text{CaCl}_2$ ) solution. The ammonium-nitrogen ( $\text{NH}_4^+\text{-N}$ ) and nitrate-nitrogen ( $\text{NO}_3^-\text{-N}$ ) in the soil were analyzed by an Autoanalyzer.

### 2.4. Data Analysis

All data were analyzed using the one-way ANOVA in SAS (SAS Institute, Inc, Cary, NC, USA, 2011). The mean values of dry matter accumulation, WUE, and  $N_{\min}$  in the soil after harvest under the different N fertilization and irrigation treatments were compared using the least significant difference (LSD), at a 0.05 significance level.

The WUE was calculated by dividing seed cotton yield per unit of land area by the total irrigation amount [29] as follows:

$$\text{WUE (kg ha}^{-1} \text{ mm}^{-1}) = \text{Seed cotton yield (kg ha}^{-1}) / \text{Total irrigation amount (mm)} \quad (3)$$

Apparent N mineralization during the cotton growing season was estimated by subtracting the initial extractable mineral soil N ( $N_{\min}$ ) in the 0–60 cm soil layer of the control plot before planting from the sum of the aboveground N uptake and residual soil  $N_{\min}$  at harvest in the same soil layer [30] as follows:

$$\text{Apparent N mineralization} = \text{Soil } N_{\min} \text{ at harvest of no N treatment (kg ha}^{-1}) + \text{N uptake of no N treatment (kg ha}^{-1}) - \text{Soil } N_{\min} \text{ before sowing of no N treatment (kg ha}^{-1}) \quad (4)$$

The  $N_{\min}$  concentration, soil bulk density, and soil water content were measured to determine the absolute  $N_{\min}$  content of the different soil layers. The total residual  $N_{\min}$  was calculated as a sum of the different soil layers.

## 3. Results

### 3.1. Rate of Nitrogen Fertilization and Irrigation

In Cele, efficiency-enhanced management based on the soil  $N_{\min}$  in the cotton root layer at different growth stages reduced the N fertilizer amount from  $432 \text{ kg ha}^{-1}$  to  $281 \text{ kg ha}^{-1}$  (35%) under conventional irrigation, and  $256 \text{ kg ha}^{-1}$  (41%) under efficiency-enhanced irrigation (Table 3). In Shihezi, the N fertilizer amount was reduced from  $345 \text{ kg ha}^{-1}$  to  $217 \text{ kg ha}^{-1}$  (37%) under conventional irrigation, and  $191 \text{ kg ha}^{-1}$  (44%) under efficiency-enhanced irrigation. Taken together, the N fertilizer amount with efficiency-enhanced irrigation was 9% (Cele) to 12% (Shihezi) lower than conventional irrigation. In Cele, the efficiency-enhanced N fertilization dramatically reduced the amount of basal N fertilizer from  $123 \text{ kg ha}^{-1}$  to  $30 \text{ kg ha}^{-1}$ . At the same time, it increased the amount of topdressing N fertilizer at the boll forming stage. In Shihezi, the efficiency-enhanced N fertilization approach reduced the amount of fertilizer applied at each top dressing.

Conventionally, single irrigation with 120–135 mm of water was used at Cele (Table 2). Efficiency-enhanced irrigation based on soil moisture monitoring using TDR probes reduced the single irrigation amount to 52–71 mm, with two additional irrigations; the total amount of irrigation water was reduced from 660 mm to 427 mm. Thus, efficiency-enhanced irrigation reduced the single irrigation amount and total irrigation amount, which increased the irrigation frequency. Meanwhile, the single irrigation amount under conventional drip irrigation in Shihezi was relatively large; efficiency-enhanced irrigation

based on soil moisture monitoring reduced the total irrigation amount from 525 mm to 399 mm.

### 3.2. Dry Matter and Yield

The analysis of dry matter and yield (Table 4) showed no significant differences in total dry matter and yield between the efficiency-enhanced N fertilization and the conventional N fertilization in both Cele and Shihezi; however, both were superior to None-N fertilization treatment. In Cele, seed cotton yield under efficiency-enhanced irrigation was similar to conventional irrigation, while the proportion of vegetative parts (shoots and leaves) under efficiency-enhanced irrigation was significantly higher. Except under None-N fertilization, the efficiency-enhanced irrigation promoted the growth of stems and leaves but did not result in a yield increase. In contrast, the efficiency-enhanced irrigation and conventional irrigation treatments resulted in similar dry matter of stems and leaves and the yield of seed cotton in Shihezi.

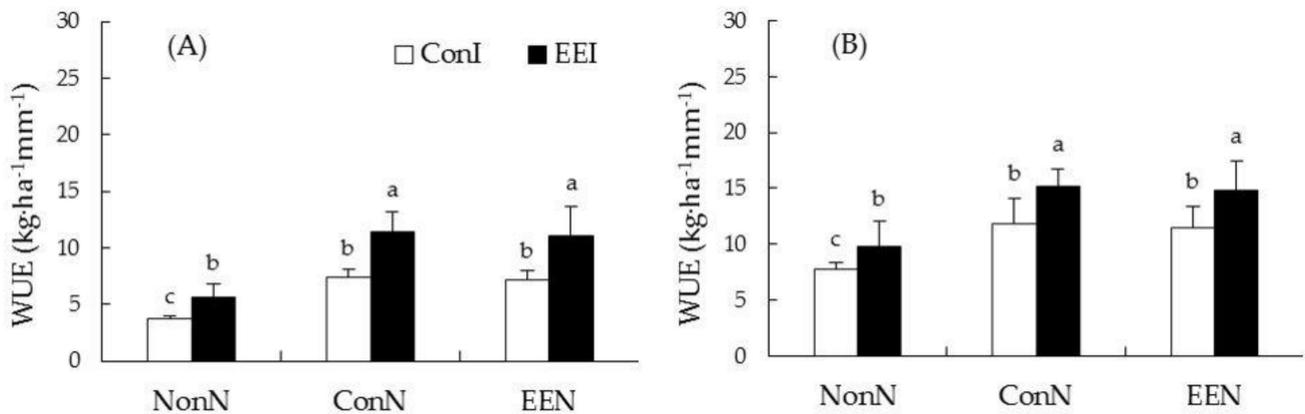
**Table 4.** Effect of irrigation and nitrogen fertilization strategies on cotton dry matter accumulation ( $\text{t ha}^{-1}$ ).

Treatments		Shoots	Leaves	Burs	Seed Cotton	Total
Cele						
ConI	NonN	1.17 c	0.78 c	0.55 b	2.44 b	4.94 b
	ConN	2.63 b	1.88 b	1.40 a	4.88 a	10.79 a
	EEN	2.43 b	1.87 b	1.56 a	4.65 a	10.51 a
EEI	NonN	1.48 c	1.04 c	0.62 b	2.40 b	5.54 b
	ConN	3.15 a	2.60 a	1.69 a	4.85 a	12.29 a
	EEN	2.94 a	2.38 a	1.60 a	4.73 a	11.65 a
Shihezi						
ConI	NonN	2.09 b	1.76 b	1.97 b	4.05 b	8.23 b
	ConN	2.73 a	2.22 a	2.63 a	6.18 a	13.01 a
	EEN	2.69 a	2.04 a	2.57 a	6.04 a	12.82 a
EEI	NonN	1.98 b	1.87 b	1.93 b	3.90 b	8.06 b
	ConN	2.70 a	2.15 a	2.48 a	6.06 a	12.03 a
	EEN	2.67 a	2.13 a	2.51 a	5.91 a	12.31 a

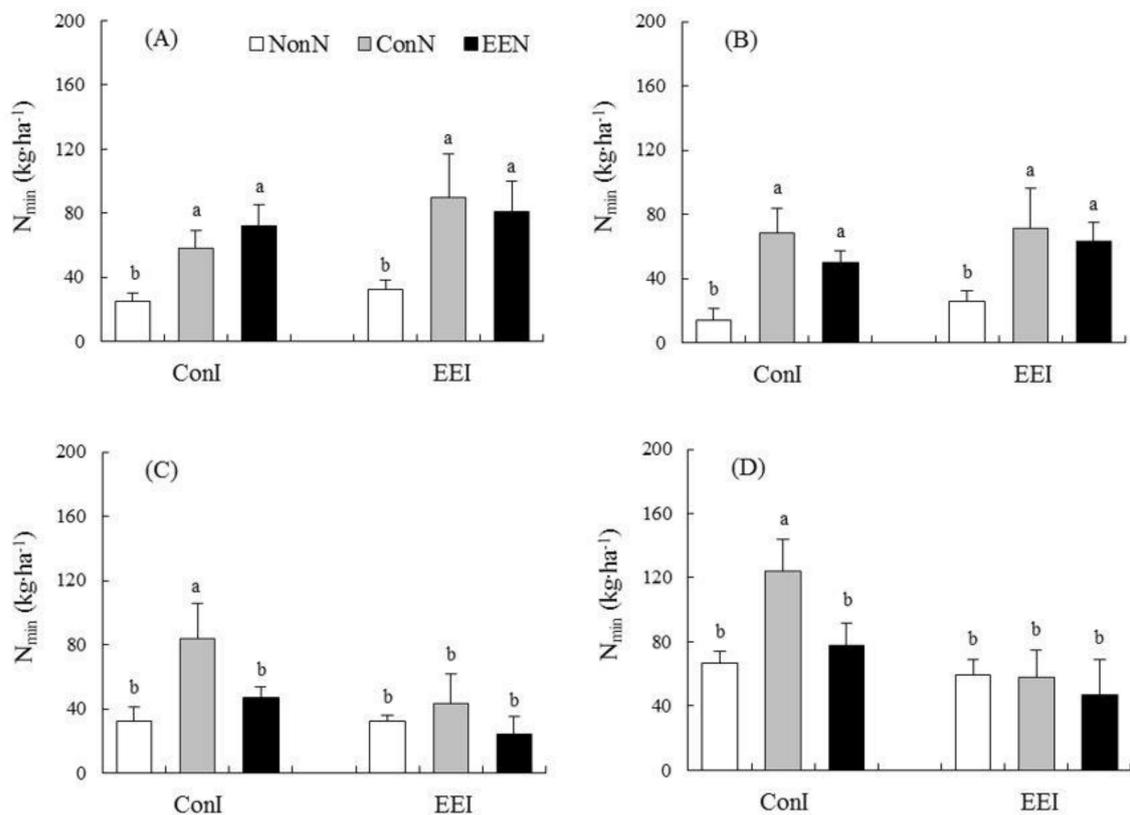
Mean values in each site column followed by the same letter are not significantly different (Duncan's multiple range test,  $p < 0.05$ ). "NonN", "ConN", and "EEN" represent no nitrogen (N) fertilization, conventional N fertilization, and efficiency-enhanced N fertilization, respectively. "ConI" and "EEI" represent conventional irrigation and efficiency-enhanced irrigation, respectively.

### 3.3. Irrigation Water-Use Efficiency (WUE), Residual Soil Nitrogen Mineralization ( $N_{\min}$ ), and Nitrogen Balance

Efficiency-enhanced irrigation significantly increased the irrigation WUE by 53.9% in Cele and 29.0% in Shihezi (Figure 1). Meanwhile, N fertilization enhanced the irrigation WUE when compared with no N treatment; however, no significant difference was observed between conventional N fertilization and efficiency-enhanced N fertilization. The soil  $N_{\min}$  in the 0–60 cm layer under conventional N fertilization and efficiency-enhanced N fertilization was significantly higher than None-N fertilization (Figure 2). The conventional N fertilization treatment increased the residual  $N_{\min}$  in the 60–120 cm soil layer, and the efficiency-enhanced N fertilization treatment decreased the residual  $N_{\min}$  significantly. Analysis of the N balance (Table 5) showed high N losses ( $179\text{--}294 \text{ kg ha}^{-1}$ ) due to a large amount of N fertilizer applied ( $345\text{--}432 \text{ kg ha}^{-1}$ ) under the conventional management system. Meanwhile, the efficiency-enhanced management approach significantly decreased the N losses ( $43\text{--}87 \text{ kg ha}^{-1}$ ).



**Figure 1.** Effect of different irrigation and nitrogen fertilization strategies on water-use efficiency (WUE;  $\text{kg}\cdot\text{ha}^{-1}\cdot\text{mm}^{-1}$ ). (A) represents the Cele site, and (B) represents the Shihezi site. “NonN”, “ConN”, and “EEN” represent no nitrogen (N) fertilization, conventional N fertilization, and efficiency-enhanced N fertilization, respectively. “ConI” and “EEI” represent conventional irrigation and efficiency-enhanced irrigation, respectively. The values (mean  $\pm$  s.e) sharing the same letter are not significantly different at  $p < 0.05$ .



**Figure 2.** Soil mineralizable N ( $N_{\min}$ ;  $\text{kg}\cdot\text{ha}^{-1}$ ) in the 0–60 cm and 60–120 cm soil layers after cotton harvest. (A,C) represent 0–60 cm and 60–120 cm soil layers of Cele, respectively; (B,D) represent the 0–60 cm and 60–120 cm soil layers of Shihezi, respectively. “NonN”, “ConN”, and “EEN” represent none nitrogen (N) fertilization, conventional N fertilization, and efficiency-enhanced N fertilization, respectively. “ConI” and “EEI” represent conventional irrigation and efficiency-enhanced irrigation, respectively. The values (mean  $\pm$  s.e) sharing the same letter are not significantly different at  $p < 0.05$ .

**Table 5.** Nitrogen balance in cotton under different irrigation and nitrogen treatments.

Parameter	Cele		Shihezi	
	ConM	EEM	ConM	EEM
N input				
(1) N supply (kg ha <sup>-1</sup> )				
(a) N <sub>min</sub> in 0–60 cm before sowing	44	44	59	59
(b) N fertilizer applied	432	256	345	191
(2) Apparent mineralization	75	92	133	128
Total N supply (= 1 + 2)	551	392	537	378
N output				
(3) N uptake by cotton (kg ha <sup>-1</sup> )	216	243	290	272
(4) N surplus	335	149	247	106
(a) N <sub>min</sub> in 0–60 cm after harvest	58	81	68	63
(b) Apparent N losses	294	87	179	43

“ConM” and “EEM” represent conventional irrigation and N fertilization management and efficiency-enhanced irrigation and N fertilization management, respectively.

#### 4. Discussion

Several researchers have analyzed the effects of water and N management on cotton [10,31]; however, the present study is the first to adopt efficiency-enhanced irrigation and N fertilizer application for cotton in the arid northwestern region of China based on the monitoring of soil water and N dynamics. In the present study, the amount of N applied was optimized based on real-time monitoring of soil N to match the cotton N demand and keep the residual N<sub>min</sub> at a reasonable range. Excessive N fertilizer used under conventional fertilization enhanced the growth of vegetative parts (shoots and leaves) with no increase in yield in Cele. Meanwhile, under efficiency-enhanced N fertilization, a dramatically reduced amount of N fertilizer (reducing basal fertilizer) was applied to cotton, which decreased the N losses and residual N<sub>min</sub> without a decrease in yield. Thus, the efficiency-enhanced N fertilization of the current study maintained a relatively high yield, reducing the environmental risk of N fertilization by decreasing the amount of fertilizer that enters environments. The analysis of the N balance revealed an imbalance between the N fertilizer application and the N losses. Therefore, the aim of high-yielding cotton field management should be to balance yield, resource-use efficiency, and environment. Typically, yield is the result of the interaction of water and fertilizer, field management, and other factors [31,32]; therefore, integrated management measures should be adopted to further improve the N fertilizer recovery and WUE, increasing the yield level.

In Cele, the soil is fine sand, with low water-holding capacity and deep groundwater (below 15 m). Though the cotton plants were irrigated five times with 660 mm water, drought still affected the growth under conventional irrigation. Efficiency-enhanced irrigation improved the soil water condition and promoted vegetative growth; however, the excessive growth of vegetative parts might have restricted the growth of reproductive parts under high plant density. The last irrigation also delayed leaf fall under efficiency-enhanced irrigation. The results of the soil N<sub>min</sub> test showed (Figure 2) that the efficiency-enhanced irrigation reduced water leaching to deep soil in Cele, which slowed down the leaching of nitrate, and improved the moisture status of cotton. Meanwhile, though drip irrigation techniques in Shihezi have efficiently managed moisture use in cotton, the efficiency-enhanced irrigation further saved 24% of the irrigation water. Under drip irrigation in Shihezi, a large amount of N<sub>min</sub> was accumulated in the 60–120 cm soil layer in conventional irrigation and N fertilization management, indicating the N leaching under drip irrigation. Occasionally, farmers adopt extensive drip irrigation to prevent salt accumulation in the soil. However, excessive drip irrigation increases the risk of N leaching loss. Under efficiency-enhanced irrigation in both sites, the irrigation frequency and amount were manipulated by monitoring the soil water status to satisfy crop demand and save water. The efficiency-enhanced irrigation approach of this study indicates that the single irrigation amount under conventional irrigation exceeds the PASW of soil in the root layer, quickly leading to infiltration and subsequent wastage. Soil moisture monitoring showed that

the irrigation interval was wide under conventional irrigation, especially in Cele, which resulted in soil moisture deficit around the roots. Compared with conventional irrigation, efficiency-enhanced irrigation saved about one-third of water without compromising yield at Cele, suggesting a huge potential to limit irrigation water used for cotton production under flood irrigation. Previously, Shen et al. (2013) reported a decrease in yield with excess water in northwestern China [21]. Therefore, to further optimize irrigation management, it is necessary to understand cotton's water requirement features.

Furthermore, the study's findings indicated that the efficiency-enhanced irrigation strategy might have reduced N losses, reducing the N fertilizer requirement in both sites. Thus, the water-fertilizer interaction effect probably played a significant role under the efficiency-enhanced irrigation and N fertilization management. The study also suggested that the dynamic monitoring of soil water and N status during the growth period would help optimize water and N application rates, as well as understand the interaction effects. Among the different techniques, drip irrigation has been popularized during the past decade for saving water and fertilizer. The drip irrigation technique accurately controls water and fertilizer input and is suitable for optimized water and fertilizer application. The study's findings suggested that even with ConI, it is feasible to achieve high yields with the efficient use of resources.

## 5. Conclusions

Irrigation water and N fertilizers are used in large amounts under conventional fertilizer management in Cele and Shihezi. In the present study, irrigation and N fertilization management based on real-time monitoring of soil N and water status significantly saved N fertilizer and irrigation water without compromising the yield. The efficiency-enhanced irrigation and N management increased irrigation WUE, and significantly reduced residual N<sub>min</sub> (0–120 cm soil) and apparent N losses when compared with the conventional irrigation and N fertilization management. In conclusion, the method described in this study is an agronomically sound and sustainable irrigation and N fertilization management strategy for cotton. The sites of this study (Cele and Shihezi) were located in arid regions of the temperate zone, where rainfall was scarce and crop growth mainly depended on irrigation. Such environmental conditions are typical in cotton growing regions around the world. Therefore, efficiency-enhanced management of this study can be used for reference in other cotton areas.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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