Compensatory Effects of Delayed Nitrogen Application on Cotton Yield Under Water Deficit During the Flowering and Boll-Setting Stage (Postprint)

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Abstract

The flowering and boll-forming stage represents the most critical period for cotton yield formation. To investigate the compensation effect of postponed nitrogen application on cotton yield under water deficit during this stage, Xinluzao 45 was utilized as the experimental material in a split-plot design. The main plot comprised two drip irrigation levels during the flowering and boll-forming stage: conventional irrigation of 2410 $m^3 \cdot hm^{-2}$ (W1) as the control and deficit irrigation of 1668 $m^3 \cdot hm^{-2}$ (W2). The sub-plot included three nitrogen fertilizer application ratios during the flowering and boll-forming stage: N1 (flower-stage fertilizer:boll-stage fertilizer = 3:3), N2 (flower-stage fertilizer:boll-stage fertilizer = 2:4), and N3 (flower-stage fertilizer:boll-stage fertilizer = 4:2). The results demonstrated that: (1) Under identical nitrogen conditions, water deficit significantly reduced leaf area index (LAI) and net photosynthetic rate (Pn) compared with normal irrigation; (2) According to the Logistic model of dry matter accumulation, the occurrence time of maximum dry matter accumulation rate (Vm) and the inflection point for entry into the rapid accumulation period (t1) were both advanced, the duration of rapid dry matter accumulation (Δt) was prolonged, while dry matter accumulation in reproductive organs and its proportion were significantly decreased; (3) Compared with normal irrigation, water deficit treatment reduced bolls per plant and boll weight by 11.7% and 45.6%, respectively, and seed cotton yield by 17.3% on average. Water consumption and nitrogen partial factor productivity decreased by 35.49% and 15.97%, respectively, whereas water use efficiency increased by 16.77% on average. Under water deficit conditions during the flowering and boll-forming stage, postponed nitrogen application (N2) increased cotton LAI and Pn relative to N1 and N3 treatments, following the trend: N2 > N1 > N3; (4) The postponed nitrogen application (N2) treatment exhibited optimal performance in dry matter accumulation, Δt, and Vm, with the most coordinated characteristic value for the rapid dry matter accumulation period (GT) and the highest transfer rate from vegetative to reproductive growth at 68.25%; (5) Compared with N1 and N3 treatments, the postponed nitrogen application (N2) treatment increased cotton bolls per plant and boll weight by 10.40% and 16.02%, and by 8.41% and 11.61%, respectively, and increased seed cotton yield by 7.32% and 13.88%, respectively. Water consumption, water use efficiency, and nitrogen partial factor productivity all displayed the pattern: N2 > N1 > N3. In conclusion, postponed nitrogen application mitigates the impact of water stress on yield by enhancing cotton LAI and Pn during the flowering stage, decelerating the decline amplitude of LAI and Pn during the late peak boll period, increasing aboveground dry matter accumulation and the proportion of reproductive organs, and regulating yield components.

Full Text

Abstract

The flowering and boll stage represents the most critical period for cotton yield formation. To investigate the compensation effect of delayed nitrogen application on cotton yield under water deficit conditions during this stage, a split-plot field experiment was conducted using *Xinluzao 45* as the test material. The main plot comprised two drip irrigation levels during the flowering and boll stage: conventional irrigation (2410 m^3 hm^{-2}, W1) as the control and deficit irrigation (1668 m^3 hm^{-2}, W2). The sub-plot consisted of three nitrogen application ratios: N1 (flowering fertilizer:boll fertilizer = 3:3), N2 (2:4), and N3 (4:2). The study examined leaf area index (LAI) and net photosynthetic rate (Pn) under identical nitrogen conditions.

Results demonstrated that under water deficit, LAI and Pn decreased significantly compared with normal irrigation. According to the Logistic model of dry matter accumulation, the maximum accumulation rate (V) occurred earlier, the inflection point for rapid accumulation (t_1) was advanced, the duration of rapid accumulation (Δt) was prolonged, while reproductive organ dry matter accumulation and its proportion decreased markedly. Water deficit reduced bolls per plant and single boll weight by 11.7% and 45.6% respectively, decreased seed cotton yield by 17.3% on average, lowered water consumption and nitrogen partial factor productivity by 35.49% and 15.97%, but increased water use efficiency by 16.77%.

Compared with normal irrigation, the N2 treatment (delayed nitrogen) under water deficit exhibited the most favorable performance: LAI and Pn increased (showing the pattern N2 > N1 > N3), dry matter accumulation and V were optimal, the rapid accumulation period characteristic value (GT) was best coordinated, and the transfer rate from vegetative to reproductive growth reached 68.25%. The N2 treatment increased bolls per plant and single boll weight by 10.40% and 8.41% respectively, and boosted seed cotton yield by 7.32% compared with N1, while water consumption, water use efficiency, and nitrogen partial factor productivity all followed the pattern N2 > N1 > N3. In conclusion, delayed nitrogen application mitigates water stress impacts by enhancing LAI and Pn during flowering, slowing their decline in late boll stage, increasing aboveground dry matter accumulation and reproductive organ proportion, thereby regulating yield components to compensate for water deficit effects.

Keywords: cotton; delayed nitrogen application; flowering and boll stage; water deficit; nitrogen management

Introduction

Water and nutrients are primary factors limiting crop growth and yield in arid and semi-arid regions. The flowering and boll stage is particularly sensitive to water and fertilizer requirements in cotton, with seasonal water shortage during this period severely affecting growth. Drought or insufficient water supply adversely affects crop nutrient absorption, while appropriate nitrogen application can regulate aboveground growth, enhance drought resistance, and improve LAI and Pn, ultimately increasing dry matter accumulation during the rapid accumulation period and benefiting cotton yield. However, excessive nitrogen leads to low utilization efficiency, reduced soil productivity, environmental degradation, and increased production costs, making nitrogen management crucial for addressing water supply insufficiency during the flowering and boll stage.

Deficit irrigation significantly affects cotton growth and development, with excessive water deficit causing premature senescence, reduced plant height, LAI, single boll weight, and boll number, while altering dry matter distribution between vegetative and reproductive organs. Previous studies have investigated nitrogen application rates and management strategies under various drought conditions, but reports on optimal nitrogen management for cotton under water deficit specifically during the flowering and boll stage remain limited. This study employed precise water and nitrogen control to explore yield improvement pathways through nitrogen management during water-limited conditions, providing theoretical support for machine-harvested cotton cultivation in northern Xinjiang.

1 Materials and Methods

1.1 Experimental Site

The field experiment was conducted in May 2020 at Sidaohezi Town, Shawan County, Xinjiang (85°57 E, 44°29 N). The region features a temperate continental arid climate with a frost-free period of 170–190 days, annual precipitation of 140–200 mm, annual evaporation of 1500–2000 mm, annual sunshine hours of 2800–2870 h, and average temperature of 6.9 °C. The previous crop was cotton, and the soil was clay loam with physicochemical properties shown in .

1.2 Experimental Design

A split-plot design was adopted with *Xinluzao 45* as the test variety. The main plot comprised two irrigation levels during the flowering and boll stage: W1 (conventional irrigation of 2410 m^3 hm^{-2}) and W2 (deficit irrigation of 1668 m^3 hm^{-2}), with total seasonal irrigation amounts of 3750 m^3 hm^{-2} and 2950 m^3 hm^{-2} respectively. The sub-plot included three nitrogen application ratios: N1 (flowering:boll = 3:3), N2 (2:4), and N3 (4:2). Total nitrogen application was 320 kg hm^{-2} pure nitrogen, with base fertilizer and bud stage fertilizer each accounting for 20% of total nitrogen, and the remaining 60% applied during the flowering and boll stage according to treatment ratios. Each treatment was replicated three times. The planting pattern used 66+10 cm row spacing with theoretical plant density of 2.25$×10^{5}$ plants hm^{-2}. Each plot measured 6.9 m × 2.3 m (15.87 m^2), with total experimental area of 1242 m^2. Irrigation was controlled by water meters, with nitrogen dissolved in fertilization tanks and applied with irrigation water. Other management followed standard field practices.

1.3 Measurements

1.3.1 Growth Process and Agronomic Traits At the cotton boll opening stage, uniform plants were selected from the middle row of each plot to measure plant height (using a tape measure), stem diameter (using vernier calipers), fruit branch number, and effective fruit branch number. Growth stages (initial flowering, full flowering, full boll, and boll opening) were recorded.

1.3.2 Leaf Area Index and Net Photosynthetic Rate LAI was measured using a CI-110 plant canopy analyzer between 19:00–21:00 when no strong direct sunlight was present. The fisheye detector was placed at the main stem position, with three sampling points per plot and three replicates per point. Images were analyzed using dedicated software. Pn was measured on sunny days between 11:30–13:30 using a portable photosynthesis system (ras-2). Before topping, the fourth leaf from the top was measured; after topping, the third leaf from the top was measured, avoiding main leaf veins. Ten leaves were measured per treatment and averaged.

1.3.3 Aboveground Dry Matter Accumulation and Distribution At initial flowering, full flowering, full boll, and boll opening stages, three representative plants per plot (nine per treatment) were sampled. Vegetative organs (stem and leaf) and reproductive organs (bud, flower, and boll) were separated and oven-dried at 105 °C for 30 minutes, then at constant temperature until reaching constant weight. Dry matter accumulation and distribution proportions were calculated.

1.3.4 Yield and Yield Components At boll opening stage, 6.67 m^2 was harvested from the middle row of each plot to count actual plant and boll numbers. Twenty naturally opened bolls were collected from lower (1-3 fruit branches), middle (4-6 fruit branches), and upper (>7 fruit branches) canopy positions, then ginned to determine single boll weight and lint percentage. Seed cotton yield was calculated based on yield components.

1.3.5 Water Consumption Water consumption (evapotranspiration, ET) was determined using the water balance method:

$$ET = 10\sum_{i=1}^{n}\gamma_i H_i(\theta_{i1} - \theta_{i2}) + P + K$$

where ET is stage water consumption (mm), n is soil layer number (3), i is layer index, γ is dry bulk density of layer i (1.448 g cm^{-3}), H is layer thickness (0.2 m), $_1$ and $_2$ are initial and final soil moisture percentages (dry weight basis), P is effective precipitation, and K is groundwater contribution (negligible below 2 m depth).

1.3.6 Water Use Efficiency Water use efficiency (WUE) was calculated as:

$$WUE = \frac{Y}{ET}$$

where WUE is water use efficiency (kg hm^{-2} mm^{-1}), Y is seed cotton yield (kg hm^{-2}), and ET is water consumption (mm).

1.3.7 Nitrogen Partial Factor Productivity Nitrogen partial factor productivity (PFP) was calculated as:

$$PFP = \frac{Y}{FN}$$

where PFP is nitrogen partial factor productivity (kg kg^{-1}), Y is seed cotton yield (kg hm^{-2}), and FN is total nitrogen input (320 kg hm^{-2}).

1.4 Data Analysis

Data were analyzed using SPSS 23.0 for ANOVA, with Duncan' s method for multiple comparisons ($P < 0.05$). GraphPad and Excel 2019 were used for data processing and figure preparation.

2 Results

2.1 Effects of Nitrogen Management on Cotton Growth Process Under Water Deficit

Growth processes began diverging among treatments from the full flowering stage (Table 3). Under identical nitrogen treatments, deficit irrigation advanced growth stages by 4–10 days compared with conventional irrigation. Within the same irrigation level, nitrogen treatments affected growth duration differently: N2 delayed growth most noticeably under conventional irrigation, while N3 caused premature senescence. Overall, W1N2 and W2N2 treatments showed the most reasonable growth periods, differing by only 2–10 days. Under deficit irrigation, N3 exhibited severe premature senescence, shortening the growth period by 2–10 days.

2.2 Effects of Nitrogen Management on Cotton Agronomic Traits Under Water Deficit

Throughout the growth period, cotton LAI increased initially then decreased, peaking at the full boll stage (Figure 1). Under deficit irrigation, LAI was significantly reduced compared with conventional irrigation, with average reductions of 21.4%, 22.4%, 17.79%, and 32.38% at full flowering, full boll, late boll, and boll opening stages respectively. At full boll stage, LAI differences among treatments were most significant.

Agronomic traits were also affected (Table 5). Under identical nitrogen treatments, deficit irrigation reduced plant height, stem diameter, effective fruit branches, and true leaf number compared with conventional irrigation, while increasing width of the fourth leaf from the top. Within the same irrigation level, plant height, stem diameter, and fourth leaf width increased with delayed nitrogen application, showing the pattern N2 > N1 > N3, while true leaf number showed no significant difference. Under conventional irrigation, no significant differences were observed in plant height, stem diameter, or fourth leaf width among nitrogen treatments, but effective fruit branches increased significantly by 18.29% under N2. Under deficit irrigation, N2 increased plant height and stem diameter, with effective fruit branches increasing by 23.3% compared with N1 and 4.63% compared with N3.

2.3 Effects of Nitrogen Management on Net Photosynthetic Rate Under Water Deficit

Pn increased initially then decreased with growth progression, with significant differences among nitrogen treatments after initial flowering (Figure 2). Deficit irrigation reduced Pn by 10.46%, 19.67%, 31.29%, and 52.36% at full flowering, full boll, late boll, and boll opening stages respectively compared with conventional irrigation. Under conventional irrigation, Pn showed the pattern N1 > N2 > N3, while under deficit irrigation it showed N2 > N1 > N3. Specifically, under deficit irrigation, N2 reduced Pn by 9.07% at full flowering and 23.65% at full boll compared with conventional irrigation N2, but performed better than other nitrogen treatments.

2.4 Effects of Nitrogen Management on Aboveground Dry Matter Accumulation

Dry matter accumulation per plant increased with growth progression (Table 6). The Logistic model revealed that under deficit irrigation, V occurred 4–8 days earlier and t_1 was advanced by 0.26–0.61 days compared with conventional irrigation, while Δt was extended by 1-7 days. Under identical water conditions, V , t_1, and Δt showed the pattern N1 > N2 > N3, while GT showed N2 > N1 > N3. Deficit irrigation reduced reproductive organ dry matter accumulation by 12.21% and total dry matter by 34.85% compared with conventional irrigation.

Under conventional irrigation, vegetative organ dry matter proportion followed N2 > N1 > N3, while reproductive organ proportion followed N1 > N2 > N3. Under deficit irrigation, both vegetative and reproductive organ dry matter accumulation showed N2 > N1 > N3. The transfer rate from vegetative to reproductive growth under deficit irrigation N2 reached 65.47%, significantly higher than conventional irrigation N2 (2.78% increase). Compared with N1 under deficit irrigation, N2 increased V by 31.25% and GT by 38.18%.

2.5 Effects of Nitrogen Management on Dry Matter Distribution

Reproductive organ dry matter accumulation increased gradually after initial flowering, while vegetative organ accumulation peaked then declined (Figure 3). Under identical nitrogen treatments, deficit irrigation reduced dry matter accumulation by 34.85% compared with conventional irrigation. At boll opening stage, N2 under deficit irrigation significantly increased reproductive organ proportion by 68.25% compared with N1 (Table 7).

2.6 Effects on Yield, Water Use, and Nitrogen Productivity

Water deficit significantly reduced bolls per plant, single boll weight, and seed cotton yield, but had no significant effect on lint percentage (Table 8). Compared with conventional irrigation, deficit irrigation decreased bolls per plant and single boll weight by 45.6% and 11.7% respectively, reduced seed cotton yield by 17.3% and water consumption by 35.49%, increased water use efficiency by 16.77%, and decreased nitrogen partial factor productivity by 15.97%.

Under conventional irrigation, N2 reduced bolls per plant and single boll weight by 7.03% and 10.63% respectively compared with N1, and decreased yield by 18.24%. Under deficit irrigation, N2 increased bolls per plant and single boll weight by 10.40% and 8.41% respectively, and increased seed cotton yield by 7.32% compared with N1. Water consumption, water use efficiency, and nitrogen partial factor productivity all showed the pattern N2 > N1 > N3 under both irrigation levels. The N2 treatment demonstrated clear compensation effects, preventing severe yield reduction under water deficit.

3 Discussion

Water deficit sensitively affects crop growth and development. Under identical water conditions, nitrogen application can prevent premature senescence. Previous studies on cotton water deficit found that flowering stage water shortage reduces fruit branches and boll numbers proportionally to irrigation amount, and inhibits plant height and LAI growth. These findings align with our results showing reduced plant height, stem diameter, leaf width, effective fruit branches, LAI, and Pn under deficit irrigation.

Nitrogen application promotes growth under drought stress. Appropriate nitrogen rates can improve cotton growth processes and maintain higher LAI and Pn during later stages. In this study, delayed nitrogen application (N2) advanced growth processes by 2–9 days under conventional irrigation but delayed them under deficit irrigation, with most severe premature senescence observed under N3. LAI and Pn increased then decreased with delayed nitrogen, peaking at full boll stage. The pattern N2 > N1 > N3 under deficit irrigation indicates that nitrogen post-shift is beneficial for maintaining photosynthetic capacity.

Dry matter accumulation is highly sensitive to nitrogen, forming the basis for high yield. Water stress and nutrient deficiency are key limiting factors. Studies show that water deficit reduces dry matter accumulation, maximum accumulation rate, and reproductive organ proportion. Appropriate delayed nitrogen application can increase dry matter formation and improve yield efficiency. Our results demonstrate that deficit irrigation shortened the rapid growth period by 0.6–3.7 days and reduced reproductive and vegetative dry matter by 12.21% and 34.85% respectively. The N2 treatment showed the most coordinated GT and highest transfer rate (68.25%), with yield increases of 10.40% (bolls per plant), 8.41% (single boll weight), and 7.32% (seed cotton yield) compared with N1 under deficit irrigation.

Delayed nitrogen application has been studied in cotton, winter wheat, and maize, but cotton research has focused on total nitrogen rate or growth-stage distribution under various irrigation levels. This study precisely controlled water and nitrogen to explore yield improvement pathways under flowering stage water deficit. However, further research is needed to elucidate the mechanisms of nitrogen metabolism and translocation in cotton under water deficit conditions.

4 Conclusion

1) Water deficit during flowering and boll stage advanced growth stages, reduced plant height, stem diameter, and effective fruit branches, significantly decreased LAI and Pn, ultimately reducing dry matter accumulation, bolls per plant, and single boll weight, causing a 20.47% yield reduction.

2) Different nitrogen application ratios during flowering and boll stage mitigated negative impacts of water insufficiency. Under deficit irrigation,

the N2 treatment showed the most reasonable growth period (only 2–10 days difference from conventional irrigation), increased plant height, stem diameter, leaf width, true leaf number, and effective fruit branches, and maintained higher LAI and Pn throughout the growth period.

3) The N2 treatment improved dry matter rapid accumulation characteristics (V , t_1, Δt, GT) and increased the vegetative-to-reproductive transfer rate to 68.25%. Compared with N1 under deficit irrigation, N2 increased bolls per plant by 10.40%, single boll weight by 8.41%, and seed cotton yield by 7.32%, while water consumption, water use efficiency, and nitrogen partial factor productivity all showed the pattern N2 > N1 > N3.

Therefore, under water supply insufficiency during the flowering and boll stage in northern Xinjiang, nitrogen fertilizer post-shift (flowering:boll = 2:4) provides the most significant compensation effect, preventing severe yield reduction.

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Tables and Figures

Soil basic physical and chemical properties

Drip irrigation scheme and fertilization scheme

Effects of different treatments on cotton growth process

Effect of different treatments on the growth stage of cotton

Effects of various treatments on main agronomic traits of cotton

The logistic model and its characteristics on dry matter accumulation of cotton

Comparison of the distribution ratio of vegetative organs and reproductive organs in cotton

Effects of different treatments on cotton yield, water use and nitrogen fertilizer partial productivity

[Figure 1: see original paper] Effects of different treatments on LAI of cotton at flowering and boll stage

[Figure 2: see original paper] Effect of each treatment on the net photosynthetic rate (Pn) of cotton in each period

[Figure 3: see original paper] Dynamic change of dry matter accumulation and distribution of vegetative organs and reproductive organs at different growth stages

Note: Figure translations are in progress. See original paper for figures.