Field Crops Research 317 (2024) 109524

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

# Deficit irrigation combined with a high planting density optimizes root and soil water–nitrogen distribution to enhance cotton productivity in arid regions

Fengquan Wu [a,b], Qiuxiang Tang [a,*], Jianping Cui [b], Liwen Tian [b], Rensong Guo [b], Liang Wang [b], Zipiao Zheng [b], Na Zhang [b], Yanjun Zhang [c], Tao Lin [b,*]

[a] College of Agronomy, Engineering Research Centre of Cotton, Xinjiang Agricultural University, Xinjiang 830052, China
[b] Institute of Cash Crops, Xinjiang Academy Sciences, Key Laboratory of Crop Physiology, Ecology and Cultivation in Desert Oasis, Ministry of Agriculture and Rural Affairs, Urumqi 830091, China
[c] Institute of Industrial Crops, Shandong Academy of Agricultural Sciences, Jinan 250100, China

A R T I C L E  I N F O

*Keywords:*
Root system
Soil water
Soil nitrate nitrogen
Water productivity

A B S T R A C T

*Context:* Increasing the cotton planting density can reduce irrigation while maintaining the seed cotton yield. However, the underlying physiological and ecological mechanisms remain unclear. We hypothesized that increasing the planting density and reducing irrigation would promote dynamic consistency in the distribution of the roots, soil water, and nitrogen, leading to improved cotton water productivity and ultimately achieving a stable seed cotton yield.
*Method:* To test this hypothesis, a 3-year field experiment (2019–2021) was conducted in Xinjiang, China. The main plots were subjected to 3 irrigation levels based on crop evapotranspiration (ETc): 0.6 (deficit), 0.8 (typical), and 1.0 ETc (adequate). Subplots were planted at 3 densities: 13.5 (low), 18.0 (typical), and 22.5 plants $m^{-2}$ (high).
*Results:* Under typical irrigation conditions, the seed cotton yield was significantly higher at a typical planting density than at a low or high planting density. However, with adequate irrigation, a low planting density resulted in a higher yield, while a high planting density combined with adequate irrigation reduced the yield by 14.7 % compared with typical conditions (typical irrigation + typical planting density). Under deficit irrigation, the seed cotton yield at a high planting density was 9.2–23.5 % higher than that at a low or typical planting density, achieving yield stability with 20 % water saving. The dry matter accumulation and harvest index showed no significant differences between typical irrigation + typical planting density and deficit irrigation + high planting density. Deficit irrigation combined with a high planting density resulted in a higher overlap rate of the root distribution area, soil water consumption area, and nitrate nitrogen consumption area, leading to higher water productivity than that of other density and irrigation combinations.
*Conclusion:* Deficit irrigation combined with a high planting density can reduce water input by 20 % without sacrificing cotton yield, likely because of increased water productivity through the enhanced dynamic consistency of root distribution and soil water-nitrogen consumption. These findings provide valuable ecological and physiological insights for achieving water savings without compromising yield in arid and water-scarce regions.

## 1. Introduction

Cotton (*Gossypium hirsutum* L.) is a vital economic crop cultivated extensively worldwide (Zhang et al., 2023). Xinjiang, the largest cotton-producing region in China, contributes to more than one-fifth of the global cotton output (Feng et al., 2024). Despite the extensive use of drip irrigation under plastic mulch, which boosts water use efficiency by 50 % (Vaddula and Singh, 2023), water scarcity remains a significant bottleneck in cotton production (Dai et al., 2024; Zhou et al., 2011). Consequently, cultivation measures such as drip irrigation, plastic mulching, and high-density planting are widely used in this region to enhance cotton yield and water productivity.

* Corresponding authors.
*E-mail addresses:* tangqiuxiang2004_2@163.com (Q. Tang), lintao_xjau@163.com (T. Lin).

https://doi.org/10.1016/j.fcr.2024.109524
Received 9 July 2024; Received in revised form 28 July 2024; Accepted 29 July 2024
Available online 12 August 2024

In arid and water-scarce regions, deficit irrigation is considered an innovative agricultural water-saving technique (Cheng et al., 2021). This practice enhances the shift in cotton from vegetative to reproductive growth, thereby increasing crop water productivity under reduced water use (Shareef et al., 2018). However, an excessive water deficit may induce premature senescence in cotton, consequently reducing the yield (Chen and Dong, 2016). The effect of water deficit on crop growth and yield has also been explored at various growth stages. Early stage deficit irrigation has been shown to promote root development, enhance the deep water absorption capacity, and improve water productivity (Xu et al., 2016), although it can also decrease the leaf area and seed cotton yield (Zhan et al., 2015). A water deficit during the mid to late growth stages can reduce the number of bolls per unit area and the weight of individual bolls, leading to a lower cotton yield (Wang et al., 2004). Therefore, determining an optimal irrigation amount and timing is crucial for maintaining the crop yield and enhancing water productivity. Furthermore, previous studies have emphasized that planting density is a vital factor affecting cotton yield (Li et al., 2020). Under deficit irrigation conditions, appropriately increasing the planting density can have water-saving effects without reducing the seed cotton yield (Chen et al., 2019; Zhang et al., 2016; Zhou et al., 2023).

Roots are the primary organs for water and nutrient absorption in plants (Guo et al., 2024; Singh et al., 2023; Wu et al., 2023a). Enhancing the root absorption capacity is crucial for improving crop yield and water use efficiency (McCormack et al., 2015). Under drip irrigation, roots are mainly concentrated in the 0–40 cm soil layer (Wang et al., 2021). Compared with conventional irrigation amounts, increasing the irrigation under drip systems expands the wetted soil area but causes nitrate leaching beyond the root zone, increasing the distance and resistance of nutrient transport to the roots (Irmak et al., 2023; Wu et al., 2023b). Deficit irrigation promotes deeper root growth (Xu et al., 2016), enhancing water and nutrient utilization from deeper soil layers. However, an excessive water deficit may cause soil compaction, hindering root growth into deeper layers and limiting water and nutrient absorption (Hodgkinson et al., 2017). The planting density is another key factor influencing root development and water and nutrient utilization (Guan et al., 2022). A high planting density can restrict the root growth space, leading to higher root overlap (Li et al., 2018). To capture more water and nutrients in a limited soil space, roots may become thinner and longer, adapting to a competitive environment (Lynch et al., 2022), thereby improving deep soil water and nutrient extraction and utilization (Chen et al., 2022b). However, an excessively high planting density can limit the root growth space, inhibit root expansion, and ultimately affect the water and nutrient absorption capacity (Gao et al., 2022), thus affecting the crop yield. In arid and water-scarce regions, there is limited research on the effects of high-density cotton planting and deficit irrigation conditions on the root distribution and dynamic consistency of soil water and nitrogen variation areas in relation to yield.

With the aim of enhancing cotton water productivity and achieving a stable seed cotton yield, it was hypothesized that increasing the planting density and reducing irrigation would promote a consistent distribution of roots, soil water, and nitrogen. To test this hypothesis, a 3-year field experiment was conducted in the water-scarce arid region of Xinjiang. The study had the following objectives: (a) to determine the effects of varying irrigation amounts and planting densities on seed cotton yield, biological yield, and harvest index; (b) to investigate the response of soil water and nitrogen consumption in the root concentration zone under deficit irrigation and high-density planting conditions; and (c) to elucidate the physiological and ecological mechanisms by which deficit irrigation and high-density planting improve cotton water productivity and yield stability. These findings can provide a theoretical basis for achieving high and stable cotton yields in arid and water-scarce regions.

## 2. Materials and methods

### 2.1. Experimental site

A 3-year field experiment was conducted from 2019 to 2021 at the Cotton Comprehensive Experimental Station in Aawti (N41°06′, E80°44′), Xinjiang Academy of Agricultural Sciences, Xinjiang, China. This site has a typical temperate continental arid climate, and the annual mean air temperature is 10.4 °C, with an above 10 °C temperature sum of 3988 °C. The annual total number of sunshine hours is 2679 h, and the frost-free period lasts for 211 days. The annual total precipitation is 46.7 mm, and the annual evaporation was 2900 mm from 1991 to 2021. In this area, agriculture is completely dependent on irrigation.

The soil is sandy loam with 10.6 g kg$^{-1}$ organic matter and 1.8 g kg$^{-1}$ total nitrogen. The bulk density in the 0–40 cm soil layer is 1.5 g cm$^{-3}$, and the field capacity is 28.9 % (volumetric water content). The maximum and minimum air temperatures and rainfall from April to October (crop-growing season) in 2019 and 2021 are shown in Fig. 1. These measurements were obtained from an automated weather station (Watch Dog 2900ET Weather Station, Spectrum, Inc., Plano, TX, USA) located adjacent to the site.

### 2.2. Experimental design and field management

The experiment was organized in a split-plot design with four replications. It included irrigation levels as the main plots: 0.6 (deficit), 0.8 (typical), and 1.0 *ETc* (adequate), as well as three plant densities as the subplots: 13.5 (low), 18.0 (typical), and 22.5 plants m$^{-2}$ (high).

*ETc* was estimated using the following equation (Hou et al., 2024) Eq. (1).

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

where *ETc* is the crop evapotranspiration (mm d$^{-1}$), and *Kc* is the crop coefficient. According to Allen et al. (1998), *Kc* at the initial, mid, and end of season stages are 0.30, 1.15, and 0.70, respectively. However, *Kc* was adjusted to 0.75, 1.15, and 0.70, considering the specific climate at the experiment site. The daily $ET_0$ was computed using the following equation (Allen et al., 1998):

$$ET_0 = \frac{0.408\triangle(R_n - G) + \gamma\frac{900}{T_{mean}+273}u_2(e_s - e_a)}{\triangle + \gamma(1 + 0.34u_2)} \tag{2}$$

where $ET_0$ is the reference evapotranspiration (mm day$^{-1}$); $\Delta$ is the slope of the saturation vapor pressure curve at air temperature (kPa °C$^{-1}$); $R_n$ is the net radiation at the crop surface (MJ m$^{-2}$ d$^{-1}$); $G$ is the soil heat flux density (MJ m$^{-2}$ d$^{-1}$); $\gamma$ is the psychometric constant = 0.665 × 10$^{-3}$ × $P$ (kPa °C$^{-1}$) (Allen et al., 1998); P is the atmospheric pressure (kPa); $u_2$ is the wind speed at a 2 m height (m s$^{-1}$); $e_s$ is the saturation vapor pressure (kPa); $e_a$ is the actual vapor pressure (kPa); $(e_s - e_a)$ is the saturation vapor pressure deficit (kPa); and $T_{mean}$ is the daily air temperature at a 2 m height (°C).

Each experimental plot was 39 m$^2$ (6.5 m long and 6.0 m wide). Surface drip irrigation under plastic mulching was used, and the tubes were set under a plastic film. The irrigation level was controlled through a solenoid valve and flowmeter. To prevent the marginal effects of water movement between plots, a narrow 50 cm ditch was dug at the boundary of each plot, and a vinyl chloride polymer was applied. The plastic film was mulched with a 2.05 m film covering three rows (81 % of the cover ratio). The row spacing was 76 cm for all treatments (Fig. 2). The drip lines were set per row, with a distance between the drippers of 25 cm and a dripper flow rate of 2.1 L h$^{-1}$. Irrigation started on June 20 and ended on August 22 in both years. During this period, different irrigation levels were delivered at 7-day intervals, for a total of 10 times.

High-yield, upland cotton (cv. Xinluzhong 88) was sown in early April, and harvest occurred in early October. At sowing, 450 kg ha$^{-1}$ diammonium phosphate ($P_2O_5$, 53.8 %; N, 21.2 %), 225 kg ha$^{-1}$

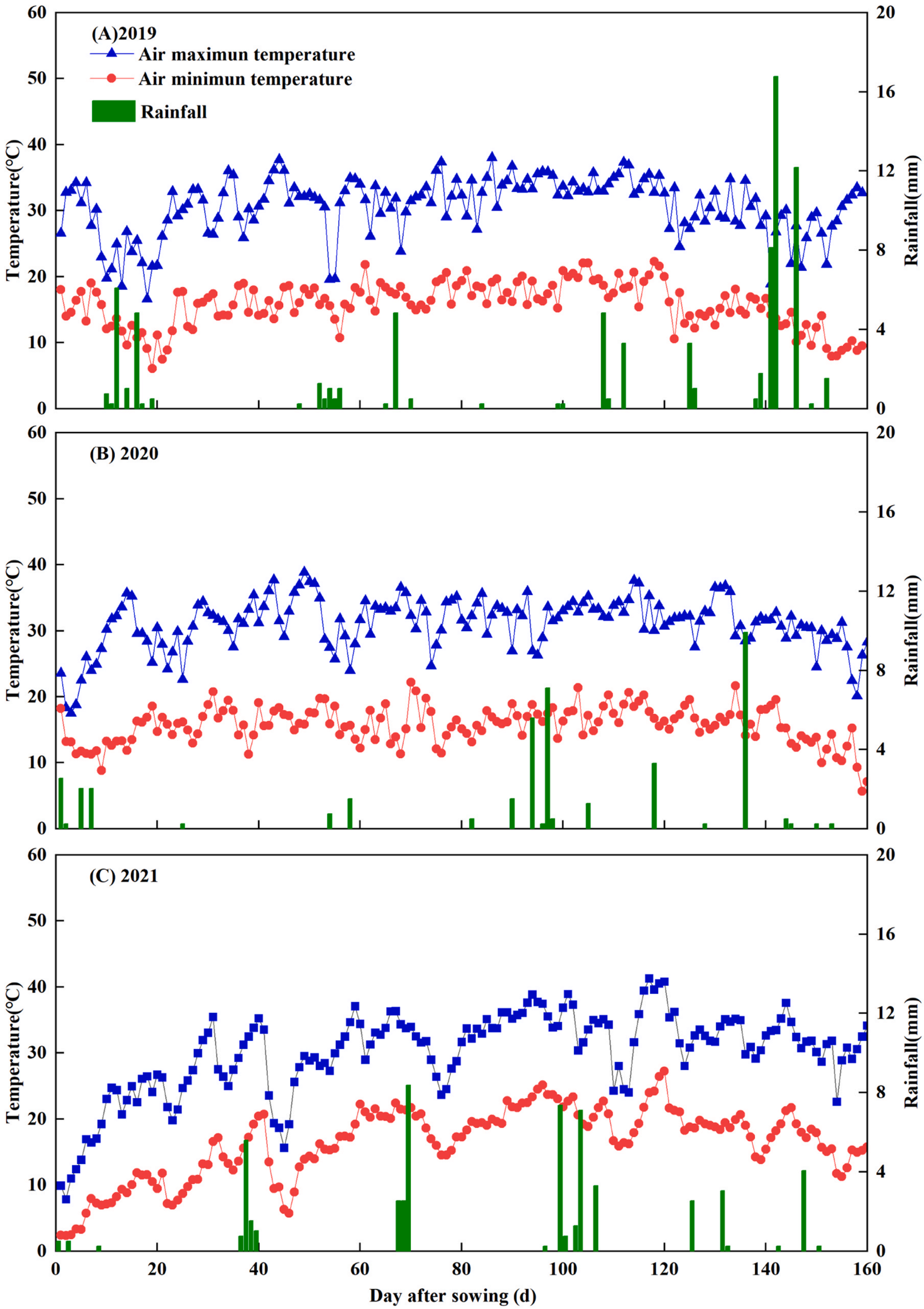


**Fig. 1.** Daily air temperatures and daily rainfall during the cotton growing season at the experimental site in 2019–2021.

potassium sulfate ($K_2O$, 51 %), and 150 kg ha$^{-1}$ urea (N, 46.4 %) were applied. A total amount of 600 kg ha$^{-1}$ urea (N, 46.4 %) was applied with drip irrigation per year for all treatments. Weeds were removed by hand.

### 2.3. *Measurements*

#### 2.3.1. *Seed cotton yield*

The final cotton yield was determined at harvest. All plants in a

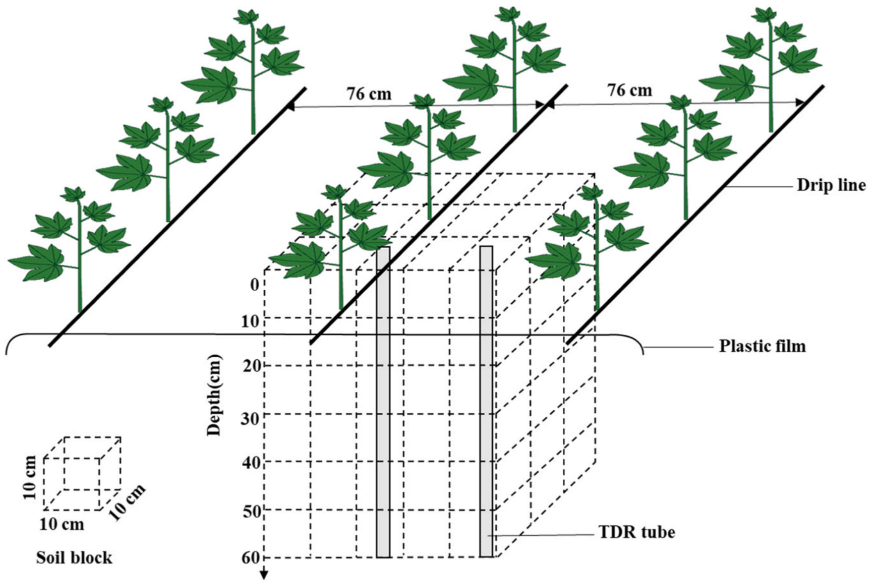


**Fig. 2.** Schematic of the planting mode, the spatial layout of root sampling and soil water content for cotton under mulched drip irrigation.

6.67 $m^2$ (2.9 m long × 2.3 m wide) sampling area at the center of each plot were harvested to determine the actual planting density, boll number per plant, and boll weight. Samples of seed cotton were sun-dried to a 11 % water content (Zhang et al., 2016). The seed cotton yield (including fiber and seeds) was calculated according to the boll number per unit ground area and single boll weight (Zhang et al., 2024).

### 2.3.2. Dry matter accumulation

Dry matter samples were collected from all plots at four different stages: 48 days after sowing (DAS) (peak squaring stage), 75 DAS (peak flowering stage), 105 DAS (peak boll-setting stage), and 135 DAS (boll opening stage) over three years. Plant samples were divided into roots and aboveground components at the cotyledonary node. Root samples were collected from the soil surrounding the plant base, covering the entire root distribution area, with a typical sampling depth of 0–40 cm. Following the determination of fresh weight, roots and aboveground tissues were dried in an oven for 30 min at 105 °C to inactivate enzymes. Subsequently, the samples were dried at 85 °C until a constant weight was achieved, and the dry weight was determined.

### 2.3.3. Root morphology

Roots were sampled three times per year for all plots at 75 (peak flowering stage), 105 (peak boll-setting stage), and 135 DAS (boll opening stage) in both years. Root samples were collected using the monolith method (Wang et al., 2020). The spatial layout of root sampling was designed according to the cotton plant and drip line arrangements in the cotton field. Soil cubes of 10 × 10 × 10 cm were dug individually in a soil area of 30 × 50 cm at a depth of 60 cm. The growth conditions of these soil cubes in the middle row, covered with 2.05 m film, were similar to those of the selected sample plot (Fig. 2). A total of 90 soil cubes were collected in each area. The soil samples were placed into a 0.5 mm mesh screen to wash the roots; dead roots and impurities were manually removed. After washing, the root samples were carefully positioned on a flatbed image scanner with tweezers, scanned with 300 dpi pixels, and analyzed using root analysis software (WinRhizo, version 2009; Regent Instrument, Quebec, Canada). The root length was measured, and the root length density (RLD, cm $cm^{-3}$) was calculated as the ratio of root length to soil volume.

### 2.3.4. Soil water content

The soil water content was measured using the time domain reflectometry (TDR) method (TRIME-T3, IMKO, Ettlingen, Germany). Measuring tubes were installed in each of the following two zones: in-row and inter-row. The spacing between adjacent measuring tubes was 40 cm (Fig. 2). Soil water content was determined at depths of 0–10, 10–20, 20–30, 30–40, 40–50, and 50–60 cm at 20, 75, 105, and 135 DAS. Based on these measurements, soil water storage (SWS) and soil water consumption (SWC) were calculated (Huang et al., 2020). To analyze the differences in SWC at various depths, the soil layers were categorized as shallow (0–20 cm), intermediate (20–40 cm), and deep (40–60 cm) (Wang et al., 2021).

### 2.3.5. Crop water productivity

The total crop water consumption, including both soil evaporation and crop transpiration, known as actual evapotranspiration (*ETa*, mm), was calculated during the growth season using the water balance equation (Xiao et al., 2023), as follows:

$$ET_a = P + I - C_r - R_f - D_p \pm \triangle S \quad (3)$$

where $P$ is the total precipitation during the cotton-growing season (mm); $I$ is the irrigation amount (mm); $C_r$ is the capillary rise (mm); $R_f$ is the runoff (mm); $D_p$ is deep percolation (mm); and $\triangle S$ is the change SWS in the 0–60 cm soil layer.

In Eq. (3), $C_r$ was considered zero because the groundwater table was more than 40 m below the surface, and $R_f$ was assumed to be negligible because the plot was flat. $D_p$ was considered zero because soil water storage below 60 cm did not reach field capacity on any sampling date, and the soil water storage was relatively stable.

The crop water productivity (*WPc*, kg $m^{-3}$) was calculated following Eq. (4), using the seed cotton yield ($Y$, kg $ha^{-1}$) produced per unit of water uptake (crop evapotranspiration $ET_a$, mm):

$$WPc = Y/ET_a \quad (4)$$

### 2.3.6. Soil nitrate nitrogen content

At 75, 105, and 135 DAS, samples were collected at depths in 10 cm intervals within the 0−60 cm soil layer. Soil samples were collected from beneath and between the drip lines. The soil solution was extracted from the soil samples using a 1:5 ratio of 2 mol $L^{-1}$ KCl solution. The nitrate nitrogen content in the solution was subsequently measured using a UV spectrophotometer (Jia et al., 2020). Total soil nitrate accumulation and soil nitrate variation (*SNV*) in the 0–0.6 m soil layer were calculated as follows (Chen et al., 2024):

$$SNA_i = 0.1 \times N \times \gamma \times h \quad (5)$$

$$TSNA = \sum_i^n SNA_i \quad (6)$$

where *TSNA* is the total soil nitrate accumulation in the 0–0.6 m soil layer (kg $ha^{-1}$); $SNA_i$ is the soil nitrate accumulation at the ith soil layer (kg $ha^{-1}$); *N* is the soil nitrate concentration (mg $kg^{-1}$); 0.1 is the conversion coefficient; $\gamma$ is the dry bulk density (g $cm^{-3}$); *i* is the soil layer, *i* = 1, 2, 3, … n, and h is the soil depth (cm).

The soil nitrate variation ($\triangle SNV$, kg $ha^{-1}$) was calculated using Eq. (7) (Wang et al., 2018):

$$\triangle SNV = SNA_{ai} - SNA_{bi} \quad (7)$$

where $SNA_{ai}$ is the accumulation of nitrate in the soil at the first growth stage of the *ith* soil layer; $SNA_{bi}$ is the accumulation of nitrate in the soil at the last growth stage of the *ith* soil layer.

### 2.4. Statistical analysis

The experimental data from the three growing seasons were analyzed using analysis of variance in SPSS 22.0 (SPSS Inc., Chicago, IL, USA). The data obtained from each sampling event were analyzed separately. When a significant treatment effect was observed at $P < 0.05$, the least significant difference (LSD) was used to determine differences between means. ANOVA was conducted using the year (Y), irrigation amount (I), and planting density (D) as the primary effects, and interactions included I×D and Y×I×D. Origin 2019b software (OriginLab, Northampton, USA) was used to generate the figures.

## 3. Results

### 3.1. Seed cotton yield and crop water productivity

The irrigation amount and planting density significantly interacted to affect cotton yield (Table 1). A 3-year study showed that under deficit irrigation conditions, the seed cotton yield increased with an increase in planting density. Specifically, the seed cotton yield at high density (D3) was 19.1 % and 10.3 % higher than that at typical (D2) and low density (D1), respectively. Under typical irrigation conditions, the seed cotton yield of D2 was the highest, being 6.1 % and 14.3 % higher than that of D3 and D1, respectively. Under adequate irrigation conditions, the seed cotton yield of D3 decreased by 4.8 % and 7.3 % compared with that of D1 and D2, respectively. Under the joint control of irrigation amount and planting density, the seed cotton yield of deficit irrigation + high density (I1D3) in 2019 was slightly lower than that of typical irrigation + typical density (I2D2) by 3.6 %, but there were no significant differences between 2020 and 2021. Under 20 % water-saving conditions, deficit irrigation and an appropriate increase in planting density maintained a stable yield.

Both irrigation amount and planting density significantly influenced water productivity (Table 1). Under deficit irrigation conditions, water productivity showed an increasing trend with a higher planting density, with D3 having an average increase of 5.5 % and 10.7 % compared with D2 and D1, respectively. Under typical irrigation conditions, D2 had a water productivity that was 10.8 % and 9.2 % higher than that of D3 and D1, respectively. Under adequate irrigation conditions, D3 had a water

**Table 1**
Effects of irrigation amount and plant density on seed cotton yield, harvest index (HI) and water productivity (WPc).

| Year | Irrigation amounts mm | Planting density (plants $m^{-2}$) | Dry matter accumulation (kg $ha^{-1}$) | Seed cotton yield (kg $ha^{-1}$) | ETa (mm) | HI | WPc (kg $m^{-3}$) |
|---|---|---|---|---|---|---|---|
| 2019 | I1 | D1 | 10401e | 4602 f | 415 h | 0.442a | 11.06b |
| | | D2 | 10859de | 4702ef | 426 g | 0.433ab | 11.02b |
| | | D3 | 12395c | 5303b | 452 f | 0.427ab | 11.71a |
| | I2 | D1 | 11082d | 4818e | 464e | 0.435ab | 10.37c |
| | | D2 | 12983bc | 5501a | 496d | 0.424bc | 11.18b |
| | | D3 | 13141b | 5146 cd | 514c | 0.401de | 10.00c |
| | I3 | D1 | 12954bc | 5274bc | 519c | 0.407 cd | 10.14c |
| | | D2 | 13314b | 5121d | 559b | 0.384e | 9.149d |
| | | D3 | 14114a | 4844e | 579a | 0.343 f | 8.364e |
| 2020 | I1 | D1 | 10015e | 4499e | 379 h | 0.449a | 11.87c |
| | | D2 | 12192d | 5337c | 406 g | 0.439ab | 13.13b |
| | | D3 | 13869ab | 5878a | 424 f | 0.425bc | 13.86a |
| | I2 | D1 | 11700d | 4972d | 429e | 0.423bc | 11.57d |
| | | D2 | 14261a | 6007a | 458d | 0.421bc | 13.09b |
| | | D3 | 14815bc | 5573b | 486c | 0.417bc | 11.44d |
| | I3 | D1 | 12921c | 5391c | 483c | 0.416c | 11.14e |
| | | D2 | 14268ab | 5280c | 512b | 0.379d | 10.30 f |
| | | D3 | 14614a | 5004d | 540a | 0.350e | 9.256 g |
| 2021 | I1 | D1 | 10508d | 4741 g | 380 h | 0.457a | 12.65c |
| | | D2 | 12075c | 5317de | 399 g | 0.444ab | 13.54b |
| | | D3 | 13666ab | 5935ab | 421 f | 0.434ab | 14.35a |
| | I2 | D1 | 11891c | 5175ef | 429e | 0.439ab | 12.09d |
| | | D2 | 13722a | 6061a | 460d | 0.442bc | 13.31b |
| | | D3 | 14428a | 5776b | 483c | 0.400bc | 12.13d |
| | I3 | D1 | 12738b | 5501c | 484c | 0.432ab | 11.23e |
| | | D2 | 13925ab | 5372 cd | 518b | 0.387 cd | 10.51 f |
| | | D3 | 14497a | 5139 f | 542a | 0.354d | 9.825 g |
| Source of variance | | | | | | | |
| Year ( Y ) | | | NS | * | NS | ** | ** |
| Irrigation (I) | | | * | ** | ** | ** | ** |
| Density (D) | | | ** | ** | ** | ** | ** |
| I × D | | | ** | ** | ** | * | ** |
| Y × I × D | | | NS | ** | ** | NS | ** |

Note: ETa: actual evapotranspiration; HI: harvest index; WPc: crop water productivity; For a given trait, treatments with the same letter within a year were not significantly different based on Duncan's multiple range test at $P < 0.05$ with a general linear model. * and ** represent a significant difference at the 5 and 1 % levels, respectively; Ns represents no significant difference at the 5 % level. I1, I2 and I3 mean irrigation amount of 0.6 ETc (deficit), 0.8 ETc (typical) and 1.0 ETc (adequate), respectively. D1, D2 and D3 mean planting density of 13.5 (low), 18.0 (typical), and 22.5 plants $m^{-2}$ (high), respectively.

productivity that was 9.1 % and 17.1 % lower than that of D2 and D1, respectively. Under the joint control of irrigation amount and planting density, I1D3 exhibited the highest water productivity, which was 5.6 % and 12.8 % higher than that of I2D2 and adequate irrigation + low density (I3D1), respectively.

### 3.2. Dry matter accumulation and harvest index

There was a significant interaction effect of irrigation amount and planting density on dry matter accumulation and partitioning, as indicated by the harvest index (Table 1). This 3-year study showed that dry matter accumulation increased with the irrigation amount. Under the same irrigation conditions, the D3 treatment had a higher dry matter accumulation (Fig. 3). Specifically, the dry matter accumulation of adequate irrigation + high density (I3D3) and typical irrigation + high density (I2D3) increased by 5.3 % and 3.2 %, respectively, compared with typical irrigation + typical density (I2D2). However, the harvest index showed an opposite trend to that of dry matter accumulation. Increasing the planting density reduced the harvest index, with D3 under deficit irrigation showing a harvest index comparable to that of D1 and D2. Under the joint influence of irrigation amount and planting density, there were no significant differences in dry matter

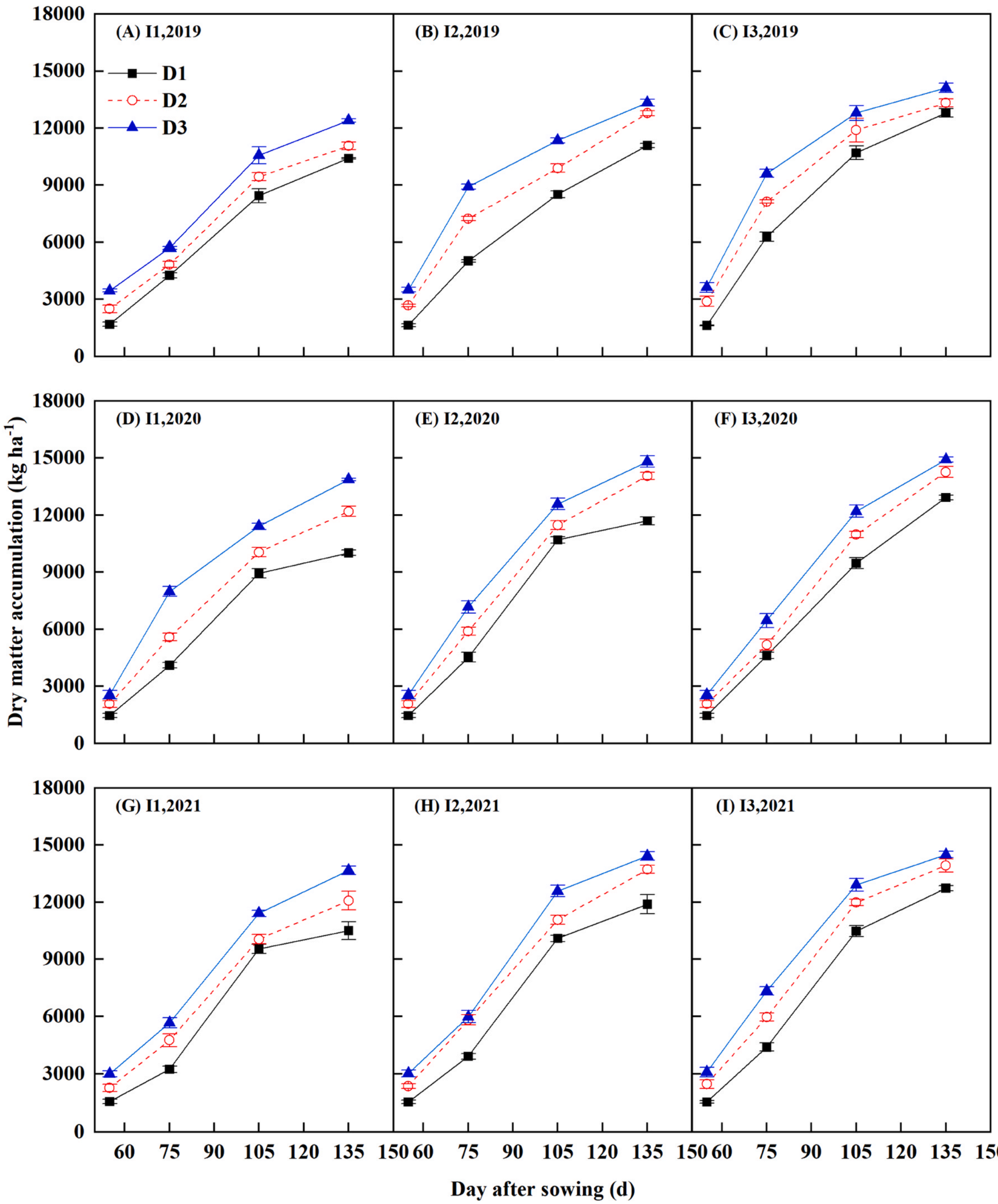


**Fig. 3.** Effects of irrigation amount and planting density on dry matter accumulation in cotton fields. The error bars indicate the standard error of four replicates. I1, I2 and I3 mean irrigation amount of 0.6 ETc (deficit), 0.8 ETc (typical) and 1.0 ETc (adequate), respectively. D1, D2 and D3 mean planting density of 13.5 (low), 18.0 (typical), and 22.5 plants $m^{-2}$ (high), respectively.

accumulation or harvest index between I2D2 and I1D3. Conversely, I3D2 exhibited a 1.3 % increase in dry matter accumulation compared with I2D2, but its harvest index underwent a significant reduction of 11.3 %.

### 3.3. Root length density (RLD) and spatial distribution

Both irrigation amount and planting density significantly influenced the average RLD (Fig. 4). Under the same planting density, the average RLD increased by 9.6 % and 17.5 % under the I2 and I3 treatments, respectively, compared with the I1 treatment. However, the average RLD significantly increased with a higher planting density. Under the same irrigation conditions, the average RLD increased by 20.5 % and 34.0 % under the D2 and D3 treatments, respectively, compared with the D1 treatment. Under the combined regulation of irrigation amount and planting density, the average RLD increased by 10.8 % under the I1D3 treatment compared with the I2D2 treatment.

Irrigation amount and planting density significantly affected RLD

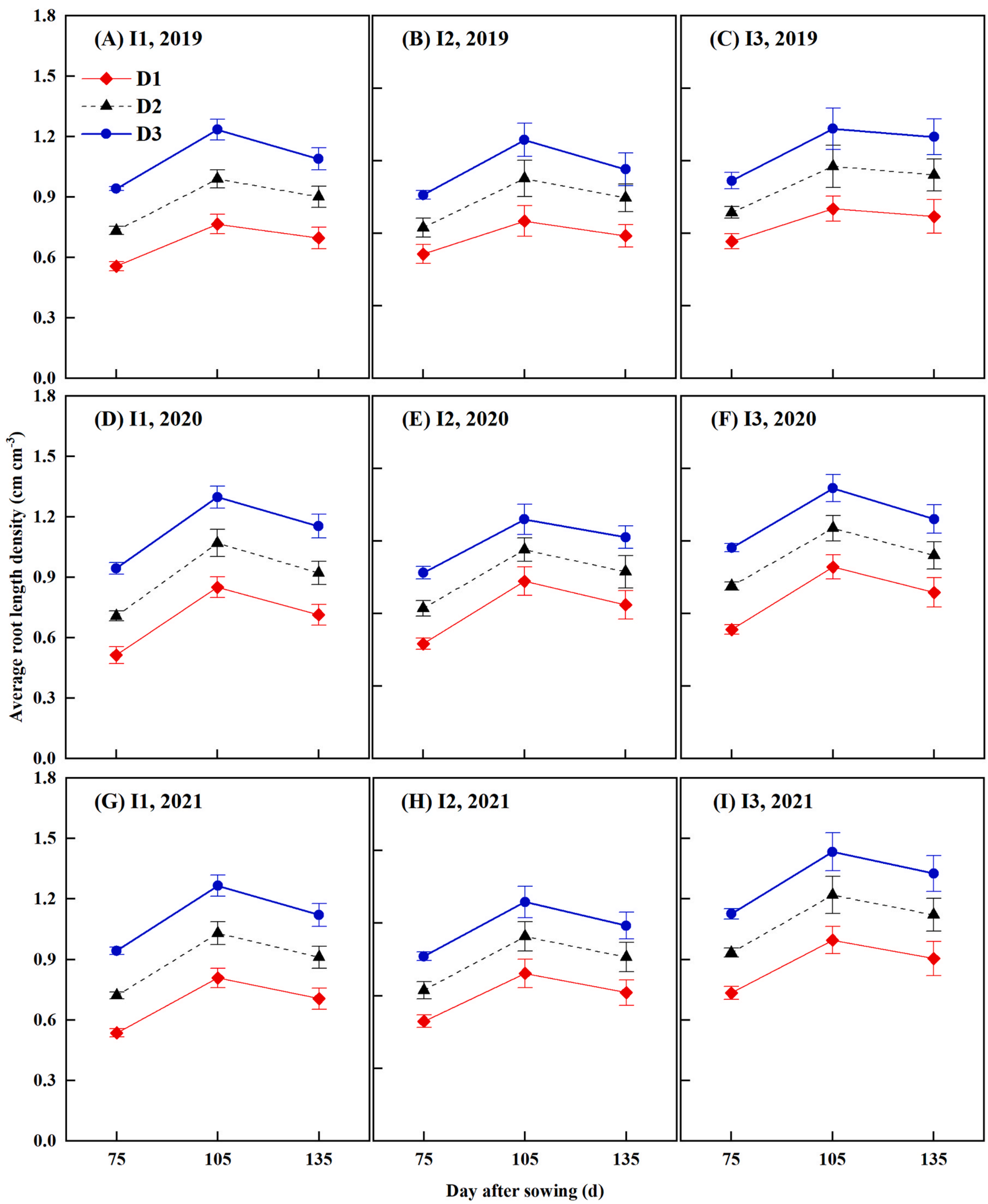


**Fig. 4.** Average root length density (RLD) of cotton under different irrigation amounts and planting densities in drip-irrigated cotton. Error bars indicate the standard error of four replicates. I1, I2 and I3 mean irrigation amount of 0.6 ETc, 0.8 ETc and 1.0 ETc, respectively. D1, D2 and D3 mean planting density of 13.5 (low), 18.0 (typical), and 22.5 plants $m^{-2}$ (high), respectively.

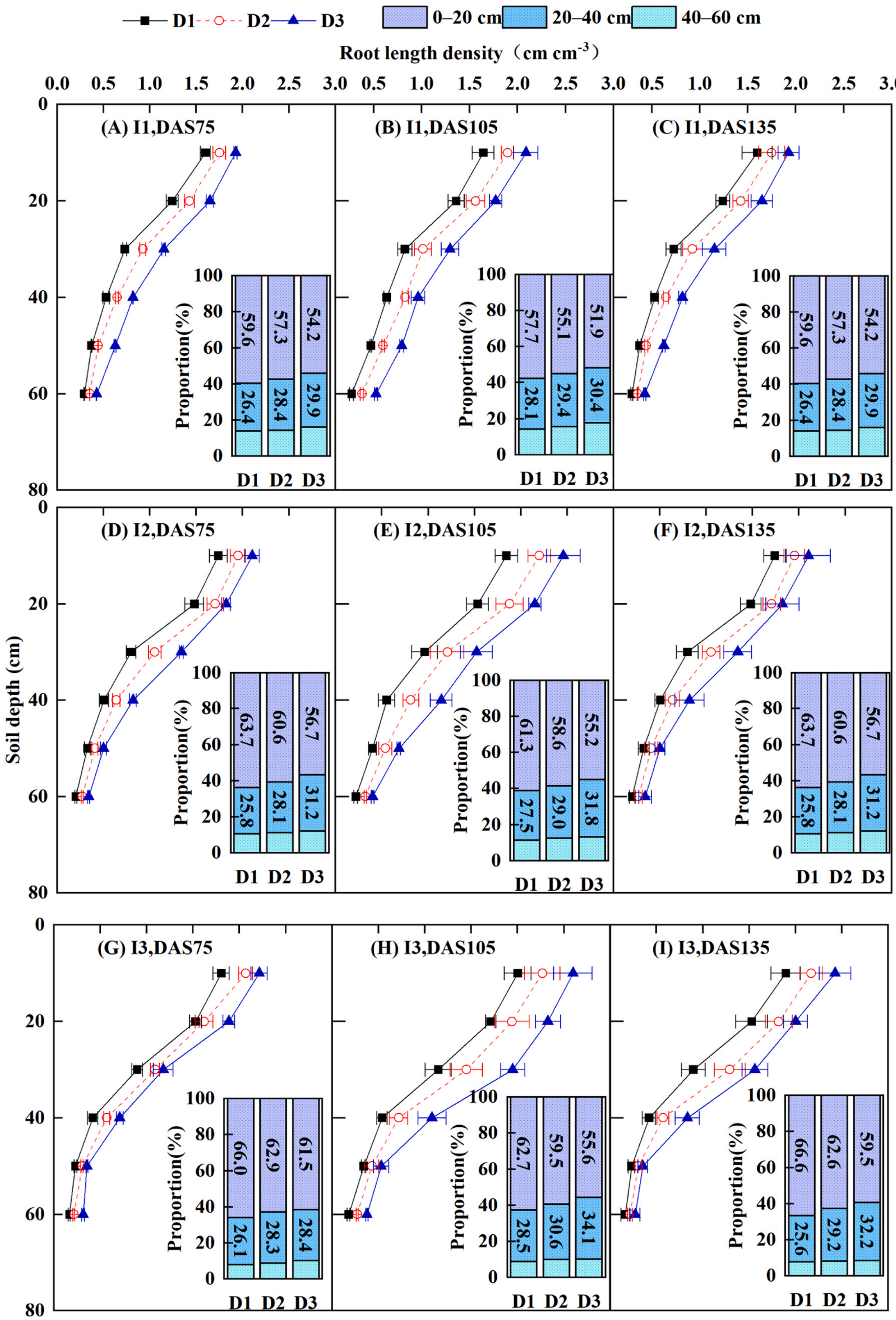


**Fig. 5.** Effects of irrigation amount and planting density on the vertical distribution and distribution proportion in different soil layers (bar charts embedded in each figure) for the root length density (RLD) of cotton at 75 (A, D, and G), 105 (B, E, and H), and 135 DAS (C, F, and I). The data presented in the figure are the mean values of the three growing seasons, and the error bars represent the standard error of the mean (n = 12). DAS, Days after sowing. I1, I2 and I3 mean irrigation amount of 0.6 ETc, 0.8 ETc and 1.0 ETc, respectively. D1, D2 and D3 mean planting density of 13.5 (low), 18.0 (typical), and 22.5 plants m$^{-2}$ (high), respectively.

(Fig. 5). Under the same planting density, the RLD increased by 10.9 % and 15.9 % in the 0–40 cm soil layer but decreased by 17.2 % and 34.8 % in the 40–60 cm soil layer under I2 and I3, respectively, compared with I1. Increasing the planting density improved the RLD in all soil layers. Under the combined regulation of irrigation amount and planting density, the RLD in the 0–40 cm soil layer in I1D3 was 2.4 % higher than that in I2D2, and in the 40−60 cm soil layer, the root length density was 19.1 %–61.6 % higher than that in the other treatments.

Under mulched drip irrigation conditions, 88.1 % of the roots were distributed in the 0–40 cm soil layer (Fig. 5). Both irrigation amount and planting density significantly affected the vertical distribution of RLD. Under the same planting density, the I1 treatment had a lower proportion of roots in the shallow soil but a higher proportion in the mid-deep soil than the I2 and I3 treatments. Under the same irrigation conditions, the RLD proportion in shallow soil decreased under the D2 and D1 treatments, but the proportion in mid-deep soil significantly increased by 1.9 % and 1.1 %, respectively, compared with the D3 treatment. Under the combined regulation of irrigation amount and planting density, the RLD proportion in shallow soil under I1D3 treatment was 6.6 % lower than that under I2D2, and the root length density proportion in mid-deep soil was 2.7 %–11.6 % lower than that in other treatments.

### 3.4. Soil water storage (SWS) and consumption

Both irrigation amount and planting density significantly affected SWS (Fig. 6). Under the same planting density, SWS increased by 9.3 % and 14.7 % under the I2 and I3 treatments, respectively, compared with the I1 treatment. However, as planting density increased, the SWS significantly decreased. Under the same irrigation conditions, SWS decreased by 6.8 % and 12.2 % under the D2 and D3 treatments, respectively, compared with the D1 treatment. Under the combined regulation of irrigation amount and planting density, SWS under the I1D3 treatment decreased by 16.9 % compared with the I2D2 treatment.

The irrigation amount and planting density significantly affected SWC. Under the same planting density, SWC increased by 52.9 % and 28.9 % under the I1 and I2 treatments, respectively, compared with the I3 treatment (Fig. 7). Increasing the planting density also significantly increased SWC; under the same irrigation conditions, SWC increased by 26.9 % and 42.5 % under the D2 and D3 treatments, respectively, compared with the D1 treatment. Under the combined regulation of irrigation amount and planting density, the I1D3 treatment had the highest SWC, with SWC in the 0−40 cm soil layer being 16.9 %–70.1 % higher than that in the other treatments.

Both irrigation amount and planting density affected the distribution of SWC (Fig. 7). Under the same planting density, the I2 and I3 treatments had a lower proportion of SWC in the shallow soil layer and a higher proportion in the mid-deep soil layer than the I1 treatment. Under the same irrigation conditions, the D2 and D3 treatments showed a decrease in the proportion of SWC in the shallow soil layer but an increase of 4.8 % and 8.1 %, respectively, in the mid-deep soil layer compared with the D1 treatment. Under the combined regulation of irrigation amount and planting density, the proportion of SWC in the shallow soil layer under the I1D3 treatment was 7.5 % lower than that under the I2D2 treatment, but the proportion of SWC in the mid-deep soil layer was 3.1 %–19.1 % higher than that in the other treatments.

### 3.5. Soil nitrate nitrogen accumulation and variation

The irrigation amount and planting density significantly affected soil nitrate nitrogen accumulation (Fig. 8). Under the same planting density, soil nitrate nitrogen accumulation decreased by 2.8 % and 7.7 % under the I2 and I3 treatments, respectively, compared with the I1 treatment. Increasing the planting density also significantly reduced soil nitrate nitrogen accumulation. Under the same irrigation conditions, soil nitrate nitrogen accumulation decreased by 4.7 % and 8.5 % under the D2 and D3 treatments, respectively, compared with the D1 treatment. Under the combined regulation of irrigation amount and planting density, soil nitrate nitrogen accumulation under the I2D2 treatment decreased by 5.5 % compared with the I1D3 treatment.

Irrigation amount and planting density significantly affected soil nitrate variation (SNV) (Fig. 9). Under the same planting density, SNV decreased by 45.6 % and 20.4 % under the I1 and I2 treatments, respectively, compared with the I3 treatment. Increasing the planting density significantly increased SNV. Under the same irrigation conditions, SNV increased by 19.6 % and 32.7 % under the D2 and D3 treatments, respectively, compared with the D1 treatment. Under the combined regulation of irrigation amount and planting density, the I1D3 treatment showed the lowest SNV, with a 13.2 % reduction in the 0–40 cm soil layer compared with the I2D2 treatment.

Both irrigation amount and planting density influenced the proportion of SNV in different soil layers (Fig. 9). Under the same planting density, the I2 and I3 treatments had a lower proportion of SNV in the shallow soil layer and a higher proportion in the mid-deep soil layer than the I1 treatment. Under the same irrigation conditions, the D2 and D3 treatments showed a decrease in the proportion of SNV in the shallow soil layer, while the proportion in the mid-deep soil layer increased by 4.2 % and 9.7 %, respectively, compared with the D1 treatment. Under the combined regulation of irrigation amount and planting density, the I1D3 treatment had a lower proportion of SNV in the mid-deep soil layer but a 1.7 % higher proportion in the shallow soil layer than the I2D2 treatment.

### 3.6. Relationship between root length density, soil water consumption, and soil nitrate nitrogen consumption

Different irrigation amounts and planting density significantly affected the overlapping areas of RLD, SWC, and SNV in various soil layers (Fig. 10). Increasing the irrigation amount resulted in a deviation of the overlapping zones of RLD, SWC, and SNV. Under the same planting density, the overlap rate of root distribution, soil moisture consumption, and nitrate nitrogen consumption areas decreased by 4.5 % under the I3 treatment compared with the I1 treatment. Conversely, increasing the planting density expanded the root distribution area, thereby reducing the deviation in the overlapping zones of RLD, SWC, and SNV. Under the same irrigation conditions, the overlap rate of RLD, SWC, and SNV areas increased by 4.8 % under the D3 treatment compared with D1. Under the combined regulation of irrigation amounts and planting density, the I1D3 treatment exhibited a 5.4 %–9.4 % increase in the overlap rate of the root distribution, soil moisture consumption, and nitrate nitrogen consumption areas compared with the other treatments.

## 4. Discussion

Under the typical irrigation conditions of drip irrigation under plastic mulching, the seed cotton yield was significantly higher with a typical density than with a low or high density. When the irrigation amount was increased to adequate irrigation, the seed cotton yield of low-density cotton is higher than that of typical density and high-density cotton. Under deficit irrigation, the seed cotton yield was 9.2 %–23.5 % higher with a high density than with a low or typical density. Compared with a typical density under adequate irrigation, the seed cotton yield was slightly reduced in 2019 (3.6 %) with a high density under deficit irrigation, but there were no significant differences in seed cotton yield in 2020 and 2021. This is because under deficit irrigation conditions, high planting density led to higher dry matter accumulation and harvest index, and the overlap rate of the root distribution area, soil water consumption (SWC) area, and soil nitrate variation (SNV) area was higher. The seed cotton yield under a combination of a high density and deficit irrigation was equivalent to that with a medium density and conventional irrigation, realizing the yield stability and improving water productivity.

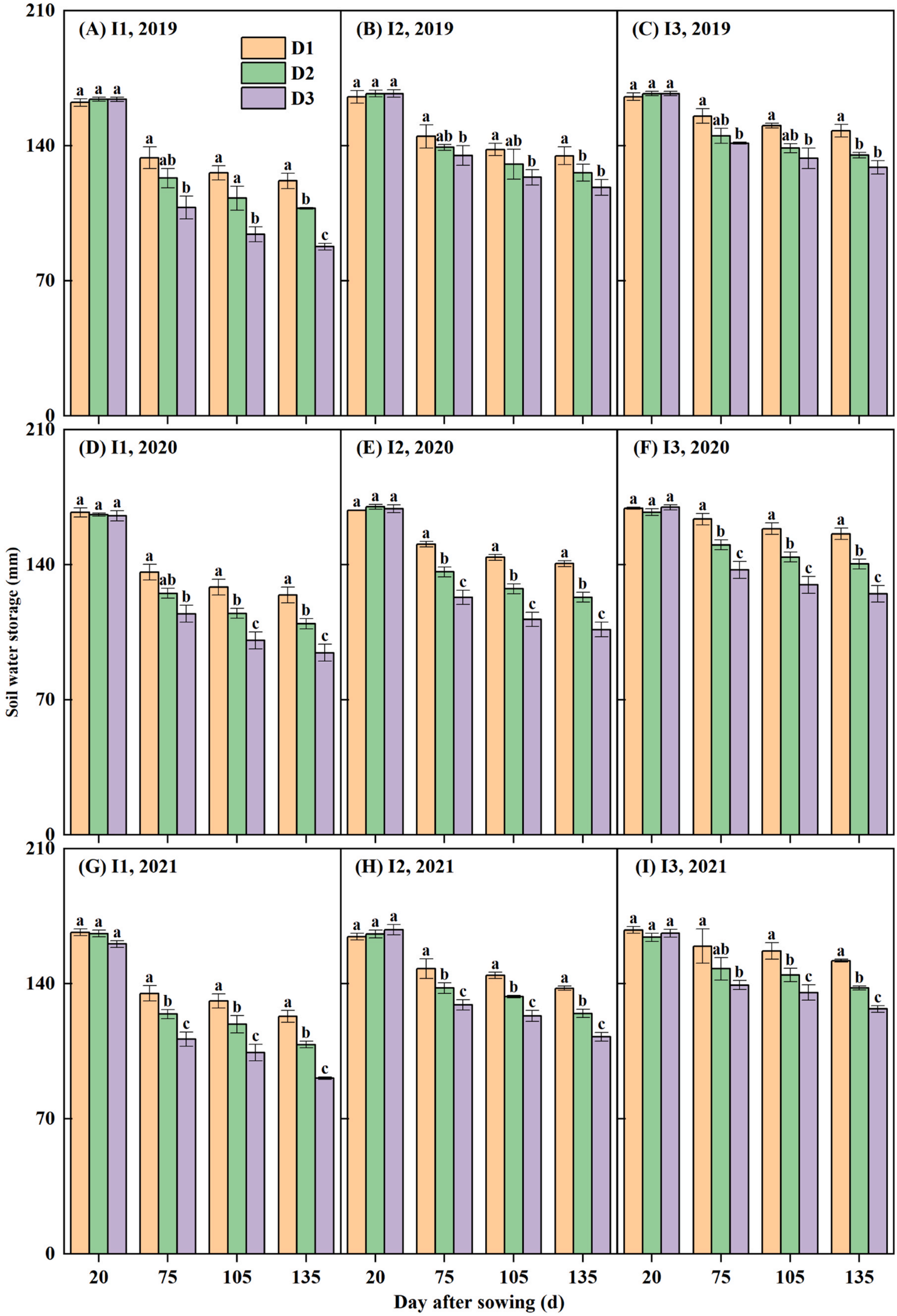


**Fig. 6.** Effects of irrigation amount and planting density on soil water storage (SWS) in cotton fields. The error bars indicate the standard error of four replicates. I1, I2 and I3 mean irrigation amount of 0.6 ETc (deficit), 0.8 ETc (typical) and 1.0 ETc (adequate), respectively. D1, D2 and D3 mean planting density of 13.5 (low), 18.0 (typical), and 22.5 plants $m^{-2}$ (high), respectively.

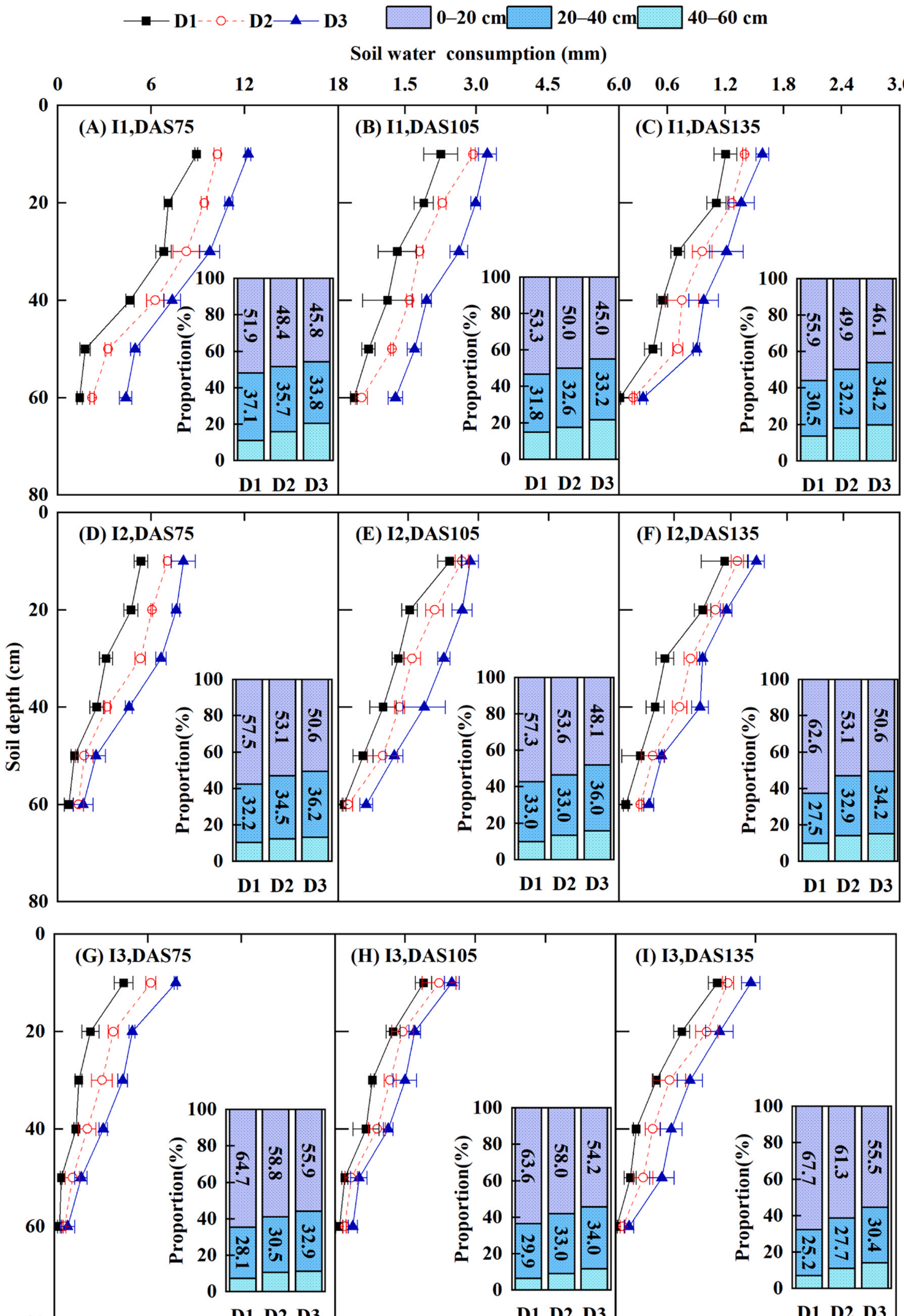


**Fig. 7.** Effects of irrigation amount and planting density on the vertical distribution and distribution proportion in different soil layers (bar charts embedded in each figure) for soil water consumption (SWC) of cotton at 75 (A, D, and G), 105 (B, E, and H), and 135 DAS (C, F, and I). The data presented in the figure are the mean values of the three growing seasons, and the error bars represent the standard error of the mean (n = 12). DAS, Days after sowing. I1, I2 and I3 mean irrigation amount of 0.6 ETc (deficit), 0.8 ETc (typical) and 1.0 ETc (adequate), respectively. D1, D2 and D3 mean planting density of 13.5 (low), 18.0 (typical), and 22.5 plants m$^{-2}$ (high), respectively.

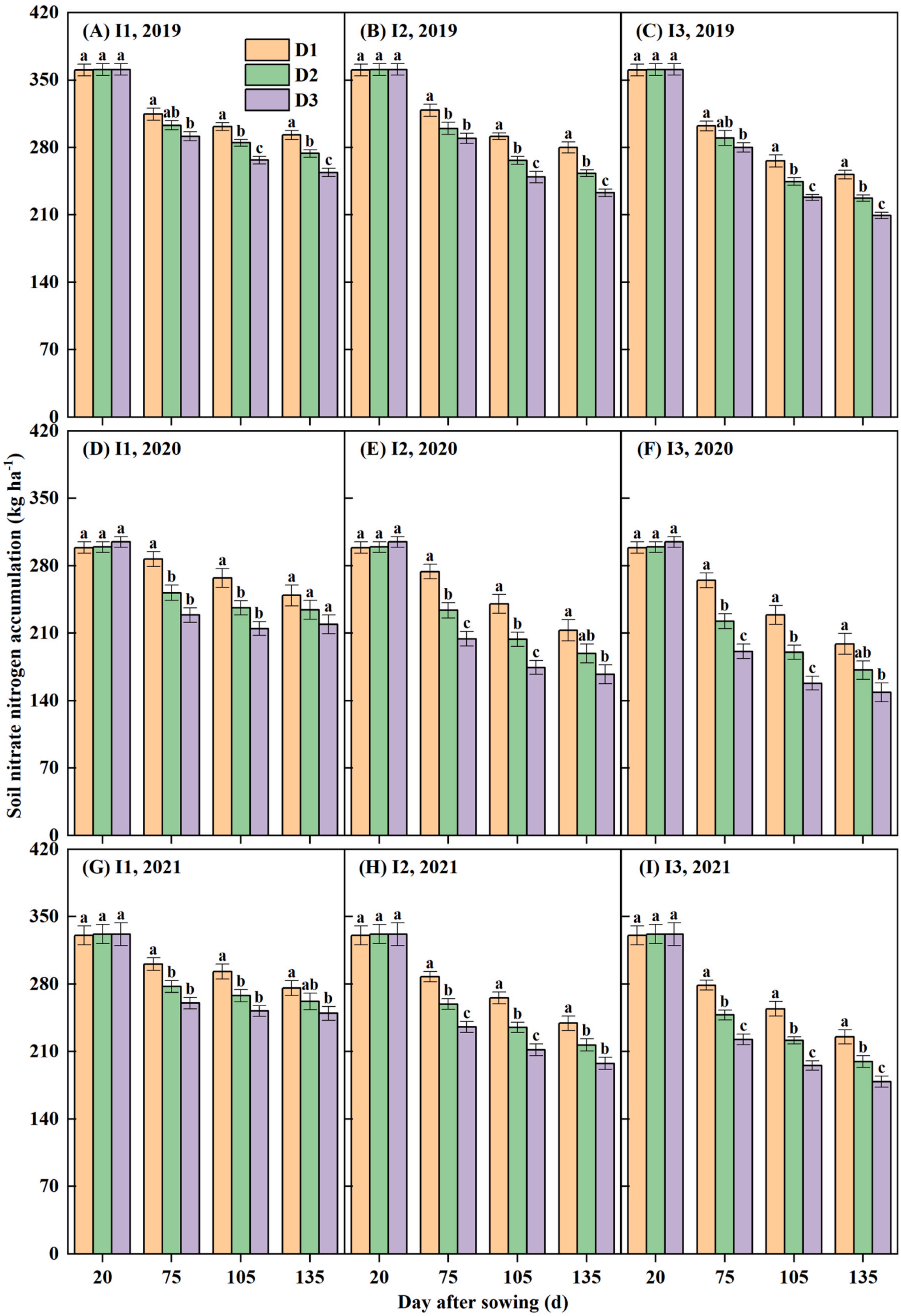


**Fig. 8.** Effects of irrigation amount and planting density on soil nitrate nitrogen accumulation in cotton fields. The error bars indicate the standard error of four replicates. I1, I2 and I3 mean irrigation amount of 0.6 ETc (deficit), 0.8 ETc (typical) and 1.0 ETc (adequate), respectively. D1, D2 and D3 mean planting density of 13.5 (low), 18.0 (typical), and 22.5 plants $m^{-2}$ (high), respectively.

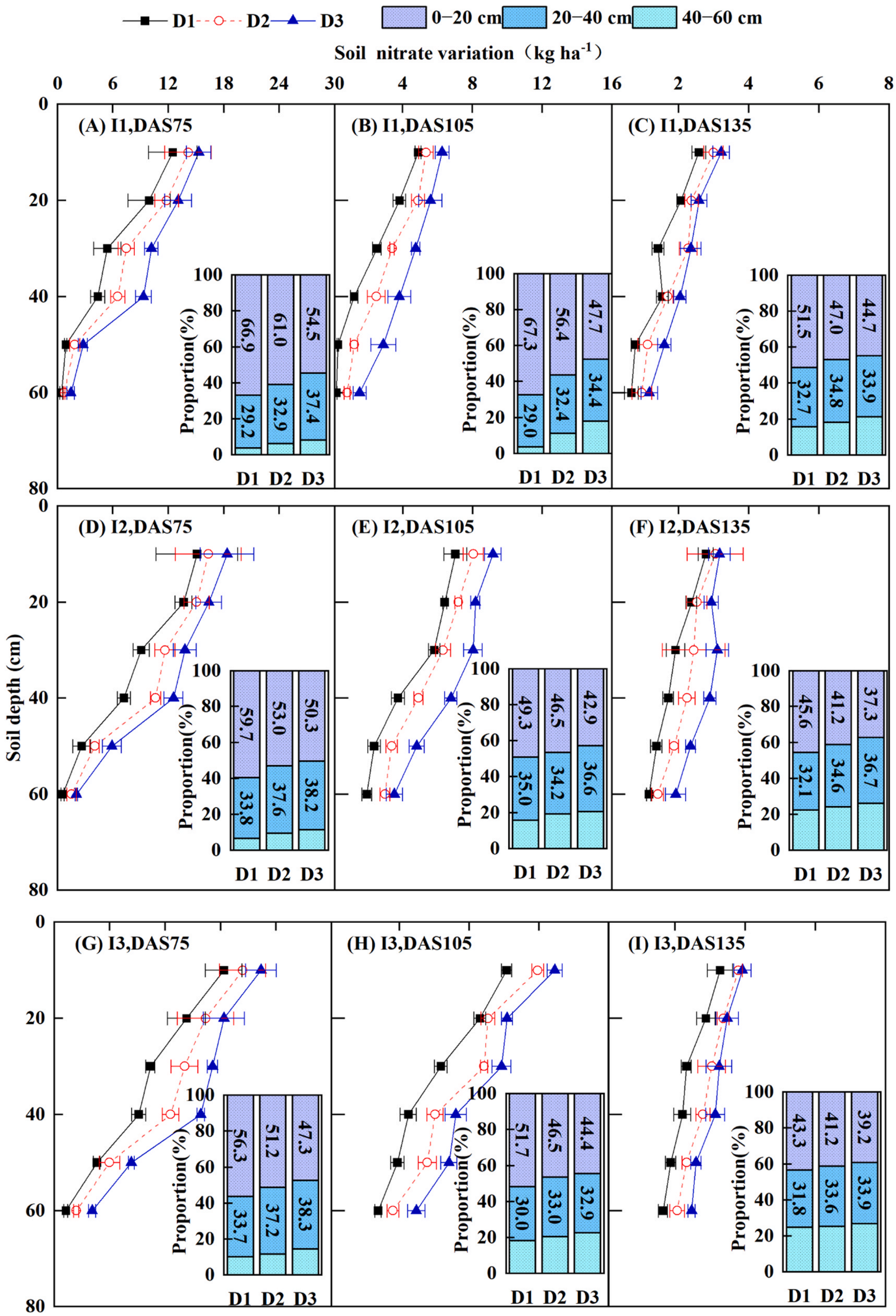


**Fig. 9.** Effects of irrigation amount and planting density on the vertical distribution and distribution proportion in different soil layers (bar charts embedded in each figure) for soil nitrate variation (SNV) of cotton at 75 (A, D, and G), 105 (B, E, and H), and 135 DAS (C, F, and I). The data presented in the figure are the mean values of the three growing seasons, and the error bars represent the standard error of the mean (n = 12). DAS, Days after sowing. I1, I2 and I3 mean irrigation amount of 0.6 ETc (deficit), 0.8 ETc (typical) and 1.0 ETc (adequate), respectively. D1, D2 and D3 mean planting density of 13.5 (low), 18.0 (typical), and 22.5 plants $m^{-2}$ (high), respectively.

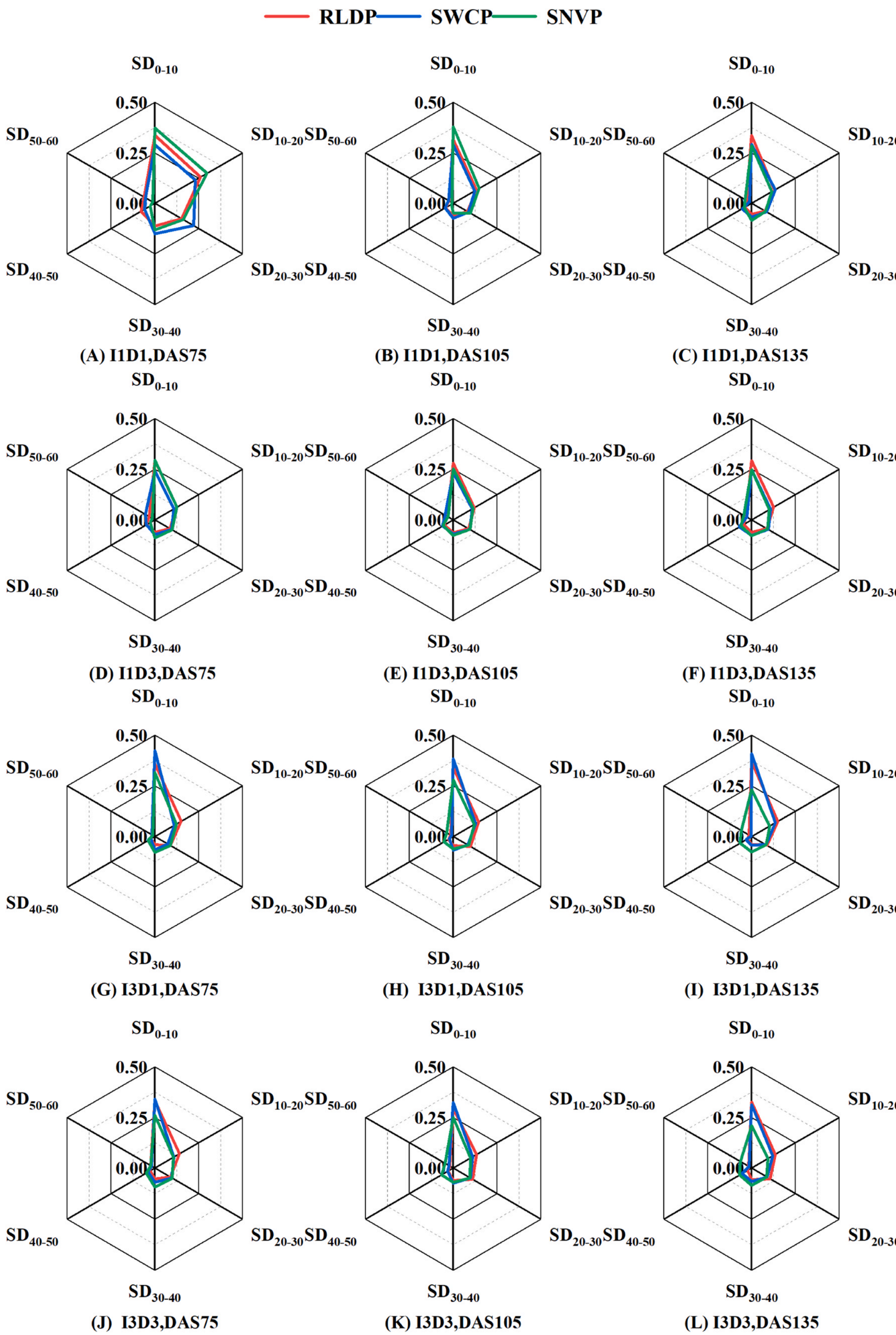


**Fig. 10.** Effects of root length density, soil water consumption, and nitrate nitrogen variation distribution proportion in different soil layers depending on the irrigation amount and planting density. RLDP, Root length density of proportion; SWCP, soil water consumption of proportion; SNVP: soil nitrate variation of proportion; and DAS, days after sowing. I1 and I3 mean irrigation amount of 0.6 ETc (deficit) and 1.0 ETc (adequate), respectively. D1 and D3 mean planting density of 13.5 (low), and 22.5 plants $m^{-2}$ (high), respectively.

 

### 4.1. Effects of irrigation amount and plant density on seed cotton yield and water productivity

Cotton is highly adaptable to water variability, with yield remaining unaffected within a certain range of water changes (Falkenberg et al., 2007; Zhang et al., 2023). When deficit irrigation is applied within an appropriate range, cotton reduces its transpiration rates by limiting vegetative growth and stomatal opening and maintaining high photosynthetic activity (Chen et al., 2022c). Water deficit can also promote the transition from vegetative to reproductive growth, increasing the harvest index and reducing water use (Ermanis et al., 2020). Although deficit irrigation enhances the harvest index by allocating more assimilates to reproductive organs (bolls), maintaining dry matter accumulation is crucial for yield stability (Dai and Dong, 2014). Increasing the planting density significantly enhances the dry matter accumulation (Dai et al., 2015), and there are significant interactive effects between planting density and irrigation amount on yield (Wei et al., 2024; Zhang et al., 2016). Similar results were observed in this study in a 3-year field experiment. Under conventional irrigation, a typical planting density produced a higher seed cotton yield than low and high densities. Regardless of the planting density, increasing the irrigation to saturation did not increase the cotton yield; saturated irrigation at a high planting density resulted in a 9.2 %–23.5 % reduction in seed cotton yield compared with conventional irrigation at medium densities. Although reducing water by 20 % decreased yield at low and medium planting densities, in 2020 and 2021, the seed cotton yield under a high planting density was comparable to that of conventional irrigation and planting density, improving water productivity. These findings further confirm that deficit irrigation and a high planting density can achieve water-saving effects without reducing the seed cotton yield in arid conditions.

### 4.2. Effects of irrigation amount and planting density on the root distribution

Roots are a crucial component of crop growth, and a slight water deficit during the growing season can increase the vertical penetration depth of roots, reducing the RLD in the upper soil layers and increasing it in the deeper soil layers (Xu et al., 2016). This study showed that under mulched drip irrigation conditions, reducing the irrigation amount decreased the proportion of RLD in the 0–40 cm soil layer, a result consistent with that of Wang et al. (2021). Under sufficient water conditions, water is not a limiting factor, and roots can absorb water from the upper soil layers, leading to a decrease in the proportion of the root length density in the deeper soil layers. Moreover, changes in planting density significantly affect root distribution patterns (Jia et al., 2018). Increasing the planting density causes roots to spread more widely in the shallow soil layers in a horizontal direction (Shao et al., 2018). In the vertical direction, the root traits of high planting density crops exhibit a general downward shift in their distribution within the soil profile (Zhang et al., 2006), a trend confirmed under different irrigation amounts in this study. However, the root distribution depth is also influenced by soil texture and structure. In areas with good soil texture, the root distribution is more uniform, and the efficiency of water and nutrient absorption is higher (Guo et al., 2023). Conversely, in areas with a poor soil texture or structure, the root distribution is restricted, reducing the water and nutrient utilization efficiency (Ahmad and Li, 2021). Therefore, further research is needed to optimize the effects of irrigation amount and planting density on the root distribution under different soil conditions.

### 4.3. Effects of irrigation amount and planting density on soil water consumption and nitrate nitrogen variation

Irrigation regimes and planting densities significantly influence soil moisture and nitrogen dynamics. Adjusting irrigation methods appropriately can ensure soil moisture remains within optimal ranges, reducing nitrogen leaching in the soil and enhancing root absorption of soil moisture and nitrogen (Qi and Hu, 2022). This study found that increasing irrigation reduces the consumption of soil moisture in cotton fields, with a greater proportion of water consumption occurring in the mid-deep soil layers under low irrigation conditions. This may be due to deficit irrigation reducing the uniformity of soil moisture (Guan et al., 2013), leading plants to expand or alter their root distribution to adapt to the uneven distribution of soil moisture (Sampathkumar et al., 2012), thereby enhancing the absorption and utilization of mid-deep soil moisture. Conversely, the variation in soil nitrogen is opposite to the trend of soil moisture consumption, with a higher proportion of changes in soil nitrate nitrogen in the root zone under deficit irrigation. This is because deficit irrigation reduces vertical soil moisture movement, weakening the leaching of soil moisture on nitrate nitrogen in the root zone(He et al., 2023), shortening the distance for root nitrogen absorption, and providing favorable conditions for the roots to absorb soil nitrate nitrogen. Additionally, increasing the planting density significantly reduces the soil moisture (Zhang et al., 2019) and nutrient content (Luo et al., 2022). A high planting density increases the proportion of water and nutrient consumption in the middle and deep soil layers (Chen et al., 2022a; Zhang et al., 2021), as confirmed in this study. However, under deficit irrigation conditions, increasing planting density enhanced the dynamic consistency of root distribution and soil water consumption and nitrogen *variation*, resulting in a 20 % reduction in irrigation water use without sacrificing cotton yield and an increase in water productivity of cotton fields. These results provide a theoretical basis for achieving a high and stable cotton yield in arid regions. However, further exploration of other irrigation and fertilization measures, such as irrigation frequency, fertilization timing, and drip tape distribution, is necessary to investigate their effects on the root–water–nitrogen distribution relationship in cotton. Additionally, the long-term impact of management measures on cotton productivity should be considered. The integration of remote sensing technology and model simulations can optimize regional irrigation and planting density management schemes, providing scientifically informed and comprehensive irrigation and fertilization management strategies for drought-prone areas.

## 5. Conclusions

Under mulched drip irrigation conditions, combining deficit irrigation with a high planting density reduced irrigation water use by 20 % without sacrificing cotton yield. By adjusting the root distribution zone, soil water consumption zone, and soil nitrate nitrogen consumption zone, the dynamic consistency between the root distribution and soil water and nutrient consumption was enhanced. This approach allows a higher planting density to achieve water-saving effects without reducing the seed cotton yield under deficit irrigation conditions. These findings provide a theoretical basis for implementing high and stable cotton yield measures in arid and water-scarce regions.

## CRediT authorship contribution statement

**Fengquan Wu:** Writing – review & editing, Writing – original draft, Investigation. **Qiuxiang Tang:** Writing – review & editing, Supervision. **Jianping Cui:** Resources. **Na Zhang:** Methodology, Investigation. **Yanjun Zhang:** Resources, Methodology, Formal analysis. **Tao Lin:** Writing – review & editing, Project administration, Funding acquisition. **Liwen Tian:** Methodology. **Rensong Guo:** Resources, Methodology. **Liang Wang:** Investigation. **Zipiao Zheng:** Methodology, Investigation.

## Declaration of Competing Interest

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

## Data Availability

The authors do not have permission to share data.

## Acknowledgements

This study has been financially supported by the Natural Science Foundation of China (31960386); Xinjiang Academy of Agricultural Sciences Agricultural Science and Technology Innovation Stability Support Project (xjnkywdzc-2023007); Xinjiang Academy of Agricultural Sciences independent cultivation project (xjnkyzzp-2022002); Tianshan Talent Training Program (2023TSYCTD004); National Modern Agricultural Industry Technology System—Cotton Industry Technology System (CARS-15–13; CARS-15–15); the earmarked fund for Xinjiang Agriculture Research System-03 (XJARS-03); the Xinjiang "Tianshan Talents" Training Program "Youth Top-notch Talent Project-Young Science and Technology Innovation Talents" (2023TSYCCX0019) and Xinjiang Uygur Autonomous Region financial special "Digital cotton Science and Technology Innovation Platform construction project.

## References

Ahmad, H., Li, J., 2021. Impact of water deficit on the development and senescence of tomato roots grown under various soil textures of Shaanxi, China. BMC Plant Biol. 21, 241. https://doi.org/10.1186/s12870-021-03018-1.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. Guidelines for Computing Crop Water Requirements – FAO Irrigation and Drainage. FAO, Rome, p. 56.

Chen, J., Wang, Y., Zhi, X., Qiu, Y., Han, Y., Feng, L., Wang, Z., Li, X., Lei, Y., Xiong, S., Wang, G., Yang, B., Li, Y., 2022a. Modifying the planting density to change water utilization in various soil layers and regulate plant growth and yield formation of cotton. Field Crops Res. 289 https://doi.org/10.1016/j.fcr.2022.108738.

Chen, S., Zhang, S., Li, H., Hu, T., Sun, G., Cui, X., Liu, J., 2024. Optimizing irrigation and nitrogen management improves soil soluble nitrogen pools and reduces nitrate residues in a drip-fertigated apple orchard on the Loess Plateau. Agric. Water Manag. 295 https://doi.org/10.1016/j.agwat.2024.108770.

Chen, W., Chen, F., Lai, S., Jin, M., Xu, S., Liu, Y., Liang, X., Ferré, T.P.A., 2022b. Spatial distribution and dynamics of cotton fine root under film-mulched drip irrigation. Ind. Crops Prod. 179 https://doi.org/10.1016/j.indcrop.2022.114693.

Chen, X., Qi, Z., Gui, D., Sima, M.W., Zeng, F., Li, L., Li, X., Feng, S., 2022c. Responses of cotton photosynthesis and growth to a new irrigation control method under deficit irrigation. Field Crops Res. 275 https://doi.org/10.1016/j.fcr.2021.108373.

Chen, Y., Dong, H., 2016. Mechanisms and regulation of senescence and maturity performance in cotton. Field Crops Res. 189, 1–9. https://doi.org/10.1016/j.fcr.2016.02.003.

Chen, Z., Niu, Y., Zhao, R., Han, C., Han, H., Luo, H., 2019. The combination of limited irrigation and high plant density optimizes canopy structure and improves the water use efficiency of cotton. Agric. Water Manag. 218, 139–148. https://doi.org/10.1016/j.agwat.2019.03.037.

Cheng, M., Wang, H., Fan, J., Zhang, S., Wang, Y., Li, Y., Sun, X., Yang, L., Zhang, F., 2021. Water productivity and seed cotton yield in response to deficit irrigation: a global meta-analysis. Agric. Water Manag. 255 https://doi.org/10.1016/j.agwat.2021.107027.

Dai, J., Dong, H., 2014. Intensive cotton farming technologies in China: achievements, challenges and countermeasures. Field Crops Res. 155, 99–110. https://doi.org/10.1016/j.fcr.2013.09.017.

Dai, J., Li, W., Tang, W., Zhang, D., Li, Z., Lu, H., Eneji, A.E., Dong, H., 2015. Manipulation of dry matter accumulation and partitioning with plant density in relation to yield stability of cotton under intensive management. Field Crops Res. 180, 207–215. https://doi.org/10.1016/j.fcr.2015.06.008.

Dai, J., Cui, Z., Zhang, Y., Zhan, L., Nie, J., Cui, J., Zhang, D., Xu, S., Sun, L., Chen, B., Dong, H., 2024. Enhancing stand establishment and yield formation of cotton with multiple drip irrigation during emergence in saline fields of Southern Xinjiang. Field Crops Res. 315 https://doi.org/10.1016/j.fcr.2024.109482.

Ermanis, A., Gobbo, S., Snider, J.L., Cohen, Y., Liakos, V., Lacerda, L., Perry, C.D., Aaron Bruce, M., Virk, G., Vellidis, G., 2020. Defining physiological contributions to yield loss in response to irrigation in cotton. J. Agron. Crop Sci. 207, 186–196. https://doi.org/10.1111/jac.12453.

Falkenberg, N.R., Piccinni, G., Cothren, J.T., Leskovar, D.I., Rush, C.M., 2007. Remote sensing of biotic and abiotic stress for irrigation management of cotton. Agric. Water Manag. 87, 23–31. https://doi.org/10.1016/j.agwat.2006.05.021.

Feng, L., Wan, S., Zhang, Y., Dong, H., 2024. Xinjiang cotton: achieving super-high yield through efficient utilization of light, heat, water, and fertilizer by three generations of cultivation technology systems. Field Crops Res. 312 https://doi.org/10.1016/j.fcr.2024.109401.

Gao, Y., Chen, J., Wang, G., Liu, Z., Sun, W., Zhang, Y., Zhang, X., 2022. Different responses in root water uptake of summer maize to planting density and nitrogen fertilization. Front. Plant Sci. 13, 918043 https://doi.org/10.3389/fpls.2022.918043.

Guan, H.-j, Li, J.-s, Li, Y.-f, 2013. Effects of drip system uniformity and irrigation amount on water and salt distributions in soil under arid conditions. J. Integ. Agric. 12, 924–939. https://doi.org/10.1016/s2095-3119(13)60310-x.

Guan, X.-j, Chen, J., Chen, X.-m, Xie, J., Deng, G.-q, Hu, L.-z, Li, Y., Qian, Y.-f, Qiu, C.-f, Peng, C.-r, 2022. Root characteristics and yield of rice as affected by the cultivation pattern of strong seedlings with increased planting density and reduced nitrogen application. J. Integ. Agric. 21, 1278–1289. https://doi.org/10.1016/s2095-3119(20)63595-x.

Guo, C., Bao, X., Sun, H., Zhu, L., Zhang, Y., Zhang, K., Bai, Z., Zhu, J., Liu, X., Li, A., Dong, H., Zhan, L., Liu, L., Li, C., 2024. Optimizing root system architecture to improve cotton drought tolerance and minimize yield loss during mild drought stress. Field Crops Res. 308 https://doi.org/10.1016/j.fcr.2024.109305.

Guo, R., Zhang, N., Wang, L., Lin, T., Zheng, Z., Cui, J., Tian, L., 2023. Subsoiling depth affects the morphological and physiological traits of roots in film-mulched and drip-irrigated cotton. Soil Tillage Res. 234 https://doi.org/10.1016/j.still.2023.105826.

He, Z., Hu, Q., Zhang, Y., Cao, H., Nan, X., 2023. Effects of irrigation and nitrogen management strategies on soil nitrogen and apple yields in loess plateau of China. Agric. Water Manag. 280 https://doi.org/10.1016/j.agwat.2023.108220.

Hodgkinson, L., Dodd, I.C., Binley, A., Ashton, R.W., White, R.P., Watts, C.W., Whalley, W.R., 2017. Root growth in field-grown winter wheat: some effects of soil conditions, season and genotype. Eur. J. Agron. 91, 74–83. https://doi.org/10.1016/j.eja.2017.09.014.

Hou, X., Fan, J., Zhang, F., Hu, W., Xiang, Y., 2024. Optimization of water and nitrogen management to improve seed cotton yield, water productivity and economic benefit of mulched drip-irrigated cotton in southern Xinjiang, China. Field Crops Res. 308 https://doi.org/10.1016/j.fcr.2024.109301.

Huang, Z., Dunkerley, D., López-Vicente, M., Wu, G.-L., 2020. Trade-offs of dryland forage production and soil water consumption in a semi-arid area. Agric. Water Manag. 241 https://doi.org/10.1016/j.agwat.2020.106349.

Irmak, S., Mohammed, A.T., Drudik, M., 2023. Maize nitrogen uptake, grain nitrogen concentration and root-zone residual nitrate nitrogen response under center pivot, subsurface drip and surface (furrow) irrigation. Agric. Water Manag. 287 https://doi.org/10.1016/j.agwat.2023.108421.

Jia, Q., Xu, Y., Ali, S., Sun, L., Ding, R., Ren, X., Zhang, P., Jia, Z., 2018. Strategies of supplemental irrigation and modified planting densities to improve the root growth and lodging resistance of maize (Zea mays L.) under the ridge-furrow rainfall harvesting system. Field Crops Res. 224, 48–59. https://doi.org/10.1016/j.fcr.2018.04.011.

Jia, Q., Yang, L., An, H., Dong, S., Chang, S., Zhang, C., Liu, Y., Hou, F., 2020. Nitrogen fertilization and planting models regulate maize productivity, nitrate and root distributions in semi-arid regions. Soil Tillage Res. 200 https://doi.org/10.1016/j.still.2020.104636.

Li, H., Wang, X., Brooker, R.W., Rengel, Z., Zhang, F., Davies, W.J., Shen, J., 2018. Root competition resulting from spatial variation in nutrient distribution elicits decreasing maize yield at high planting density. Plant Soil 439, 219–232. https://doi.org/10.1007/s11104-018-3812-5.

Li, X., Han, Y., Wang, G., Feng, L., Wang, Z., Yang, B., Du, W., Lei, Y., Xiong, S., Zhi, X., Xing, F., Fan, Z., Xin, M., Li, Y., 2020. Response of cotton fruit growth, intraspecific competition and yield to plant density. Eur. J. Agron. 114 https://doi.org/10.1016/j.eja.2019.125991.

Luo, Z., Hu, Q., Tang, W., Wang, X., Lu, H., Zhang, Z., Liu, T., Kong, X., 2022. Effects of N fertilizer rate and planting density on short-season cotton yield, N agronomic efficiency and soil N using 15N tracing technique. Eur. J. Agron. 138 https://doi.org/10.1016/j.eja.2022.126546.

Lynch, J.P., Mooney, S.J., Strock, C.F., Schneider, H.M., 2022. Future roots for future soils. Plant Cell Environ. 45, 620–636. https://doi.org/10.1111/pce.14213.

McCormack, M.L., Dickie, I.A., Eissenstat, D.M., Fahey, T.J., Fernandez, C.W., Guo, D., Helmisaari, H.S., Hobbie, E.A., Iversen, C.M., Jackson, R.B., Leppalammi-Kujansuu, J., Norby, R.J., Phillips, R.P., Pregitzer, K.S., Pritchard, S.G., Rewald, B., Zadworny, M., 2015. Redefining fine roots improves understanding of below-ground contributions to terrestrial biosphere processes. N. Phytol. 207, 505–518. https://doi.org/10.1111/nph.13363.

Qi, D., Hu, T., 2022. Effects of nitrogen application rates and irrigation regimes on root growth and nitrogen-use efficiency of maize under alternate partial root-zone irrigation. J. Soil Sci. Plant Nutr. 22, 2793–2804. https://doi.org/10.1007/s42729-022-00846-4.

Sampathkumar, T., Pandian, B.J., Mahimairaja, S., 2012. Soil moisture distribution and root characters as influenced by deficit irrigation through drip system in cotton–maize cropping sequence. Agric. Water Manag. 103, 43–53. https://doi.org/10.1016/j.agwat.2011.10.016.

Shao, H., Xia, T., Wu, D., Chen, F., Mi, G., 2018. Root growth and root system architecture of field-grown maize in response to high planting density. Plant Soil 430, 395–411. https://doi.org/10.1007/s11104-018-3720-8.

Shareef, M., Gui, D., Zeng, F., Waqas, M., Zhang, B., Iqbal, H., 2018. Water productivity, growth, and physiological assessment of deficit irrigated cotton on hyperarid desert-oases in northwest China. Agric. Water Manag. 206, 1–10. https://doi.org/10.1016/j.agwat.2018.04.042.

Singh, M., Singh, S., Deb, S., Ritchie, G., 2023. Root distribution, soil water depletion, and water productivity of sweet corn under deficit irrigation and biochar application. Agric. Water Manag. 279 https://doi.org/10.1016/j.agwat.2023.108192.

Vaddula, Y., Singh, K., 2023. Progression of drip irrigation and fertigation in cotton across the globe and its future perspectives for sustainable agriculture: an overview. Appl. Water Sci. 13 https://doi.org/10.1007/s13201-023-01986-3.

Wang, C., Isoda, A., Wang, P., 2004. Growth and yield performance of some cotton cultivars in Xinjiang, China, an arid area with short growing period. J. Agron. Crop Sci. 190, 177–183. https://doi.org/10.1111/j.1439-037X.2004.00090.x.

Wang, D., Zheng, L., Gu, S., Shi, Y., Liang, L., Meng, F., Guo, Y., Ju, X., Wu, W., 2018. Soil nitrate accumulation and leaching in conventional, optimized and organic cropping systems. Plant Soil Environ. 64, 156–163. https://doi.org/10.17221/768/2017-pse.

Wang, J., Du, G., Tian, J., Zhang, Y., Jiang, C., Zhang, W., 2020. Effect of irrigation methods on root growth, root-shoot ratio and yield components of cotton by regulating the growth redundancy of root and shoot. Agric. Water Manag. 234 https://doi.org/10.1016/j.agwat.2020.106120.

Wang, J., Du, G., Tian, J., Jiang, C., Zhang, Y., Zhang, W., 2021. Mulched drip irrigation increases cotton yield and water use efficiency via improving fine root plasticity. Agric. Water Manag. 255 https://doi.org/10.1016/j.agwat.2021.106992.

Wei, J., Chai, Q., Yin, W., Fan, H., Guo, Y., Hu, F., Fan, Z., Wang, Q., 2024. Grain yield and N uptake of maize in response to increased plant density under reduced water and nitrogen supply conditions. J. Integ. Agric. 23, 122–140. https://doi.org/10.1016/j.jia.2023.05.006.

Wu, B., Yang, P., Zuo, W., Zhang, W., 2023a. Optimizing water and nitrogen management can enhance nitrogen heterogeneity and stimulate root foraging. Field Crops Res. 304 https://doi.org/10.1016/j.fcr.2023.109183.

Wu, Y., Si, W., Yan, S., Wu, L., Zhao, W., Zhang, J., Zhang, F., Fan, J., 2023b. Water consumption, soil nitrate-nitrogen residue and fruit yield of drip-irrigated greenhouse tomato under various irrigation levels and fertilization practices. Agric. Water Manag. 277 https://doi.org/10.1016/j.agwat.2022.108092.

Xiao, C., Ji, Q., Zhang, F., Li, Y., Fan, J., Hou, X., Yan, F., Liu, X., Gong, K., 2023. Effects of various soil water potential thresholds for drip irrigation on soil salinity, seed cotton yield and water productivity of cotton in northwest China. Agric. Water Manag. 279 https://doi.org/10.1016/j.agwat.2023.108172.

Xu, C., Tao, H., Tian, B., Gao, Y., Ren, J., Wang, P., 2016. Limited-irrigation improves water use efficiency and soil reservoir capacity through regulating root and canopy growth of winter wheat. Field Crops Res. 196, 268–275. https://doi.org/10.1016/j.fcr.2016.07.009.

Zhan, D., Zhang, C., Yang, Y., Luo, H., Zhang, Y., Zhang, W., 2015. Water deficit alters cotton canopy structure and increases photosynthesis in the mid-canopy layer. Agron. J. 107, 1947–1957. https://doi.org/10.2134/agronj14.0426.

Zhang, D., Luo, Z., Liu, S., Li, W., WeiTang, Dong, H., 2016. Effects of deficit irrigation and plant density on the growth, yield and fiber quality of irrigated cotton. Field Crops Res. 197, 1–9. https://doi.org/10.1016/j.fcr.2016.06.003.

Zhang, L., Li, B., Yan, G., van der Werf, W., Spiertz, J.H.J., Zhang, S., 2006. Genotype and planting density effects on rooting traits and yield in cotton (Gossypium hirsutum L.). J. Integ. Plant Biol. 48, 1287–1293. https://doi.org/10.1111/j.1744-7909.2006.00367.x.

Zhang, Y., Wang, R., Wang, S., Ning, F., Wang, H., Wen, P., Li, A., Dong, Z., Xu, Z., Zhang, Y., Li, J., 2019. Effect of planting density on deep soil water and maize yield on the Loess Plateau of China. Agric. Water Manag. 223 https://doi.org/10.1016/j.agwat.2019.05.039.

Zhang, Y., Hu, Y., You, Z., Li, Z., Kong, M., Han, M., Liu, Z., Zhang, J., Yao, Y., 2021. Soil ventilation benefited strawberry growth via microbial communities and nutrient cycling under high-density planting. Front. Microbiol. 12, 666982 https://doi.org/10.3389/fmicb.2021.666982.

Zhang, Y., Li, Y., Liang, T., Yuan, Y., Li, Z., Xu, S., Dai, J., Fan, S., Li, C., Dong, H., 2023. Field-grown cotton shows genotypic variation in agronomic and physiological responses to waterlogging. Field Crops Res. 302 https://doi.org/10.1016/j.fcr.2023.109067.

Zhang, Y., Liang, T., Dong, H., 2024. Melatonin enhances waterlogging tolerance of field-grown cotton through quiescence adaptation and compensatory growth strategies. Field Crops Res. 306 https://doi.org/10.1016/j.fcr.2023.109217.

Zhou, J., Nie, J., Kong, X., Dai, J., Zhang, Y., Zhang, D., Cui, Z., Hua, Z., Li, Z., Dong, H., 2023. Cotton yield stability achieved through manipulation of vegetative branching and photoassimilate partitioning under reduced seedling density and double seedlings per hole. Field Crops Res. 303 https://doi.org/10.1016/j.fcr.2023.109117.

Zhou, S., Wang, J., Liu, J., Yang, J., Xu, Y., Li, J., 2011. Evapotranspiration of a drip-irrigated, film-mulched cotton field in northern Xinjiang, China. Hydrol. Process. 26, 1169–1178. https://doi.org/10.1002/hyp.8208.