Effects of water-fertilizer coupling on root distribution and yield of Chinese Jujube trees in Xinjiang

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Abstract: Water and fertilizer are the two main factors which promote the rapid growth of Jujube (*Ziziphus jujuba*) trees. Studies of root systems and the nutrition-use efficiency of dense, dwarfed fruit trees are limited, especially in an extremely arid region with drip irrigation. The experiment was conducted in a 12-year-old dwarf jujube planting basement in Hami from 2013 to 2015. In this experiment, root length density and root weight density were calculated and found to range from 75 cm to 275 cm in horizontal distance, and from 0 to 90 cm in vertical depth, treated with three drip irrigation quota gradients and three fertilizer rates with each treatment replicated three times. The results showed that, as the amount of nitrogen applied increased gradually, the jujubes' growth amount increased, reaching a maximum when an optimal concentration was applied. However, the jujubes' growth was inhibited, and the growth declined when the amount of nitrogen applied was more than the optimal concentration. At an appropriate level of nitrogen, the growth, yield and quality of jujube trees could be guaranteed. If the rate of nitrogen application was lowered, the jujubes' growth would inhibit, and hence the yield wound be seriously impacted. The optimal irrigation quota and fertilization amount were found to be 900 mm and 1500-1800 kg/hm^2, respectively. The research findings were of significance and hold great promise for the development of the forestry and fruit industries in the arid region of Xinjiang. At the same time, there was a further study on irrigation technique, focusing on the combined effect of the dwarfed-planting technique and drip irrigation on jujube trees; with this information, the application efficiency of water and fertilizer can be optimized, leading to higher profits and economic efficiency.

Keywords: water-fertilizer coupling, root distribution, yield, dense dwarf trees, *Ziziphus jujuba*

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1 Introduction

Agriculture plays a key role in the region's socio-economic development in Xinjiang Province in China, which heavily depends on irrigation[1]. Water is the lifeline of the socio-economic development of this

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region[2,3]. Restricted by water availability, the agricultural industry must develop more efficient water-saving technologies as well as more accurate irrigation and fertilization techniques[4]. Locating in the easternmost part of the Xinjiang Uyghur Autonomous Region, the Hami district spans from south to north across Tian Mountains, covering a total area of 142 100 km^2. Irrigation water comes solely from groundwater, which makes Hami a good example of a region using pumped wells for drip irrigation. Jujube, cotton, grapes and other economic crops are the main plants grown here[5]. In 2014, the area of jujube planted was about 21 800 hm^2, yielding 15000 t of fresh jujube per year[6]. As dwarfing and the close-planting technique gained popularity, these were applied to jujube cultivation in Hami as well.

Water is the most important factor governing crop productivity, particularly on the 40% of global land under arid or semi-arid climatic conditions where irrigation is the only way to maintain stable food production[7,8]. Water and fertilizer are indispensable nutrition for crops and fruits in the farming industry. The coupling of water and fertilizer in the farmland system refers to either the symbiotic relationship between irrigation water or soil moisture and fertilizer, or the dynamic equilibrium relationship between water and fertilizer, such as nitrogen, phosphorus and potassium[9,10]. Insufficiency of water or a certain nutrient element can lead to an imbalance of water and fertilizer factors, thus impacting crop growth, development and yield[11]. The current researches on the coupling effects of between water and nutrients are focused on wheat, cotton and maize, and the study of separate and coupling effects of water and nutrients on jujube trees is limited, especially in extremely arid regions utilizing underground drip irrigation. Cheng et al.[12] reported that water deficiency would inhibit the absorption, utilization and transformation of nutrients to some extent, while at the same time, fertilizer deficiency would restrain the absorption and utilization of water, thus retarding the growth of crops. Liu et al.[13] investigated the law of diminishing returns of cotton for water as well as for nutrients, and that in the coordinate application of water and fertilizer, each promoted the other's utilization efficiency, otherwise, the utilization efficiency would be reduced.

Roots are the organs of a plant that can absorb water and nutrition from soil for it, and are also important parts of the plant's biomass[14,15]. To adapt to their habitat, different kinds of plants will form some unique features in different water and fertilizer conditions[16]. At the same time, the distribution of roots plays a significant role in plants' water and fertilizer absorption. Plants' capability of absorbing water and fertilizer largely depends on the spatial and temporal distribution of their roots[17,18]. Therefore, it is very important to obtain quantitative data on the root distribution of dense, dwarfed jujube trees, which created guidelines on row spacing as well as water and fertilizer management when planting jujube trees. Root weight density and root length density are two important indices that reflect root distribution[19].

Few studies have demonstrated the influence of water-nutrient coupling on distribution of jujube tree roots, especially in extremely arid regions in China where drip irrigation is applied. Root research is critical not only for understanding soil water characteristics, but also for enhancing crop productivity[20]. In this study, field experiments were conducted in an experimental station in the suburb of Hami City in the Xinjiang Uyghur Autonomous Region of China, from 2013 to 2015. The specific objectives of this study were as follows: (1) to determine the influence of coupling water and fertilizer on horizontal and vertical root distribution characteristics; (2) to determine the influence of coupling water and fertilizer on jujube production and nitrogen-use efficiency; (3) to find the optimum drip irrigation quota and fertilization amount for the dense, dwarfed Chinese Jujube (*Ziziphus jujuba*) in Xinjiang. Studying the adaptability of dense, dwarfed jujube trees to drip irrigation in the Hami district can help get further understanding of changes in the indicators of jujube growth with drip irrigation, and identify the response mechanism of jujubes to water and nutrient conditions, thus providing insights into improving cultivation.

2 Material and methods

2.1 Study area

The experiments were conducted in a dwarf jujube planting basement in Hami from 2013 to 2015. The site is in the 13th Division of the Xinjiang Production and Construction Army Corps (42°32'N and 94°11'E), 20 kilometers away from the Hami City in Xinjiang province (Figure 1). The climate in this area is typical of an extremely arid region: the average annual precipitation is very low with less than 50 mm. The total rainfall throughout the jujube growing period is 30 mm and the average annual evaporation is 3000 mm; thus, the water shortage is extremely serious. Average annual sunshine time is 3360 h, accumulated temperature over 10°C is 4260°C and the frost-free period is probably 160 d. Regarding groundwater, the water table is deeper than 15 m, while the jujubes' root systems mainly stay within the top 100 cm of the soil, so groundwater recharge will have no advantage on the planted jujube trees. The soil type is sandy, with a bulk density of 1.5 g/cm^3; the field water quality is 16% and the capacities for water and nutrient retention are poor.

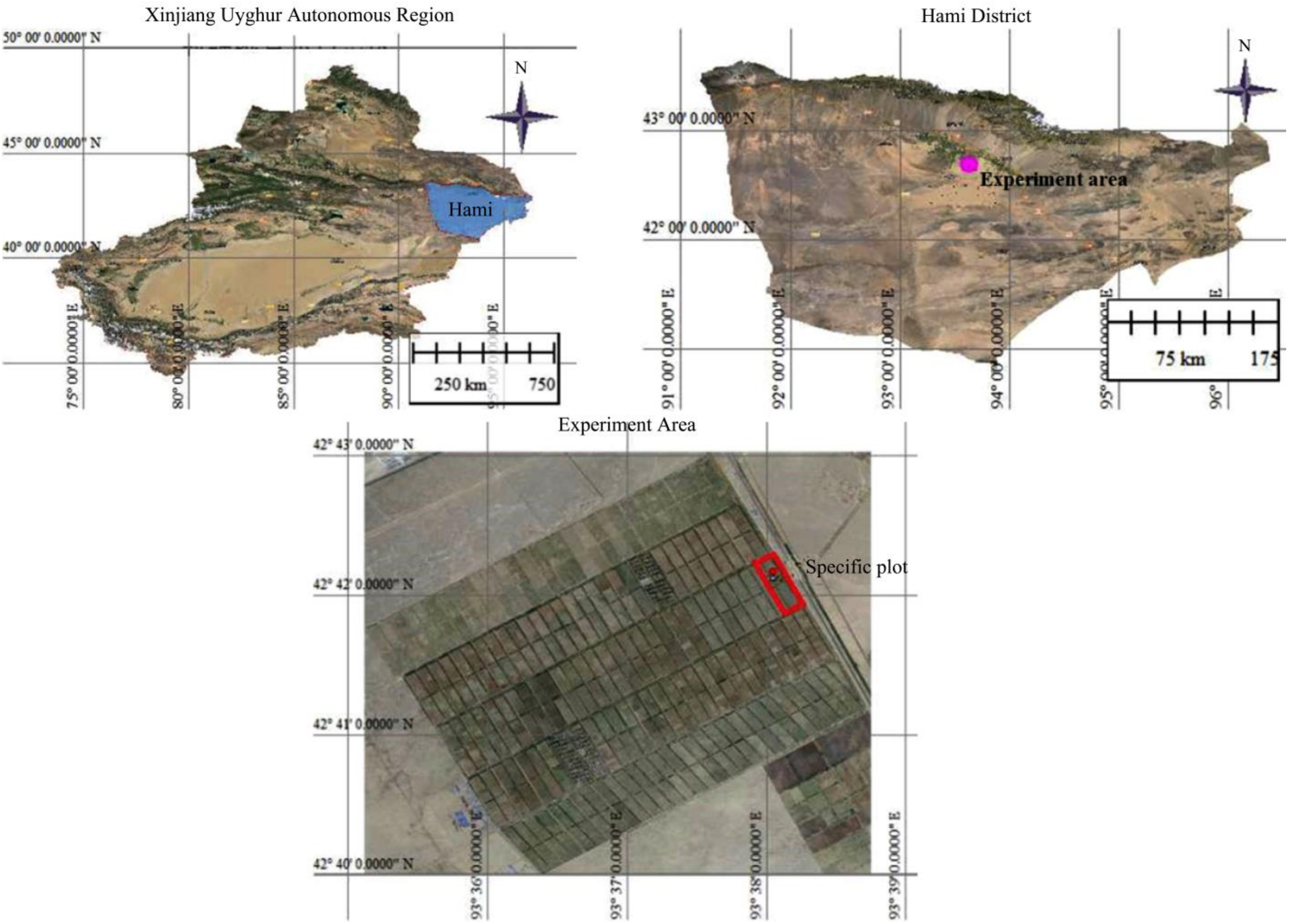


Figure 1 Schematic of the experiment area's geographical position

2.2 Irrigation and N-fertilization treatments

The age of the jujube trees in the experimental zone was 13 years, with an average height of 1.65 m, 2 m of spacing between trees and 5 m of spacing between rows. The treatment comprised three levels of drip irrigation quotas and three N-fertilization rates; orthogonal testing was used. One flooding irrigation was set as the control treatment. The experimental design is shown in Table 1. Irrigation quota gradients, from smallest to largest, were indicated by A, B and C, respectively; fertilization rate gradients, from smallest to largest, were indicated by 1, 2 and 3, respectively; and the flooding control was indicated by CK. Each treatment cell included three consecutive lines with a line length of 30 m. To avoid interference, the middle line was selected as the test area. The irrigation and fertilization conditions were consistent in each treatment cell, and each treatment set was replicated three times.

The drip irrigation zone employed single-wing labyrinth tape. The pressure head of the water flow was

3.2 L/h, and the distance of the two drops of head was 30 cm. The drip irrigation belt was designed as two drip tubes arranged near one row of trees, with one tube on each side of the trees. The interval between drip irrigation belts was 120 cm: 60 cm away (on either side) from the trunks of the trees (Figure 2).

Table 1 Experiment design

Treatment	Irrigation quota /mm	Urea /kg hm^{-2}	Di-ammonium phosphate /kg hm^{-2}	Potassium sulfate /kg hm^{-2}	Total fertilization /kg hm^{-2}
CK	1300	240	450	510	1200
A1	820	240	450	510	1200
A2	820	330	570	600	1500
A3	820	420	690	690	1800
B1	900	240	450	510	1200
B2	900	330	570	600	1500
B3	900	420	690	690	1800
C1	980	240	450	510	1200
C2	980	330	570	600	1500
C3	980	420	690	690	1800

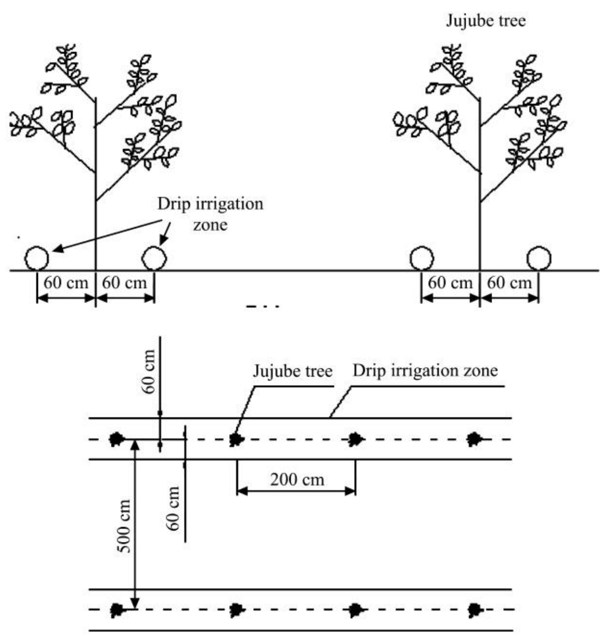


Figure 2 Drip irrigation layout diagram

2.3 ^{15}N labeling, sampling and measurements

^{15}N-labeled fertilizer (produced by the Shanghai Chemical Industry Research Institute; the abundance of ^{15}N was 5.22 atom %) was applied on five trees in the new-shoot growth phase, replacing conventional fertilization. The five trees were randomly selected and marked. Roots, branches, leaves and jujube fruit from each treatment were collected after the jujube harvest (October 5th, 2015; Table 2) by using a Cobra impact drill (inner diameter 10 cm); the sample depth was 90 cm. A soil block was collected from each 10-cm layer of depth, preserved in a labeled ziplock plastic bag and sieved to obtain roots for study in the laboratory. The specific sampling steps are shown in Figure 3.

Roots were separated by elutriating the soil blocks in clean water in the laboratory. Then, they were neatly placed on A3 paper with a 30-cm-long black tick mark and photographed. After vectorization using R2V vector analysis software, root length density was calculated via length conversion based on scaling relation in Excel. Later, the roots were put into dried kraft envelopes with known mass and were dried to a stable weight in a drying oven at 105°C. Then, the root weight density could be obtained by weighing the roots. Dried plant materials were fine-ground and analyzed by an elemental analyzer (FlashEA 1112 NC) connected to an isotope ratio mass spectrometer (Finnigan MAT 253) for their tissue N concentrations and ^{15}N isotope ratios. The atom% ^{15}N was determined and used to quantify the ^{15}N content of each plant component, which was calculated as the product of the dry weight of the plant component and the N concentration and corresponding atom% ^{15}N. Total ^{15}N uptake per plant (mg) was calculated as the difference between the sum of ^{15}N contents of all labeled plant components and corresponding control plant components. ^{15}N uptake rates by roots were expressed on a root dry mass basis (μmol/g·h).

Table 2 Growth period of Hami jujubes from 2013 to 2015

Year	Items	Germination	New shoot growth	Full bloom	Stigmas period	White-mature period	Full ripeness period	Whole growth period
2013	Start date	4/17	5/1	5/27	6/17	7/18	8/24	4/17
	End date	4/30	5/26	6/16	7/17	8/23	9/21	9/21
	Growth period/d	14	26	21	31	37	29	157
2014	Start date	4/15	4/30	6/6	7/2	8/1	9/4	4/15
	End date	4/29	6/5	7/1	7/31	9/3	9/26	9/26
	Growth period/d	15	37	26	30	34	23	164
2015	Start date	4/17	5/3	6/8	7/6	8/11	9/12	4/17
	End date	5/2	6/7	7/5	8/10	9/11	10/3	10/5
	Growth period/d	16	36	28	36	32	22	170

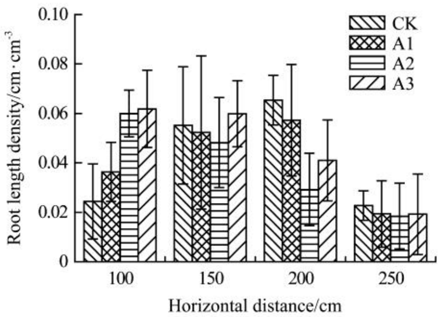
Figure 3 Photos of root collection

3 Results and discussion

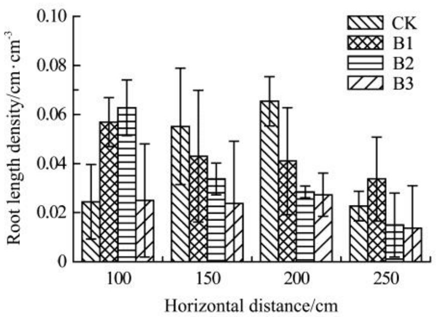
3.1 Horizontal distribution characteristics of dense, dwarfed jujubes' roots

3.1.1 Horizontal distribution of root length density

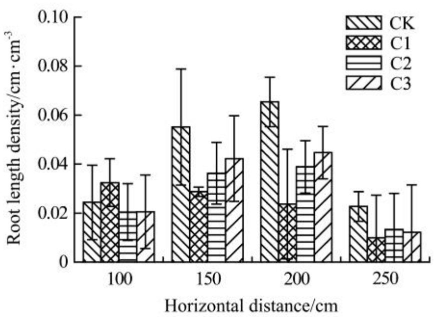
Horizontally, the closer to the trunk, the higher the root length density, and the larger the irrigation amount, the higher the root length density[21]. Comparison of root length density between drip irrigation treatment A groups (under the irrigation quota of 820 mm) and the CK group showed that, within a horizontal distance of trunk from 75 cm to 125 cm (Figure 4), root density was higher in the A groups than that in the flood irrigation treatment groups, and it was higher in high-fertilizer groups than in low-fertilizer groups[22]. Within the distance of 125-175 cm, root length density was not much different between drip irrigation treatment and flood irrigation treatment groups, ranging from 0.05 cm/cm^3 to 0.06 cm/cm^3, just as that in flood irrigation treatment groups. Within the distance of 175-225 cm, there was a variation trend that the higher the fertilizer amount, the lower the root length density, precisely the opposite of what happened within the distance of 75-125 cm. Comparing to flood irrigation control group CK, the root length densities of drip irrigation treatment groups were all relatively low. At a distance of 225-275 cm, the root length densities of drip irrigation and flood irrigation groups were both low, about 0.02 cm/cm^3, which was the lowest among all treatment groups.



a. Irrigation quotas of 820 mm



b. Irrigation quotas of 900 mm



c. Irrigation quotas of 980 mm

Figure 4 Horizontal distribution of root length densities

Under the irrigation quota of 900 mm, within the 75-125 cm distance from the trunks, root length density of the treatment B groups was higher than that of the flood irrigation group CK. Among the B groups, the group B2 with 1200 kg/hm^2 fertilization had the highest root length density, 0.063 cm/cm^3. Within the 125-175 cm distance from the trunks, flood irrigation group CK had the highest root length density, and in the B treatment groups, root length density lessened as the fertilizer amount was increased. From highest to lowest, the root length density of the four groups was CK > B1 > B2 > B3, and the differences between B1, B2, B3 and CK were 0.01 cm/cm^3, 0.02 cm/cm^3 and 0.03 cm/cm^3, respectively. Within the distance of 175-225 cm, the variation was almost the same as that within the 125-175 cm range, except that the differences were 0.02 cm/cm^3, 0.04 cm/cm^3 and 0.04 cm/cm^3, respectively. Within the distance of 225-275 cm, root length densities were all low, and compared to CK, B2 and B3 were lower, while B1 was slightly higher than CK.

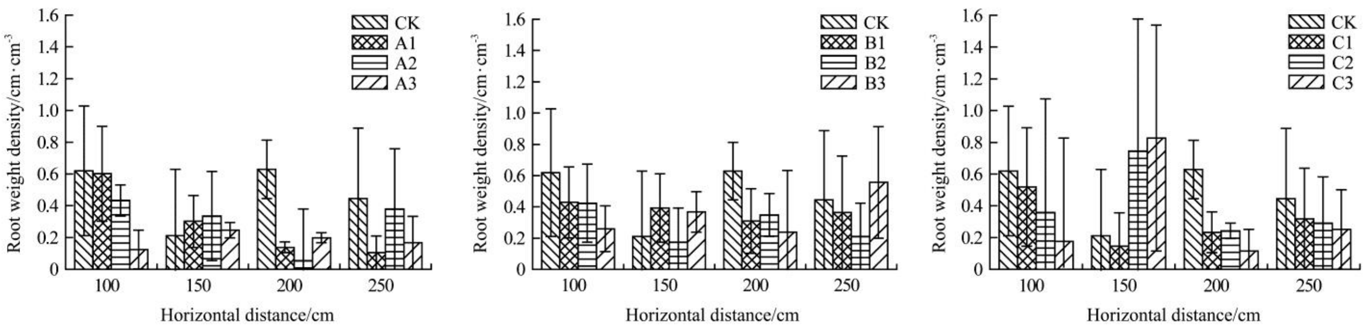
Under the irrigation quota of 980 mm, it can be seen in Figure 4 that the root length densities of drip irrigation C treatment groups were basically lower than that of CK. Within the distances of 75-125 cm and 225-275 cm from the trunks, differences in root length density between the drip irrigation groups and CK were not distinct, and differences among the C groups were quite small. Within the 125-225 cm distance from the trunks, the root length densities of C1, C2 and C3 were all lower than that of CK. At the same time, there was a trend of root length density increasing as the fertilizer amount was increased, such that C3 > C2 > C1.

The variation in root length density fit a single-peak curve that rose first and then decrease as the distance from the trunk increased[21]. The peak range of the A treatment groups, which had the lowest irrigation amount, was narrower than that of the B treatment groups. However, with the largest amount of irrigation, the peak range of the C treatment groups was larger than that of the B treatment groups.

3.1.2 Horizontal distribution of root weight density

The horizontal distribution of root weight density was similar to that of root length density; the horizontal distribution of root weight density showed that comparatively high values occurred in the range of 175-225 cm, while beyond that range, the farther from the trunk, the lower the root weight density. As the drip irrigation amount was increased, root weight densities at various horizontal distances from the trunk were like those for flood irrigation groups. With the same amount of drip irrigation, the root length density was comparatively higher when the fertilization amount was large[23].

From the figure above, it can be seen that in the CK group (flood irrigation), the variation in root weight densities showed two peaks at the distances of 75-125 cm and 175-225 cm from the trunk (Figure 5), showing that when applying flood irrigation, the roots did not only distribute densely when close to the trunk, but also distributed densely when far from the trunk.



a. Irrigation quotas of 820 mm b. Irrigation quotas of 900 mm c. Irrigation quotas of 980 mm

Figure 5 Horizontal distribution of root weight densities

In the A treatment groups, overall, the farther from the trunk, the lower the root weight density. Within the 75-125 cm distance from the trunk, group A1 had the highest root weight density, which was slightly lower than that of group CK (where flood irrigation was applied), followed by A2 and A3. With the increase of fertilization, the difference in value among the A treatment groups was not remarkable when the distance was 125-175 cm from the trunk, indicating that within this distance, fertilization amount had less effect on absorption of water and nutrients by the jujubes' roots. This suggests that water and nutrients mainly distributed close to the drip irrigation zone; only a small portion could reach far from that zone, influenced by plants' growth, water and nutrient absorption and water transfer in soil, resulting in a lower root weight density at the farther distances.

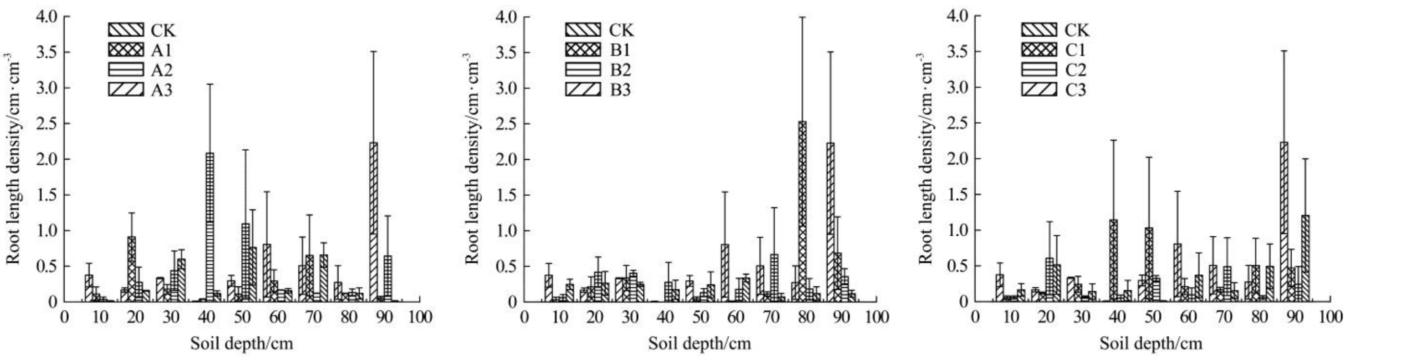
With different fertilization amounts and different distances to the trunk, root weight density in the B treatment groups with drip irrigation was applied was higher than that in the A groups overall. The reduction in density as the distance from the trunk increased was not as distinct as that in the A groups, indicating that the distribution range of water and nutrients was more extensive with a larger irrigation amount. Among the B groups, with different fertilization amounts, the differences among densities were not distinct, which implied that irrigation amount was the major factor influencing root weight density when the irrigation quota was 900 mm.

In general, root weight densities in the C treatment groups were slightly lower than those in the B groups, indicating that when the irrigation quota was 900 mm, and its effects on root weight density were restrained. With different amounts of fertilizer applied in the C groups, at distances of 75-125 cm and 175-250 cm, the larger the fertilization amount, the lower the root weight density, whereas root weight density increased as fertilization amount increased within the distance of 125-175 cm. In group C1, the root weight density reached 0.5 mg/cm^3 from 75 cm to 125 cm, and as the distance lengthened the root weight density lowered. In groups C2 and C3, the maximum root weight density occurred at a distance of 125-175 cm from the trunk.

3.2 Vertical distribution characteristics of dense, dwarfed jujubes' roots

3.2.1 Vertical distribution characteristics of root length density

Vertically, root length density showed that roots mainly distributed at depths of 20-30 cm and 60-80 cm[35]. Impacted by the artificial application of farmyard manure, the loosened soil had a greater capacity for water and fertilizer conservation, which made it suitable for root growth. Additionally, the latter depth resulted from migration characteristics of water and nutrients as well as the growth characteristics of the jujubes' roots. Fertilization amount had different effects on root weight density when the irrigation amount was equal, but its effect subsided as irrigation amount was increased to a certain point, which meant irrigation amount was the major factor that impacted root weight density[25]. Under the CK treatment, where flood irrigation was applied, root length density mainly occurred at depths of 20-30 cm and 90 cm (Figure 6)[26]. This was because at depths of 20-30 cm, farmyard manure was used frequently, resulting in loose soil with a great capacity for retaining water and nutrients, which was beneficial for root growth. However, impacted by actions such as digging holes during farmyard manure application, many roots were destroyed in this zone. Close to the water-obstructed layer, when water infiltrated to a depth of 90 cm, it concentrated there, thus water was sufficient for absorption and utilization. Moreover, without disruption by humans all year round, root growth flourished at this depth.



a. Irrigation quotas of 820 mm b. Irrigation quotas of 900 mm c. Irrigation quotas of 980 mm

Figure 6 Vertical distribution of root length densities

Under the A treatment, root length densities were mainly distributed at depths of 20-30 cm and 50-70 cm in the soil layer. The main reason was that farmyard manure application loosened soil and provided the capacity for conserving water and fertilizer at depths of 20-30 cm. Within the low irrigation quota of 820 mm, water and fertilizer could be absorbed and utilized by jujubes mainly in the 50-70 cm layer, with a small amount infiltrating to the deeper soil layer.

In the B treatment groups, where the drip irrigation quota was 900 mm, root length density increased at first, then decreased, but later increased again as depth increased. The low point was at depths of 40-50 cm, while in the 50-90 cm soil layer, it increased continuously and rapidly as depth increased. And in the zones below 90 cm deep, root length density was quite low. In the

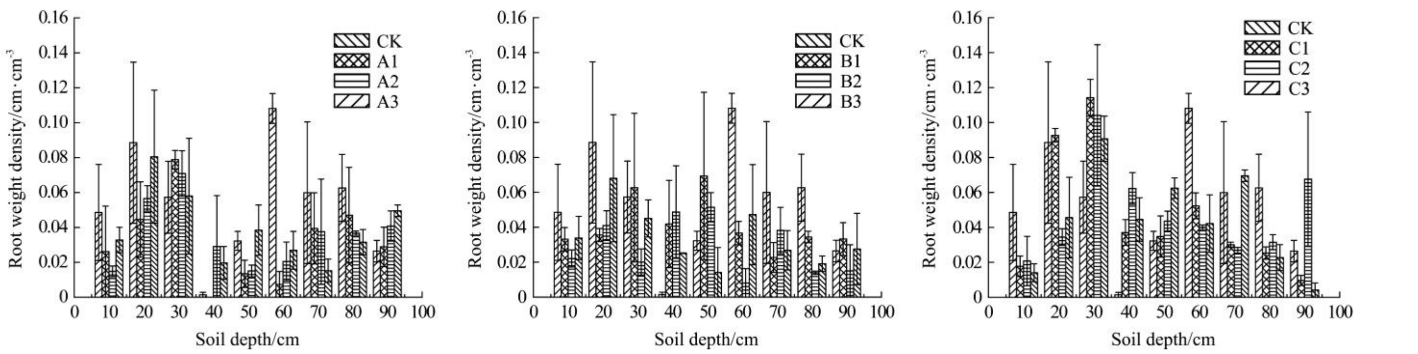
10-60 cm soil layer, root length density in the B treatment groups, where drip irrigation was applied, increased as fertilization amount increased; namely, B1 < B2 < B3. At a depth of around 70 cm, variation in root length density was not obvious with the change in fertilization amount. In the soil layer below 80 cm, root length density declined as fertilization amount increased; the trend was B1 > B2 > B3. Under the C treatment, root length density stayed high at depths of 20 cm and 40 cm.

3.2.2 Vertical distribution characteristics of root weight density

Under the CK treatment, root weight density was mainly distributed at depths of 20-30 cm and 60-80 cm (Figure 7). The distribution characteristics of root weight density in drip irrigation treatment A were the same as those in group CK, though with lower values than those in group CK because of the low irrigation quota. Root weight density at various depths of soil in treatment A varied with fertilization amount: the larger the fertilization amount, the higher the root weight density; the rank was A1 < A2 < A3.

In general, root weight densities in the B drip irrigation treatment groups were basically lower than those in the CK flood irrigation group. Layer depths with high root weight densities were identical to those in group CK, and no distinct rules were found regarding the effects of fertilization amount on root weight density.

Root weight density in the C drip irrigation groups mainly occurred in two soil layers of 20-30 cm and 60-80 cm. The variation tendency of root weight density as depth changed was similar to that in group CK, but with higher values of root weight density in the layer of 20-40 cm deep and lower values at depths of 60-80 cm than those in group CK. This was mainly due to the fact that more water reached the deeper soil layer (60-80 cm) providing better conditions for root growth, since the irrigation quota and the irrigation amount on each application was high when applying flood irrigation. Furthermore, in the C drip irrigation groups, root weight density did not show an obvious correlation under various amounts of fertilization, indicating that irrigation amount remained the major factor impacting root growth.



a. Irrigation quotas of 820 mm b. Irrigation quotas of 900 mm c. Irrigation quotas of 980 mm

Figure 7 Vertical distribution of root weight densities

3.3 Effects of water-fertilizer coupling on the yield of dwarfed, dense jujube

According to the randomly selected samples, the production of each experimental group in the experimental field from 2013 to 2015 was measured (Figure 8). The annual outputs in 2013, 2014 and 2015 reached 8783 kg/hm^2, 7764 kg/hm^2 and 7754 kg/hm^2, respectively. With a low or proper irrigation quota, increased the fertilization amount was beneficial to yield improvement, whereas a too-high irrigation quota led to a decline in yield when the fertilizer amount was increased[27]. With the same fertilization amount, the yield of fruits improved as the irrigation amount was increased[21]. In the case of fertilization with drip irrigation, the yield increased as the irrigation and fertilizer amounts were increased until the irrigation rate reached 900 mm and total fertilization reached 1500 kg/hm^2. After that, increasing the amount of irrigation and fertilization did *not* contribute to an increase in yield, but led to a decrease in yield to a certain extent, and the use efficiencies of irrigation water and fertilizer were reduced. We can predict that, when the irrigation quota is 900 mm and the total amount of fertilization is 1500 kg/hm^2, the moisture and nutrient requirements for the growth of dwarfed, close-planted jujubes can be satisfied and this guideline can be followed with confidence.

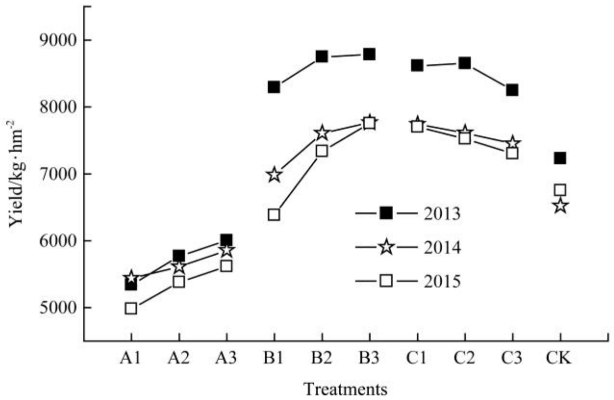


Figure 8 Jujube production under different treatments from 2013 to 2015

The mean yields of dense, dwarfed jujube trees in Hami under different treatments are shown in Table 3. The maximum yield per plant of jujubes occurred under the B treatment. The yield under treatment C was 104 g less, and under treatment A, 2904 g less, significantly lower than that of treatment B. This suggests that the drip irrigation quota was the important factor affecting the production ability of dense, dwarfed jujube trees. The yield per plant increased gradually with an increase in irrigation quota until the irrigation volume reached a certain level (900 mm); further increase in irrigation resulted in the opposite phenomenon. Moreover, the difference between the jujube yield per plant under the A, B and C treatments and the flooding treatment CK was 1526 g, 1378 g and 1274 g, respectively. It means that, as the drip irrigation quota rose to 900 mm, this increase ensured or even promoted the jujube production, while the increase in jujube production was inhibited when the irrigation quota was relatively low. To ensure the yield of jujubes, drip irrigation uses 31% less water than flooding at a high irrigation rate.

Table 3 Jujube production under different treatments

Treat-ments	Irrigation /mm	Number of jujubes per plant/date	Yield per plant /g	Dry matter /g
CK	1300	783±52	7230±114	9.23±0.14
A	820	670±27	5704±34	8.51±0.31
B	900	869±26	8608±36	9.90±0.27
C	980	852±32	8504±54	9.98±0.29

Similar to trends in the jujube yield per plant under treatments A, B and C and the flooding treatment CK, the minimum single-fruit weight among the drip irrigations and the flooding was 8.51 g under the minimum amount of treatment A. The single-fruit weights of B and C were similar, both being at least 16% heavier than those under treatment A. Compared to the CK group, the single-fruit weight under treatment A was 0.72 g less, while it increased by 0.67 g and 0.75 g under treatments B and C, respectively. This means that deficit irrigation will have a significant effect on the dry-matter accumulation of jujube fruits. When the amount of drip irrigation water is sufficient, the yield of dried jujubes can reach or even exceed that under flooding irrigation, because drip irrigation can ensure a relatively stable soil temperature, air humidity and other field microclimates, which are benefit to fruit growth[28]. Above all, compared to the flooding irrigation group, the 900 mm drip irrigation quota can meet the requirements of the dwarf jujubes' growth in Hami; the yield increased by 1378 kg/hm^2 with an increase rate of 19%, and 400 mm of irrigation water were saved at a saving rate of 31%. However, increasing the irrigation rate beyond this level will not only waste water resources, but also reduce production to a certain extent.

To sum up, with the appropriate irrigation quota, increasing the amount of fertilizer is conducive to the increase in production[29], but with an excessive irrigation quota, increasing the amount of fertilizer applied may adversely affect production. Under the same amount of fertilizer, the dwarf, close-planted jujube yield increased with the increase of irrigation water.

3.4 Effects of water-fertilizer coupling on nitrogen-use efficiency and fertilizer contribution for dense, dwarfed jujube

3.4.1 Effects of water-fertilizer coupling on nitrogen-use efficiency (NUE)

Nitrogen-use efficiency (NUE) is a term used to indicate the ratio of the amount of fertilizer N removed from the field by the crop to the amount of fertilizer N applied. It was calculated using the output-input ratio (crop N removal/mineral N fertilizer input)[30]. Generally, the NUE increased with an increase in fertilization rate (Figure 9). The NUE of the third level of total fertilizer application (1800 kg/h) was the highest

(40.8%), followed by that of the second level of total fertilizer application (1500 kg/h), 38.3%, and last was the lowest total fertilizer application (1200 kg/h), with a NUE of 37.4%. However, under the treatments with the same irrigation quota, the NUE didn't show a trend of increasing with the increase of the fertilization rate except under treatment B. Under treatment B, the NUEs of B1, B2 and B3 were 44.38%, 47.37% and 55.49% (B1 < B2 < B3), respectively. However, under treatment A, the order of NUEs was A1 (29.41%) > A2 (24.25%) > A3 (24.04%). Under treatment C, the NUE trend showed that C2 (43.29%) > C3 (42.82%) > C1 (38.26%). Under the treatments with the same fertilization rate, the NUE of irrigation quota B was larger than that of quota C, which was larger than that of quota A. This shows that under the same fertilization level, to a certain extent, increasing the irrigation quota is advantageous to the nitrogen uptake, but too low or too high irrigation quotas will inhibit the absorption of nitrogen fertilizer.

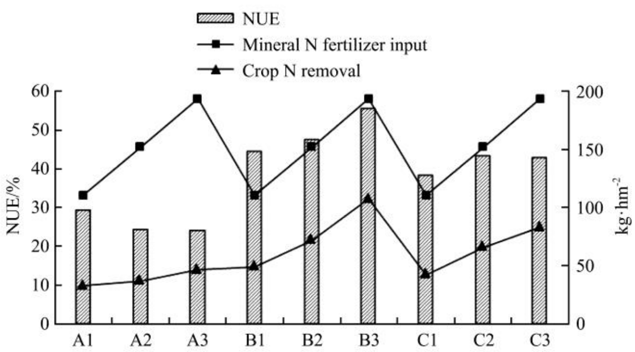


Figure 9 NUE values under different treatments

3.4.2 Effects of water-fertilizer coupling on Ndff (%)

Nitrogen fertilizer containing ^{15}N enabled the nitrogen derived from the fertilizer (Ndff) to be estimated, which reflects the plant organs' ability to absorb ^{15}N-labeled fertilizer[31]. The Ndff (%) was calculated using the following equation: Ndff (%) = (^{15}N atom% excess of plant sample/^{15}N atom% excess of fertilizer) × 100.

Under the same irrigation quota, the Ndff (%) in the roots of the dwarfed, close-planted jujube trees decreased with an increase in fertilizer application (Table 4). When the irrigation quota was 820 mm, the maximum value of Ndff (%) in the root occurred under treatment A1 (3.93%); the minimum value occurred under treatment A3 (1.11%). When the irrigation quotas were 900 mm and 980 mm, the Ndff (%) variation trends in the root following the increase of fertilizer application were consistent with that under the irrigation quota of 820 mm. Under the same amount of fertilizer, the Ndff (%) in the root under treatment C (4.02%) was largest, followed by treatment A (2.65%) and least in treatment B (2.02%). The difference between the Ndff (%) values in the root under the low irrigation quota and the high irrigation quota was very small.

Table 1 Production efficiency of different fertilizer treatments

Treatment	Yield /kg·hm^{-2}	N fertilizer rate/kg·hm^{-2}	Ndff in root/%	Ndff in whole plant/%	PFP /kg·kg^{-1}
CK	6757.5	110.4	-	-	61.21
A1	4982.7	110.4	3.93	13.26	45.13
A2	5381.1	151.8	2.90	11.68	35.45
A3	5617.4	193.2	1.11	10.89	29.08
B1	6384	110.4	2.14	5.72	57.83
B2	7339.2	151.8	2.55	8.65	48.35
B3	7758	193.2	1.37	7.12	40.16
C1	7705.1	110.4	5.82	13.68	69.79
C2	7527.3	151.8	4.18	7.02	49.59
C3	7307.1	193.2	2.07	5.83	37.82

Judging from the whole plant, the Ndff (%) of the dwarfed, close-planted jujube trees was highest under the lower irrigation quota, and decreased with an increase in fertilizer application rate. When the irrigation quota was 820 mm, the trend of Ndff (%) in the whole plant was A1 > A2 > A3, which was the same as that under the irrigation quota of 980 mm (C1 > C2 > C3). Under the same amount of fertilizer, the Ndff (%) was highest under the lower irrigation quota rate, and decreased with an increase in irrigation quota. When the amount of fertilizer is 1500 kg/hr, the trend of Ndff (%) in the whole plant was A2 > B 2> C2, which was same as that under the amount of fertilizer of 1800 kg/hr (C1 > C2 > C3). Within a certain range, the Ndff (%) in the whole plant decreased with an increase in irrigation and fertilization.

3.4.3 Effects of water-fertilizer coupling on partial factor productivity of nitrogen (PFP)

Nitrogen (N) is the key nutrient in jujube production. A low utilization efficiency of N means the nutrient is prone to leaching, volatilization, etc. To determine the efficiency of applied nutrients, Cassman et al.[32,33] introduced the term PFP. The advantage of this index is that it quantifies total economic output from any particular factor/nutrient, relative to its utilization from all resources in the system, including indigenous soil nutrients and nutrients from applied inputs. Thus, the value of PFP for N can be calculated using the following equation: PFP = jujube yield or dry-matter accumulation/N fertilizer rate, used to indicate the sustainability of the jujube planting production system.

Compared with that of the flood treatment (61.21 kg/kg), the PFP values for all the drip irrigation treatments were lower, except that under the treatment C1 (69.79 kg/kg), with an irrigation quota of 980 mm and a fertilization amount of 1200 kg/hr. Under the same irrigation quota condition, the PFP values of low-fertilizer treatment were lower than those of high-fertilizer treatment; that is, A1(45.13 kg/kg) > A2 (35.45 kg/kg) > A3 (29.08 kg/kg), B1 (57.83 kg/kg) > B2 (48.35 kg/kg) > B3 (40.16 kg/kg) and C1 (69.79 kg/kg) > C2 (49.59 kg/kg) > C3 (37.82 kg/kg). C1 was the most efficient fertilizer, indicating that moisture in extremely arid areas is a key factor in improving the fertilizer-use efficiency of jujube trees.

Under the same fertilization conditions, the PFP values increased with an increase in irrigation water. In the low-fertilizer treatment (1200 kg/h), the trend of PFP values was C1 > B1 > A1, which was same as that in the mid-fertilizer treatment (1500 kg/h), C2 > B2 > A2; the differences between the maximums and the minimums was 24.66 kg/kg and 14.14 kg/kg, respectively. However, in the high-fertilizer treatment (1800 kg/h), the trend of PFP values was B3 > C3 > A3. This result shows that when the amount of fertilizer is low, the improvement in PFP by increasing irrigation quantity is obvious. However, when the amount of fertilizer is high, increasing irrigation significantly reduces the improvement in PFP or even decreases the PFP value.

4 Conclusions

Our results describe root distribution and clarify nutrient-use efficiency with various rates of drip irrigation and N-fertilization treatment during a period of jujube development from 2013 to 2015. The different treatments resulted in the changes in spatial distribution of the jujube tree root systems. Flood irrigation group CK had the maximum root length density, with a relatively even distribution over various distances. In the drip irrigation treatment groups, the closer to the trunk, the higher the root length density. With the increase of dense, the optimum irrigation quota for the dwarfed jujube trees in the Hami district was 900 mm and fertilization amount was 1500-1800 kg/hm^2. When the irrigation quota was 900 mm, drip irrigation not only provided enough water for the jujubes' growth, but also facilitated better field relative humidity, soil temperature and other field environmental conditions, meaning that the jujubes grow in a suitable environment during the whole growth period, leading to high jujube yield and quality. The reasonable combination of irrigation quota and fertilization can improve the utilization and production efficiency of water and fertilizer, which developed more scientific field management, thus achieving higher yield.

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