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Interactive Effects of Nitrogen and Drip Irrigation Rates on Root Development of Corn (Zea Mays L.) and Residual Soil Moisture

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Abstract

Deficiencies in water and nitrogen (N) can lead to poor crop growth and production. This study was carried out during 2012–2014 to determine (1) the effect of drip irrigation regimes and N fertilizer rates on root length density (RLD) of corn (Zea mays L. cv. Single cross 704) and soil moisture dynamics and (2) the relationship between root development and water availability. The experiment was arranged into a split-plot design with three irrigation regimes as the main factor ($I_1 = 60$, $I_2 = 80$, and $I_3 = 100\%$ evapotranspiration [ET_c]) and five levels of N fertilizer ($N_1 = 0$, $N_2 = 50$, $N_3 = 100$, $N_4 = 150$ and $N_5 = 200$ kg/ha) as the subfactor. The combination I_1N_4 produced the highest grain yield and yield components while I_3N_5 gave the lowest performance. The highest RLD was recorded at full irrigation water requirement and it increased with increasing N rate, but not in a linear trend, as higher N rates showed less effect. Nitrogen application under drip irrigation increased the RLD in soil depending on irrigation level. Soil moisture was optimized at full irrigation water requirement and 150 kg/ha N.

Keywords Corn · Moisture distribution · Root length density · Drip irrigation · Water absorption

Auswirkungen von Stickstoff- und Tropfbewässerungsraten auf die Wurzelentwicklung von Mais (Zea mays L.) und die Restbodenfeuchte

Zusammenfassung

Ein Mangel an Wasser und Stickstoff (N) kann zu einem schlechten Pflanzenwachstum und einer schlechten Pflanzenproduktion führen. Diese Studie wurde im Zeitraum 2012–2014 durchgeführt, um (1) den Effekt von Tropfbewässerungssystemen und N-Düngerraten auf die Wurzellängendichte (RLD: root length density) von Mais (Zea mays L. cv. Single Cross 704) und die Dynamik der Bodenfeuchte und (2) die Beziehung zwischen Wurzelentwicklung und Wasserverfügbarkeit zu bestimmen. Das Experiment wurde in einem Split-Plot-Design mit drei Bewässerungsregimen als Hauptfaktor ($I_1 = 60$, $I_2 = 80$ und $I_3 = 100\%$ Evapotranspiration [ETc]) und fünf N-Düngergaben ($N_1 = 0$, $N_2 = 50$, $N_3 = 100$, $N_4 = 150$ und $N_5 = 200$ kg/ha) als Subfaktor durchgeführt. Die Kombination I_1N_4 lieferte den höchsten Kornertrag und die höchsten Ertragskomponenten, während I_3N_5 die geringste Leistung erbrachte. Die höchste RLD wurde bei vollem Bewässerungswasserbedarf verzeichnet und stieg mit zunehmender N-Rate an, jedoch nicht in einem linearen Trend, da höhere N-Raten eine geringere Wirkung zeigten. Die Stickstoffanwendung unter Tropfbewässerung erhöhte die RLD im Boden in Abhängigkeit vom Bewässerungsgrad. Die Bodenfeuchte wurde bei vollem Bewässerungswasserbedarf und 150 kg/ha N optimiert.

Schlüsselwörter Mais · Feuchtigkeitsverteilung · Wurzellängendichte · Tropfbewässerung · Wasseraufnahme

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Introduction

In irrigated areas, high yield can be achieved with appropriate water and fertilizer regimes. Technologies and methodologies are well developed and studied to define appropriate water regimes for different crops in the agricultural sector (Akhavan et al. 2019; Kosari et al. 2013), but the combination of water management with different farm input like fertilizer needs to be studied under different environmental conditions. Plant root systems are responsible for their growth and absorption of water and nutrients (Lynch 1995; Sathiyavani et al. 2017). Water and nitrogen (N) fertilizer are the most effective factors in agricultural production (Cassman 2001; Gonzalez-Dugo et al. 2010), so that a deficiency of these two elements can lead to an imbalance in crop growth with a negative impact on production and yield (Wang et al. 2017; Hongguang et al. 2017). The application of N fertilizer can also affect water use efficiency by influencing root growth and distribution in the soil. Therefore, to improve the cycle of nutrients in the soil-plant continuum, recognizing the most influncial factors in root growth and distribution is very important (De Giorgio and Fornaro 2012). The root length (RL) and root length density (RLD) distribution which is related to the root architecture, determines the absorption of water and nutrients from the soil (Gregory 2006; Chopart et al. 2008; Chilundo 2017). In other words, higher absorption of water is a function of root distribution, hence the provision of sufficient moisture and nitrogen will enable roots have more hairs, thus resulting in greater growth and yield (Ehdaie et al. 2010; Qi et al. 2017; Sathiyavani et al. 2017). Research related to roots is very important not only to understanding the properties of water and soil but also to increase crop productivity (Raven and Edwards 2001; Hongguang et al. 2017). Hoad et al. (2001) showed that surface application of N fertilizer increases root length density in the surface layers of the soil. Also, increases in root length and root surface area following the application of N fertilizer have been reported (Costa et al. 2002). Wang et al. (2008) found that corn root growth under application of 100 and 200 kg/ha N fertilizer was optimal but root growth was limited at 400 kg/ha nitrogen. De Giorgio and Fornaro (2012) showed that N fertilizer at 50 and 100 kg/ha had a greater effect on root development within the 20–30 cm soil depth than without N. These authors also showed that without N, the root growth was slower during the initial stage, but afterward, the root system was mainly developed within the 30–40 cm soil depth. Sathiyavani et al. (2017) found that higher nutrient supplies in the soil may also decrease root length but increase root weight. The root length density and specific root length of corn and cowpea decreased with soil depth (Mahgoub et al. 2017). Irrigation with high intervals such as drip irrigation that keeps the environment moist enough for water absorption prevents root growth to different soil depths. Moreover, soil N fertilizer and water availability are closely related and mutually affect each other (Hodge and Neculai 1994). Different corn hybrids may have different root phenology depending on rates of N fertilizer and soil moisture conditions, but this has been less considered. Since advanced irrigation systems such as drip irrigation has become a reliable strategy for improving agricultural water productivity in arid and semiarid regions and regions with water deficit due to climate change, this study aimed to determine (1) the effect of drip irrigation regimes and nitrogen rates on root length density (RLD) of corn (Zea mays L. cv. Single cross 704) and soil moisture absorption and (2) the relationship between root developmental dynamics and water availability under water stress.

Materials and Methods

Experimental Site

The experiment was carried out at the Research and Natural Resources Center of Kerman province, Iran (31°07′ N;

Table 1 Physicochemical properties of the experimental soil and irrigation water

Soil	Texture	Clay	Sand	Silt	FC	PW	SO_4^{-2}	HCO_3^-	CO_3^{-2}	Cl^-	Na^+	Mg^{+2}	Ca^{+2}	Fe^{++}	SAR	pH	EC_e (dS/m)
Soil depth		(%)					(Meq/l)										
0–30	Silty clay loam	6	86	8	16.3	5.84	8.63	2.8	–	8	5.21	10	10	–	1.65	8	0.85
30–60	Silty clay loam	10	81	9	16.5	6.6	7.9	4	–	4	4.78	4	6	–	2.13	7.59	0.9
60–90	Silty clay loam	9	80	11	17.2	7.3	5.52	4	–	2	4.93	10	4	–	1.78	7.53	0.78
Water	–	–	–	–	–	–	1.6	3.2	3.2	2	3.2	2.4	1.4	0.078	–	7.9	0.63

Table 2 Field and irrigation system information

Crop		Experimental design		Irrigation system	
Crop	Corn	Number of plots per block	15	Irrigation system	Drip irrigation (tape)
Field size	1 ha	Number of lines per plot	4	Emitter spacing	20 cm
Row spacing	75 cm	Length of each line	6 m	Nominal flow rate	2 Lit/h
Crop spacing	17 cm	Distance between repetitions	2 m	Pressure bearing	0.6 atm
–	–	Number of treatments	15	–	–
–	–	Total of experimental plots	45	–	–

Table 3 Monthly mean: minimum (T_{min}) and maximum (T_{max}) temperature, relative humidity (RH), Precipitation (P), and wind speed (U_2) at the experimental site during 2012–2014 growing seasons

Month	Season 2012–2013						Season 2013–2014					
	Sunshine duration (h)	RH (%)	Tmax (°C)	Tmin (°C)	P (mm)	U2 (m/s)	Sunshine duration (h)	RH (%)	Tmax (°C)	Tmin (°C)	P (mm)	U2 (m/s)
June	9.8	17.09	32.25	14.85	0	4.02	12.11	21.75	33.06	14.7	0	3.51
July	10.75	22.2	32.98	15.76	0.0003	3.85	11.42	16.9	37.02	19.28	0.0003	3.48
August	11.17	23	35.92	18.43	0.0003	3.72	12.08	17.75	37.89	18.77	0	3.76
September	11.96	22.74	33.72	14.25	0	3.64	10.93	23.58	35.27	16.25	0.245	3.60
October	9.87	27.51	31.31	12.53	0.1	3.32	10.86	18.6	34.03	12.58	0	3.075

57°14′ E, 1749 m above sea level) during the 2012–2014 agricultural season. The area is semi-arid with 2793 mm annual evaporation, 17 °C average temperature, 31.5% average relative humidity, and 124 mm average annual precipitation. The soil was silty clay loam with average field capacity and permanent wilting point of 16.66 and 6.58%, respectively. The soil and water characteristics of the experimental site are shown in Table 1.

Experimental Design and Treatments

The experiment was laid into a split-plot design with three irrigation regimes ($I_1 = 60$, $I_2 = 80$, and $I_3 = 100\%$ evapotranspiration [ET_c]) as main factor and five levels of nitrogen fertilizer ($N_1 = 0$, $N_2 = 50$, $N_3 = 100$, $N_4 = 150$ and $N_5 = 200$ kg/ha) as subfactor. Each treatment was replicated three times in a randomized complete block design. Nitrogen (N) was applied as urea three times: before planting, during stem giving and emergence of male inflorescences. Some information about the selected farm is presented in Table 2.

Irrigation Scheduling

Crop evapotranspiration (ET_c) was obtained with the following formula:

$$ET_c = ET_o \times K_c$$

Where ET_c is daily evapotranspiration (mm/day), ET_o is reference evapotranspiration (mm/day), K_c is the daily

crop coefficient for corn at different growth stages that was obtained from recommended values in FAO 56 and modified for the region (Allen et al. 1998). The K_c values for the initial, crop development, mid-season, and end-season of the corn growth stages were 0.4, 0.7, 1.1, and 0.5, respectively. The ET_o was estimated using Penman-Monteith-FAO (PMF-56) equation (Allen et al. 1998) recommended by Dehghanisanij et al. (2004) for the region.

The daily meteorological data, including the maximum and minimum air temperature, maximum and minimum relative humidity, wind speed at 2 m height, rainfall, and solar radiation were obtained from Kerman meteorology station. The weather data for the experimental site during the growing seasons of 2012–2014 is presented in Table 3.

Net irrigation depth (d_n) was calculated (mm) based on ET_c and by applying shading level and irrigation interval (which was twice a week). Gross irrigation depth (d_g) was obtained with the following formula:

$$d_g = \frac{d_n}{E_a}$$

The irrigation efficiency (E_a) was 95%. The volume of applied water for each treatment was measured using the volume meter. The irrigation interval was twice a week in this study.

Determination of Root Length Density (RLD)

Soil samples were collected 20, 45, 75, and 105 days after planting (DAP) at four depths of 10, 20, 30, and 40 cm to estimate the root length density (RLD). Newman's method

was used to measure root length. Using a special auger, the soil sample was collected at desired depths and analyzed in the laboratory. Roots were separated from the soil by first soaking the mixture overnight in 25 ml of Calgon solution to soften the soil. Then, 300 ml of water was added and stirred in an electric stirrer for 5 min and finally washed over a sieve of 53 km mesh to get roots onto the sieve. The suspension containing the root was then stirred and funneled into a cylindrical container and attached to a vacuum pump to slowly remove the water. After water removal, any root attached to the wall of the cylinder was slid with a thin wire to enter the suspension. After the smoothing operation is completed the flattened paper from which the roots were spread was slowly removed and placed on a clear plexiglas plate.

Then, after selecting another plexiglas page with a square grid (with black lines of 1×1 cm), it was placed on filter paper and randomly selected several squares (for example 20 squares) from the grid, numbered from 1–20. It should be noted that the squares do not have a common side with each other. Then each square was seen with a magnifying glass and the intersection of the roots with the sides of this square were counted. After the counting operation was complete, the sum of the intersections or contacts of the roots with the sides of the selected squares (for example 20 squares that are randomly selected) were counted to get the value of N. The total length of roots (RL) was estimated by the line intersection method (Newman 1966):

$$RL = \frac{\pi N A}{2H}$$

Where R is the total length of root (cm/gr), N is the number of intersections between the roots and the straight lines, A is the area on the grid of each square (cm²), H is the total length of the straight line and g is the soil weight. Root length density (RLD) was then calculated as follows:

$$RLD = RL \times \rho d$$

Where RLD is the root length density (cm/cm³) and ρd is the average Bulk Density at each depth (cm/gr). The sampling steps from the root are given in Table 4.

Table 4 Sampling times

Day after planting			
20	45	75	105
Root sampling depth			
–	–	0–10	0–10
–	0–10	10–20	10–20
0–10	10–20	20–30	20–30
10–20	20–30	30–40	30–40

Soil Moisture Measurement

To measure soil moisture, the weighting soil sampling method was used in different soil depths. Soil samples were manually collected with an auger at depths 0–10, 10–20, 20–30, 30–40, and 40–50 cm. The samples were placed in labeled plastic bags and weighed straight away. The samples were then oven-dried at 120 °C for at least 24 h until a constant weight was reached and then reweighed. The following formula was used to estimate the moisture content:

$$\theta = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

Where θ is the soil moisture (%) of each soil sample, W_1 is the empty weight (gr) of the container, W_2 is the total of container weight, and wet soil (gr), W_3 is the total container weight and dry soil (gr).

Corn Yield and Yield Components

For measurement of the corn growth parameters, the two middle rows were harvested. After excluding the border rows, plants were harvested to determine the grain yield and yield components: (thousand) grain weight, number of kernel rows, number of kernels per row, ear length and ear diameter. Also, the leaf area index (LAI) and water use efficiency were determined.

Statistical Analyses

Statistical analysis of the data was performed with MSTAT-C software. Duncan multiple range tests were applied to compare means of each trait at 5% probability.

Results and Discussion

Corn Yield and Yield Components

A summary of the analysis of variance for the measured traits of corn grown under different irrigation regimes and nitrogen fertilizer rates is shown in Table 5. Both, the irrigation regimes and nitrogen rates as well as their interactions had a significant effect ($p < 0.01$) on corn yield and yield components. The LAI was not affected by irrigation regimes or nitrogen rates, but by their interactions showed significant effects ($p < 0.01$).

The highest seed yield (8.85 ton/ha) and (thousand) kernel weight was achieved under I_1 treatment and the lowest kernel weight was under I_3 (Table 6). Previous studies have attributed corn grain yield loss due to drought stress at the reproductive stage to reduced photosynthesis efficiency and

Table 5 Summary of analysis of variance of irrigation regimes and different nitrogen fertilizer rates on corn yield and yield components

Sources of changes	Df	Seed yield ◦	Thousand-grain weight	Number of kernels per row	Number of kernels row	Ear length	Ear diameter	Leaf area index (LAI) (m^2/m^2)
Year	1	187,250.899 ns	613.126 ns	5.378 ns	0.900 ns	7.056 ns	1.496 ns	0.022 ns
Repeat * Year	4	674,423.636	361.513	14.711	2.756	2.396	18.13	1.911
Irrigation regime	2	484,503,082.648**	169,376.350**	3005.744**	71.244**	148.265**	843.242**	1.105 ns
Year * Irrigation regime	2	90,005.851 ns	36.918 ns	0.011 ns	0.133 ns	0.569 ns	0.012 ns	0.001 ns
Error	8	85,796.546	29.481	0.344	0.106	0.728	0.193	0.001
Fertilizer	4	22,929,531.685**	34,433.757**	833.928**	21.139**	96.147**	264.360**	3.835 ns
Year * Fertilizer	4	13,172.278 ns	3.032 ns	0.239 ns	0.150 ns	26.816 ns	0.021 ns	0.021 ns
Irrigation regime * Fertilizer	8	854,858.292**	1258.190**	29.411**	1.606**	24.925**	82.163**	0.034**
Year * Fertilizer * Irrigation regime	8	42,607.988 ns	1.443 ns	0.539 ns	0.050 ns	14.155 ns	0.072 ns	0.008 ns
Error	48	52,777.839	2.503	0.119	0.142	3.788	0.057	0.001
% CV	–	36.72	0.79	0.79	2.7	9.97	0.49	0.44

ns non-significant

**significant level 1%,*significant level 5%

Table 6 Main effects of irrigation regimes and nitrogen rates on corn yield and yield components

Treatments		Seed yield (ton/ha)	Thousand kernels weight (gr)	Number of kernels per row	Number of kernels row	Ear length (cm)	Ear Diameter (mm)
Irrigation regime	I_1	8.85a	254.1a	50.63a	14.90a	21.02a	51.13a
	I_2	8.35a	240.4a	47.83a	14.76a	20.74a	50.75a
	I_3	1.60b	99.6b	32.06b	12.16b	12.78b	35.27b
Nitrogen rates	N_1	5.33d	165.6d	34.11d	12.50d	17.08c	43.82c
	N_2	5.69d	178.4c	38.50c	13.38c	17.53bc	45.39bc
	N_3	6.76b	206b	47.44b	13.94b	18.88a	46.75ab
	N_4	7.43a	227.5a	49.61a	15.33a	19.40a	48.37a
	N_5	6.13c	212.8b	47.88b	14.56b	18.00b	44.26c

Means with non-like characters differ significantly at the 1% probability level

growth period (Schussler and Wastage 1991; Earl and Davis 2003; Nejad et al. 2017). There is a direct relationship between low crop yield and reduced crop water requirement over the whole crop season. Most plant processes directly or indirectly depend on availability of water (Sander and Bastiaanssen 2004). The highest number of kernel rows per cob (14.9) and number of kernels per row (50.63) was obtained in treatment I_1 while the lowest (12.16 and 32.06, respectively) was under I_3. The increase in the number of kernels row along with increased irrigation indicated a variation in the receipt of photosynthetic material for physiological purposes with levels of irrigation.

By reducing the amount of water consumed, the ear length was reduced from a maximum value of 21.02 cm under I_1, which was statistically similar to the value under I_2 (20.74 cm) to the lowest value of 12.78 cm under I_3 (Table 6). Corn yield and yield components were also

influenced by nitrogen fertilizer rates. Excessive consumption of nitrogen fertilizer adversely affected yield so that between the two rates of of $N_4 = 150$ and $N_5 = 200$ kg of N, the performance of N_4 was better than N_5 treatment. Excessive consumption of N prolongs crop growth period, increases plant foliage, and subsequently increases the crop biological yield, and this can decrease corn seed yield (Zeidan et al. 2006). Typically, in soils with low N content, seed yield increases by adding N fertilizer, but after reaching the peak yield, adding N fertilizer does not affect seed yield but may even reduce it. By increasing the N fertilizer rates to the recommended amount, the kernel weight increased, and with further increases in N, it decreased (Table 6). The N_4 treatment had the highest number of kernels per row (49.61) while N_1 had the lowest number (34.11). The highest number of kernel rows (15.33) was under N_4 and the lowest (12.5) was under N_1. By increasing the ap-

Table 7 Summary of analysis of variance of root length density (RLD) at different soil depths at 105 days after planting

Sources of changes	Df	RLD (cm/cm^3)			
		Depth of 0–10 cm	Depth of 10–20 cm	Depth of 20–30 cm	Depth of 30–40 cm
Year	1	0.004 ns	0.001 ns	1.145 ns	0.022 ns
Rep. * Year	4	0.025	0.235	0.385	0.159
Irrigation regimes	2	7.104**	19.003**	19.872**	26.980**
Year * Irrigation regimes	2	0.076 ns	0.091 ns	0.069 ns	0.150 ns
Error	8	0.031	0.105	0.105	0.199
Nitrogen fertilizer	4	1.294**	2.013**	2.397**	16.543**
Nitrogen fertilizer * Year	4	0.010ns	0.012ns	0.021 ns	0.042 ns
Irrigation regimes * Nitrogen fertilizer	8	0.119**	0.111**	0.069**	2.096**
Year * Irrigation regimes * Nitrogen fertilizer	8	0.008 ns	0.009 ns	0.012 ns	0.015 ns
Error	48	0.011	0.015	0.018	0.052
CV (%)	–	4.66	2.43	1.82	2.94

ns non-significant
** significant level 1%

Table 8 Interaction effects of irrigation regimes and nitrogen rates on corn yield and yield components

Treatments	Seed yield (ton/ha)	Thousand kernels weight (gr)	Number of kernels per row	Number of kernels row	Ear length (cm)	Ear Diameter (mm)	Leaf area index (LAI) (m^2/m^2)
I1*N1	7.56 e	213.4f	42.16f	13.17e	19.67d	49.97d	5.55def
I1*N2	8.13 d	234.7e	46.66d	14.33d	19.95d	50.52 cd	5.84cde
I1*N3	9.5 b	262.4c	5316b	15.17c	21.85c	51.23bc	6.24abc
I1*N4	10.60a	287.2a	55.50a	16.33a	22.15a	53.15a	6.63a
I1*N5	8.39d	272.7b	54.66ab	15.05bc	21.48bc	50.80 cd	6.53b
I2*N1	6.87f	187.5h	39.33h	13.83de	19.43d	48.37e	5.41ef
I2*N2	7.32e	201.8g	44.00e	14.50d	19.95d	49.87d	5.81cde
I2*N3	8.9 c	253.2d	51.33c	14.50d	21.42bc	51.32bc	6.05bcd
I2*N4	9.86b	284.1a	52.33bc	15.33b	22.03ab	52.58ab	6.40ab
I2*N5	8.75 c	275.5b	51.16c	15.67b	20.88c	51.62bc	6.41ab
I3*N1	1.55g	95.87k	26.83k	12.33fg	12.15gh	33.12i	5.03f
I3*N2	1.63g	98.68jk	41.00g	12.50f	12.70g	35.80h	5.57de
I3*N3	1.73g	102.4j	37.83i	12.17fg	13.38f	37.70g	5.83cde
I3*N4	1.83g	111.1i	36.83j	11.33g	14.02e	39.38f	6.36abc
I3*N5	1.24h	90.18l	23.83l	10.50h	11.63h	30.37j	6.10abcd

Means with non-like characters differ significantly at the 1% probability level

plication of N to 150 kg/ha, the ear length increased and the longest (19.40 cm) was under N_4. Excessive consumption of N fertilizer reduced the ear length. As shown in Table 7, the N_4 treatment had the highest ear diameter. Interaction of different irrigation regimes and N rates showed a significant effect on seed yield, and I_1N_4 had the highest seed yield (10.6 ton/ha) while I_3N_5 had the lowest (1.24 ton/ha). One of the remarkable points is the performance of I_2N_4 relative to I_1N_3. Although less water was used under I_2N_4, further application of fertilizer increased yields to some extent (Table 8).

Thus, it seems that applying more N fertilizer under water stress leads to higher yields compared to no-water stress

conditions as reported in Zeidan et al. (2006). The heaviest kernels were harvested under I_1N_4 and I_2N_4 treatment with values of 287.2 and 284.1 g per thousand grains, respectively. The lowest kernel weight was obtained under I_3N_5 treatment. Also, the highest number of kernels per row, number of kernels row, ear length, and ear diameter were under I_1N_4 treatment, and the lowest were under I_3N_5. I_1N_4 had the highest LAI (6.63 m^2/m^2), the lowest (5.03 m^2/m^2) being under I_3N_1 (Table 8).

Table 9 Main effects of irrigation regimes and nitrogen rates on root length density (RLD) at 105 days after planting

Treatments	Df	RLD (cm/cm^3)			
		Depth of 0–10 cm	Depth of 10–20 cm	Depth of 20–30 cm	Depth of 30–40 cm
Irrigation regimes	I1	2.76 a	5.70 a	8.08 a	7.45 a
	I2	2.42 ab	5.17 b	7.41 ab	7.08 ab
	I3	1.75 c	4.13 c	6.46 c	5.65 c
Nitrogen fertilizer	N1	1.95 d	4.56 d	6.83 d	5.1 e
	N2	2.15 c	4.80 c	7.1 c	5.29 d
	N3	2.31 bc	5.03 b	7.36 b	5.98 c
	N4	2.66 a	5.41 a	7.76 a	6.91 a
	N5	2.40 b	5.20 ab	7.53 ab	6.37 b

Means with non-like characters differ significantly at the 1% probability level

Table 10 Interaction effects of irrigation regimes and nitrogen rates on root length density (RLD) at 105 days after planting

Treatments	RLD (cm/cm^3)			
	Depth of 0–10 cm	Depth of 10–20 cm	Depth of 20–30 cm	Depth of 30–40 cm
I1*N1	2.38 abcd	5.17 bcde	7.57 cde	5.88 cdef
I1*N2	2.59 abcd	5.36 abcd	7.77 bcd	6.51 cd
I1*N3	2.72 abc	5.70 ab	8.14 abc	7.77 b
I1*N4	3.07 a	6.30 a	8.58 a	8.24 a
I1*N5	2.74 abc	5.97 ab	8.36 ab	8.13 ab
I2*N1	1.88 cd	4.64 cdefg	6.77 fgh	5.54 ef
I2*N2	2.20 abcd	5.03 bcdef	7.23 defg	6.17 cde
I2*N3	2.44 abcd	5.24 bcde	7.49 cdef	6.79 c
I2*N4	2.97 ab	5.55 abc	7.89 abcd	6.78 a
I2*N5	2.61 abc	5.39 abcd	7.63 bcd	6.13 ab
I3*N1	1.58 d	3.86 g	6.14 h	5.18 f
I3*N2	1.65 d	4.02 g	6.30 h	5.50 ef
I3*N3	1.76 cd	4.15 fg	6.46 gh	5.70 def
I3*N4	1.93 bcd	4.38 defg	6.82 efgh	6.0 cdef
I3*N5	1.84 cd	4.26 efg	6.59 gh	5.86 cdef

Means with non-like characters differ significantly at the 1% probability level

Root Length Density (RLD)

Summary of analysis of variance of different irrigation regimes and nitrogen fertilizer rates on corn yield and yield components at final sampling time (105 DAP) are presented in Table 7. As shown, both irrigation regimes and N fertilizer rates as well as their interactions had a significant effect ($p < 0.01$) on RLD.

Under different irrigation regimes, the RLD increased with an increase in soil depth (up to 30 cm), but after that, it decreased with increasing depth. At the 20–30 cm depth, the highest RLD was 8.08 cm/cm³ under I_1 treatment and the lowest was 1.75 cm/cm³ at a depth of 0–10 cm under I_1. The RLD increased with increasing N fertilizer rates (up to 150 kg/ha), then decreased thereafter and the highest RLD was under N_4 treatment at the 20–30 cm depth; the lowest was 1.95 cm/cm³ under N_1 at the 0–10 cm depth (Table 9). These results are in agreement with previous re-

ports (Materechera and Mloza-Banda 1997; Raj et al. 2013; Mahgoub et al. 2017; De Giorgio and Fornaro 2012).

The interaction between irrigation regimes and N fertilizer rates had significant effects on RLD (Table 10). Nitrogen application at 150 kg/ha under I_1 irrigation regime (I_1N_4) gave the highest RLD (8.58 cm/cm³) at the 20–30 cm soil depth. The lowest RLD was 1.58 cm/cm³ at the 0–10 cm soil depth with no N fertilizer under I_3 irrigation regime (I_3N_1) (Table 10).

The mean RLD at each soil depth for I_1 under different N fertilizer rates are shown in Fig. 1. The RLD increased consistently with increasing soil depth (to 30 cm) across N rates during crop growth stages, but decreased with increasing depth thereafter. Across soil depths, the highest RLD was observed at 105 DAP which was the last sampling time. Accordingly, the different N fertilizer rates caused a change in RLD, but the high N rates had no significant effect and even caused a reduction in RLD. Comfort et al. (1988) also found that higher rates of nitrogen fertilizer re-

Fig. 1 The interaction of different N rates and I₁ treatment on root length density (RLD) at the different soil depths
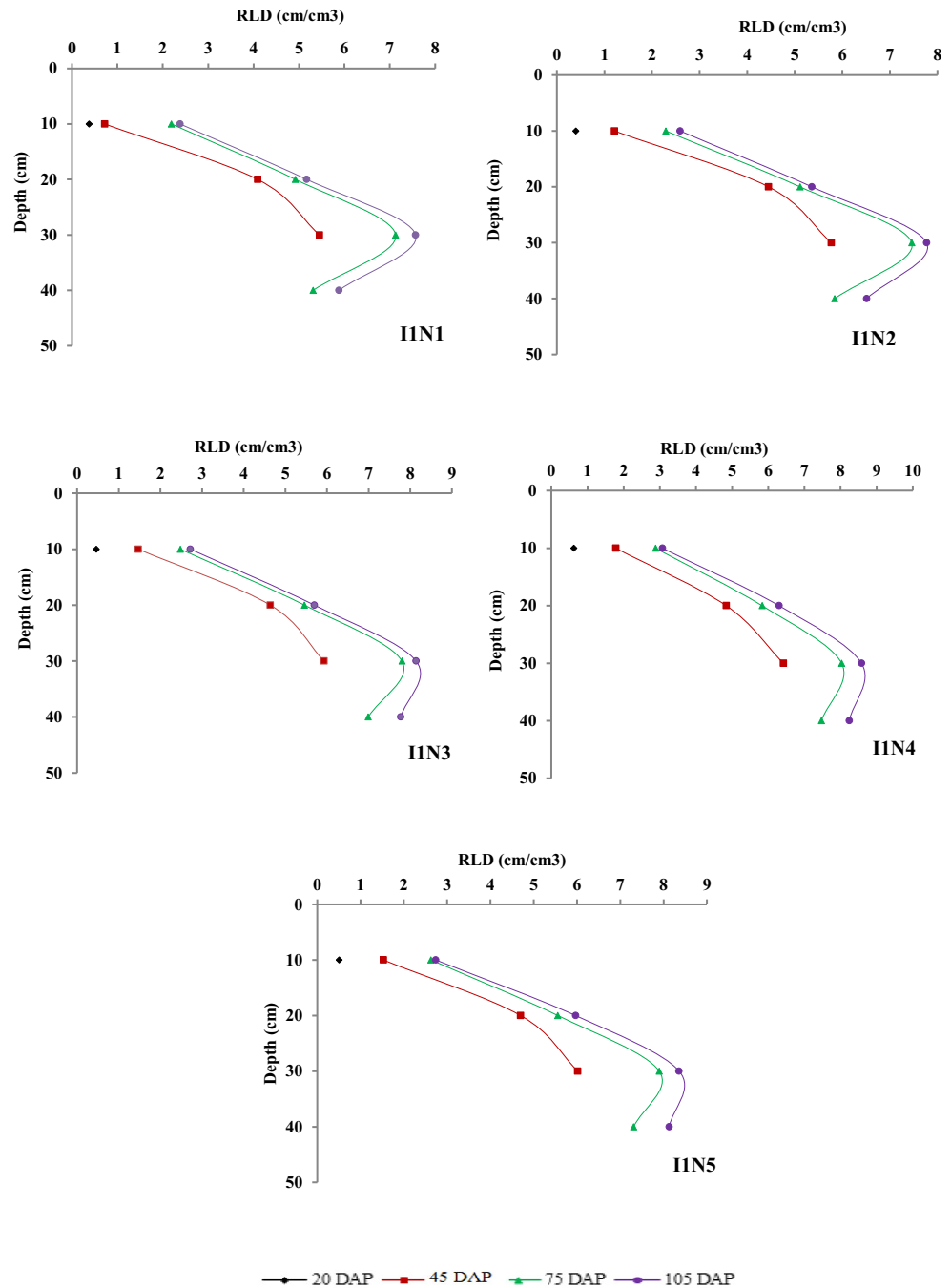

duced root growth and depth of rooting in wheat. There was little difference in RLD between N_1 and N_2 treatments, as well as between N_3 and N_5 treatments.

Under I_1 treatment at different N fertilization rates, the RLD increased in all depths and times of sampling, but the high N rate (N_5) did not sustain the increase and even reduced it; at 105 DAP, the highest RLD was at the 20–30 cm soil depth under N_4 treatment. The interaction effects of I_2 and the different N fertilization rates on RLD was significant across soil depths (Fig. 2). However, for the 0–10 and

10–20 cm depths, only small statistical differences among different treatments were observed at 75 and 105 DAP. At the 10–30 cm soil depth, the increase in RLD occurred across treatments, but at the 30–40 cm depth, there were reductions in RLD, especially under N_1 (Fig. 2). At the 10–20 cm soil depth, the RLD increased across treatments except N_1 treatment. At 75 and 105 DAP, and in N_2 and N_3 treatments, the RLD values were very close to each other.

Across soil depths, there was no significant difference between the last two growth stages compared to 45 DAP

Fig. 2 The interaction of different N rates and I_2 treatment on root length density (RLD) at the different soil depths
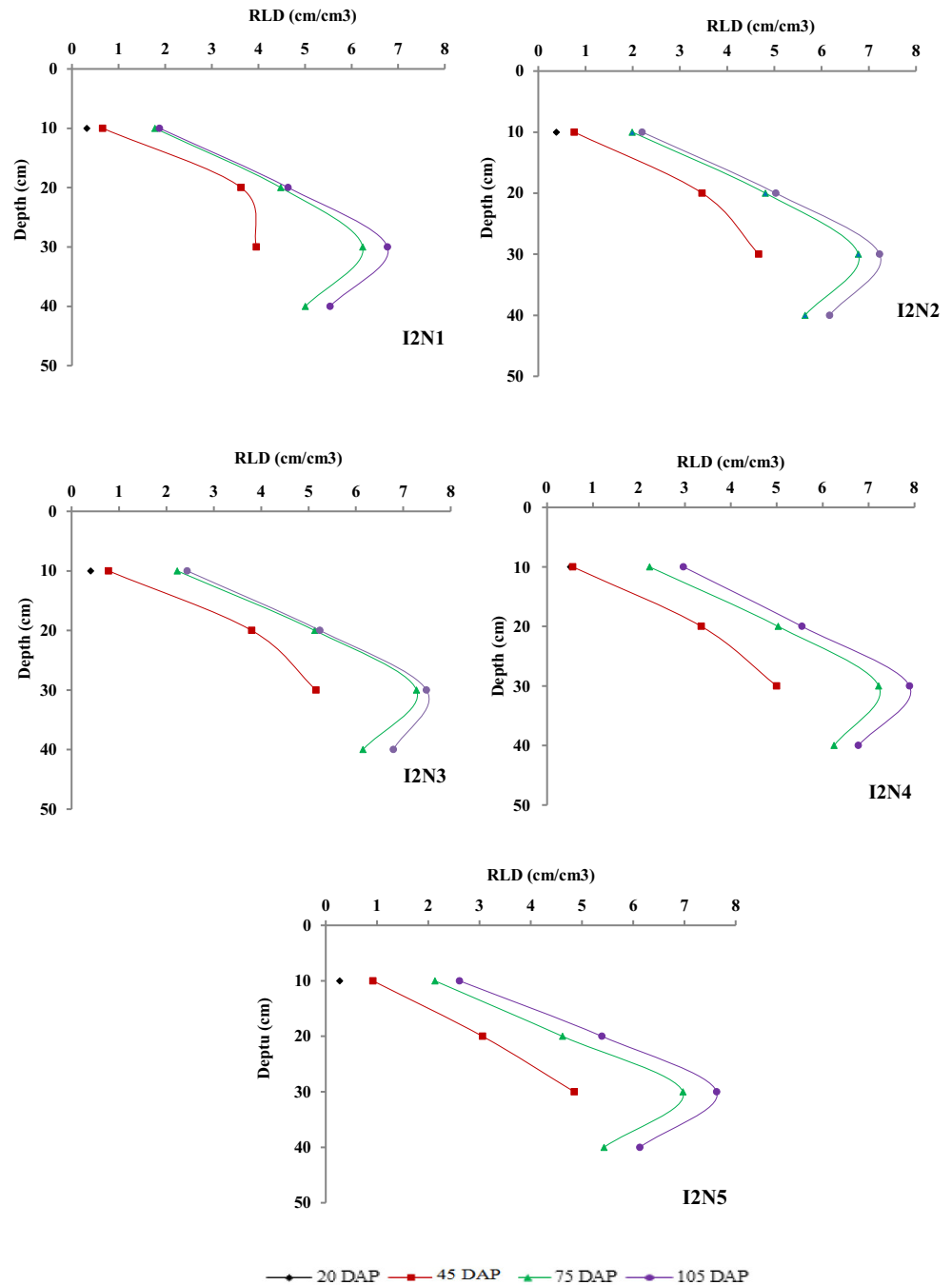
(Fig. 2). For the 30–40 cm soil depth, an increase was observed for all N fertilizer treatments. In particular, the RLD increased with increasing N rate (Fig. 3) at all times of sampling. Overall, the results indicated that with N fertilizer treatment, increases in RLD are still visible, even at the end-season stage. Among treatments, the lowest RLD was under N_1 treatment at the 0–10 cm soil depth and 25 DAP and the highest was under N_4 treatment at the 20–30 cm soil depth and 105 DAP. These results are consistent with those of Lv et al. (2010) and Gao et al. (2010) who found that

corn root length density was high in the topsoil layer. Mengel and Barber (1974) found that root length and RLD increased rapidly within 80 days after planting and remained constant for 14 days. However, when the plant was in the reproductive stages, it decreased quickly.

The changes in RLD under the interaction of I_3 and different N rates are presented in Fig. 3. At the 0–10 and 10–20 cm soil depths, only small differences were observed among treatments at 75 and 105 DAP. The lowest RLD was under I_3 and N_1 treatments, which indicated that deficit

Fig. 3 The interaction of different N rates and I_3 treatment on root length density (RLD) at the different soil depths
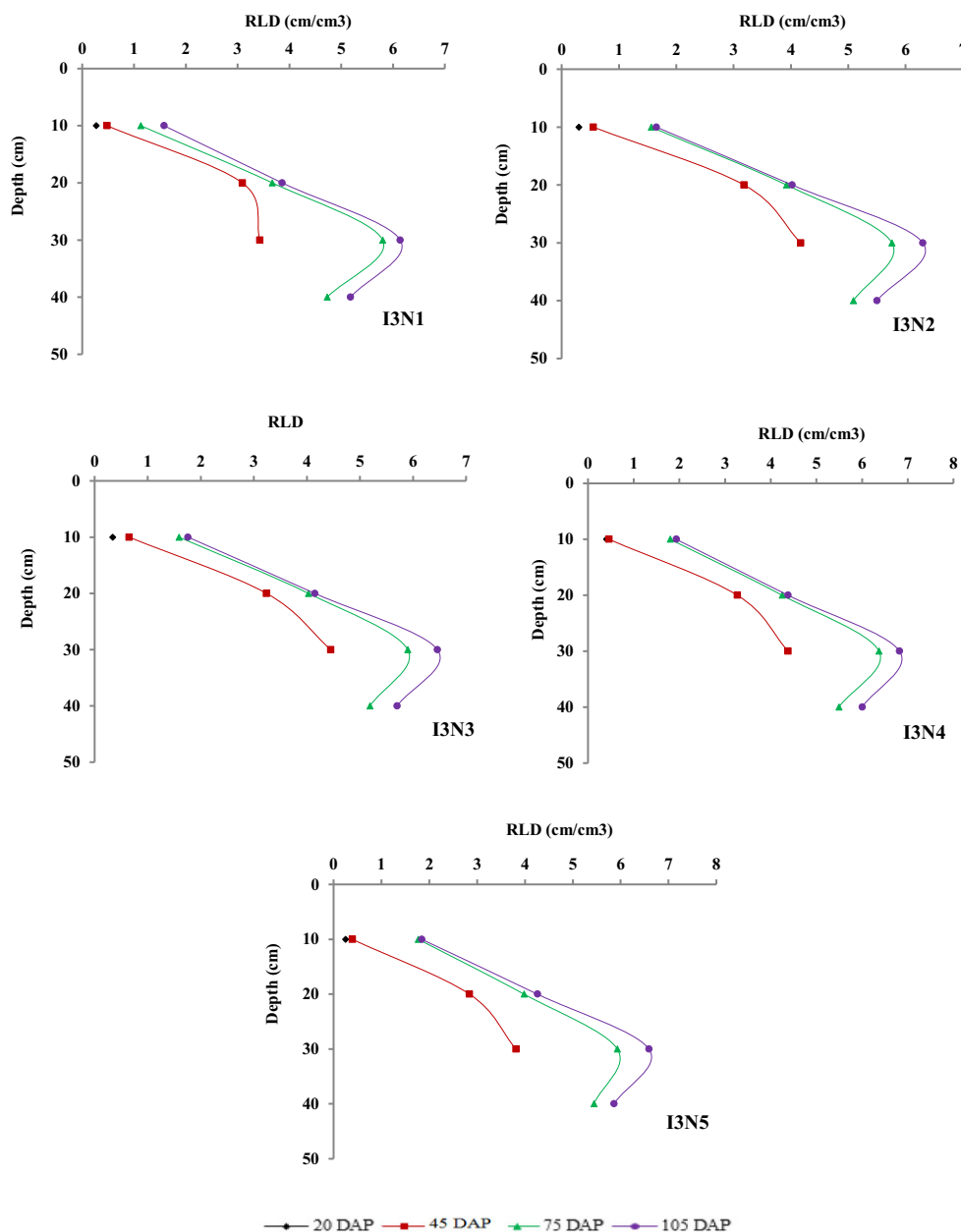
irrigation and no fertilizer application can cause a severe reduction in RLD. These results are compatible with those of Eghball et al. (1993) and De Giorgio and Fornaro (2012) who found that N stress in crop reduced root branching. At other depths despite high water reduction, N application increased the RLD. The increase in RLD following increases in N rates was not linear. Duriex et al. (1994) found that the maximum RLD for silking plant was achieved with 140 kg/ha N fertilizer in a clay sandy loam soil at the 60 cm depth. In their research, the highest root length was accumulated in the soil surface layers, because at the final growth stage, N fertilizer uptake caused a decrease in RLD. Similar to this study, De Giorgio and Fornaro (2012) showed

that the amounts of nitrogen (N) fertilizer 50 and 100 kg/ha had a greater effect on root development in the 20–30 cm soil depth than the control test (N_0) without nitrogen fertilization. In general, by applying 60% water requirements (I_3) across N rates, the RLD decreased sharply at all stages of sampling compared to 80 and 100% water requirements (Fig. 3).

At the final sampling time (105 DAP), on average, about 10.80% RLD was in the 0–10 cm depth, 23.76% in the 10–20 cm depth, 34.95% in the 20–30 cm depth, and 30.50% in the 30–40 cm depth, which had the task of water absorption (Fig. 4). From these results, the RLD increased with increasing soil depth up to 30 cm and decreased there-
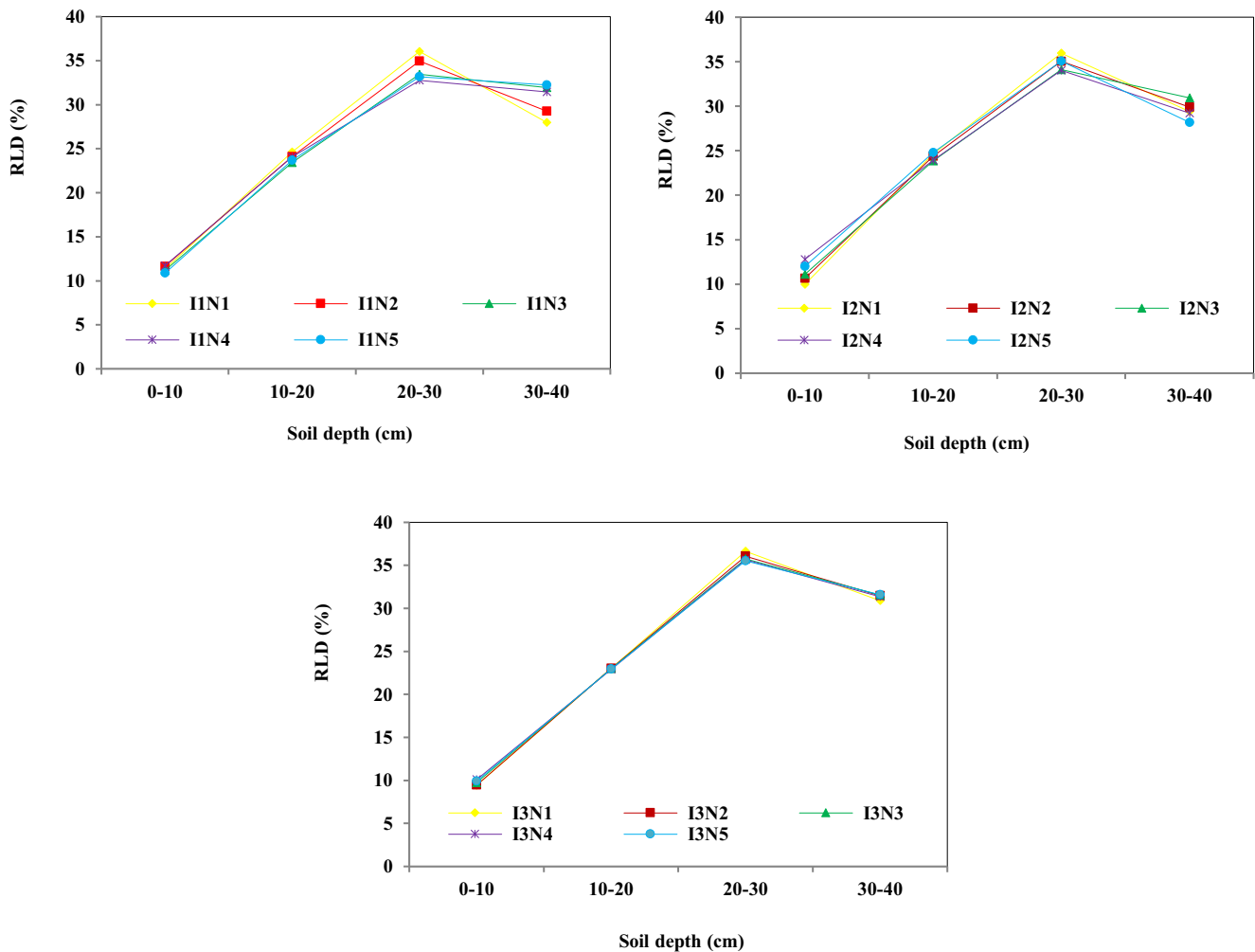
Fig. 4 Percentage of root length density (RLD) in different treatments at the final sampling time (105 DAP)

after as reported previously (Qi et al. 2017; Gao et al. 2010; Mahgoub et al. 2017).

The residual soil moisture (RSM) at different soil depths and N rates under I_1 during the four sampling times (20, 45, 75, and 105 DAP) are presented in Fig. 5. At 20 DAP, the RSM in the surface (0–10 cm) soil under N_1 and N_2 treatments (11.68 and 13.3%, respectively) reached the permanent wilting point because of the low plant canopy cover of the soil and high soil evaporation at the initial stage. At the other N fertilizer rates, there were relatively better moisture conditions, especially under the I_1N_4 treatment. At the 10–20 cm depth, all treatments had better moisture conditions (Fig. 5).

Due to increased crop growth and temperature in the second time of sampling (45 DAP), the RSM at the 0–10 cm depth was significantly reduced across fertilizer treatments to only about 5–6%. At the 10–20 cm depth, almost all N fertilizer treatments had ample soil moisture which is normal during the initial stage as the plant's water demand is low in this stage and soil evaporation is also low at this depth. Moisture levels in the 20–30 cm soil depth were high across treatments, ranging from 18–20% (Fig. 5).

Due to crop development at 75 DAP, soil moisture depletion at the 0–10, 10–20 and 20–30 cm depth was very intense because these layers had more root accumulation. High moisture depletion at the two depths of 0–10 and 10–20 cm was especially noticeable and the RSM at these two layers was even less than the permanent wilting point. Herein, vegetation level caused less evaporation and water depletion on the surface layers contributed to corn growth and production. As a result, the residual moisture at the 20–30 cm depth was also at the permanent wilting point, which indicates excessive use of the moisture in this layer by the plant. Also, at the 30–40 cm depth, only N_4 and N_5 treatments had good moisture conditions, and the other three layers lacked adequate moisture. As a result, the root length density was very low at the 30–40 cm depth, thus, the differences in RSM under different N fertilizer treatments indicated less water requirements in treatments with high N fertilizer.

Fig. 5 Residual soil moisture at different depths under I_1 treatment and N rates
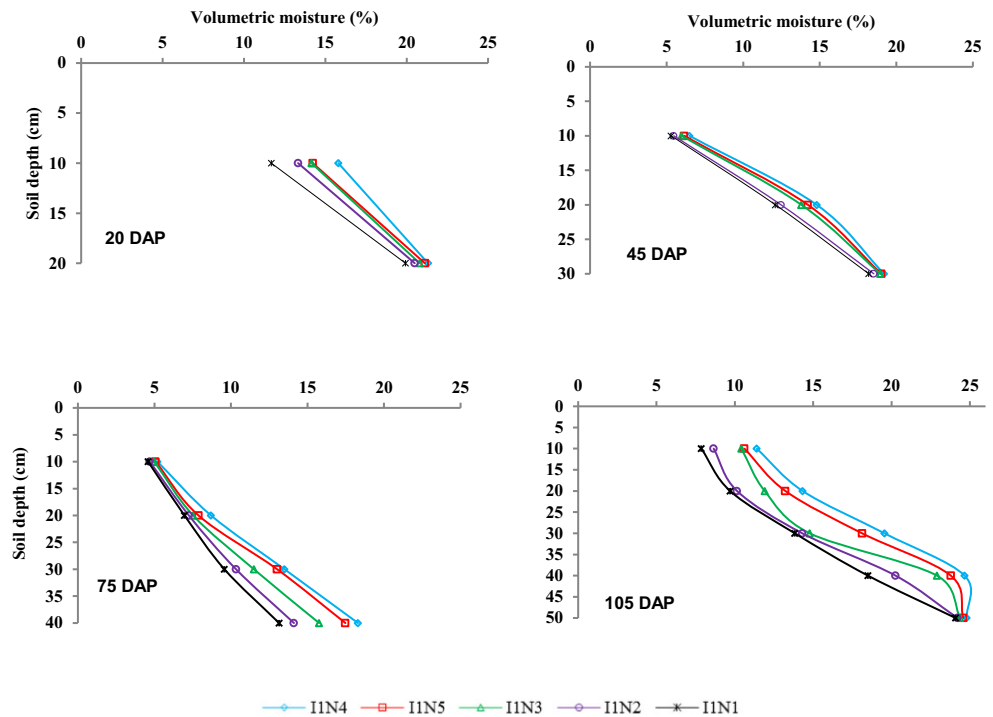
At 105 DAP, when the plant was at the end of its growth, the situation was completely different. As shown in Fig. 5, the RSM across N rates at depths of 0–10 and 10–20 cm was at the permanent wilting point. Also, the difference in residual moisture between high and low N rates was 4%. At the 20–30 cm depth, RSM under N_4 and N_5 treatments was close to 20%, but for N_1, N_2, and N_3 treatments, it was

at permanent wilting point. This is because at these depths, there was no evaporation due to the complete vegetation cover and the excessive depletion of soil moisture was due to the high water demand by the plant. At the 30–40 cm depth, with less root density, the RSM was very close to N_3, N_4, and N_5 treatments, which varied between 20 and 21% (Fig. 5). For the N_2 treatment, the RSM was about

Fig. 6 Residual soil moisture at different depths under I_2 treatment and N rates
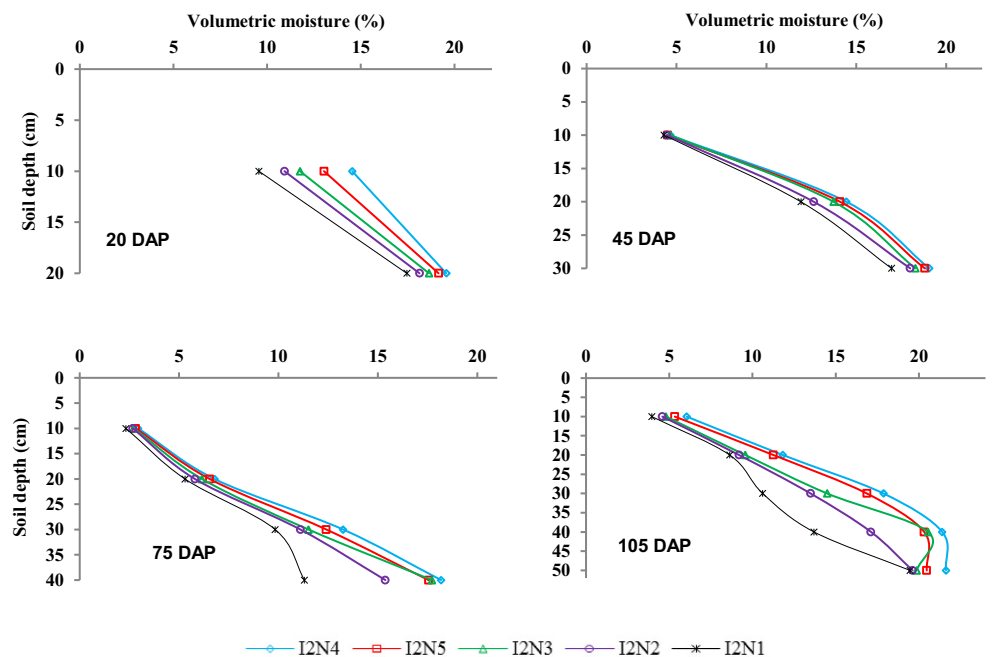
17%, but the N_1 treatment had about 13%, which indicates high water absorption. At the 40–50 cm depth, there was little difference in soil moisture across treatments, indicating the absence of absorption and moisture depletion from this depth, which is expected due to the low root length density at this depth.

The RSM at different depths under I_2 treatment across N rates and sampling times is presented in Fig. 6. At 20 DAP, the RSM (0–10 cm) under N_1 treatment was 9.5% and for the other N rates, it was between 11 and 14%, which is at the permanent wilting point level. Low vegetation at the time of sampling, evaporation from the soil surface, and reduction of irrigation water by 20% exacerbated the moisture depletion. Although plants were in their early stages of growth and root length was low; there was a 10% difference in moisture content among fertilizer treatments and N_1 treatment with 9.5% had the lowest and N_4 treatment with 14.5% the highest RSM. At the 10–20 cm depth, RSM across N rates was close, being between 17 and 20%, which is expected because of the low root density at this depth.

At 45 DAP, the RSM across N treatments was about 2–4% at the 0–10 cm depth and 11–14% at the 10–20 cm depth. At the 20–30 cm depth, it was 17–19%, which was higher than that at the 0–10 cm depth. At this depth, soil evaporation was lower than that at the top layers and under the N_2 treatment, corn growth was also affected, thus the moisture at this depth exceeded that at the top layers. As a result, the absorption of water from this layer was less than the other two depths. For all three depths, the difference in RSM among fertilizer treatments was very low. Due to the low irrigation water and high water demand by the plant,

the rate of N fertilizer had little effect on the water level (Fig. 6).

At 75 DAP, the plant needed sufficient water and nutrients to grow normally, so the main task of the root was to absorb more water and nutrients from the soil. Due to the high RLD in the 0–10 cm depth at this stage of sampling, the RSM across N rates decreased sharply, being between 2.33 and 2.94%. At the 10–20 cm depth, the RSM was very low (between 5.3 and 6.8%); at the 20–30 cm depth, it was between 9.8 and 13.2%, which is the permanent wilting point level. Although at this stage, evaporation from the soil surface was low, the high water demand by corn led to intense moisture depletion in surface soil layers. The application of N fertilizer had little effect on water absorption by roots at the 0–10 and 10–20 cm depths. However, at the 20–30 cm depth, there were obvious differences among N rates (Fig. 6). At the 30–40 cm depth, the RSM was relatively satisfactory but there were considerable differences among N rates. The N_1 treatment with 11.3% and N_4 treatment with 18.2% had the lowest and highest RSM, respectively. At 105 DAP, the total RSM (0–10 and 10–20 cm) across N rates was less than the permanent wilting point, being only 4–6%, and 8.5–11.8%, respectively. However, at the 20–30 cm depth, the RSM under N_1, N_2, and N_3 was at the permanent wilting point, but that under N_4 and N_5 were higher. At the 30–40 cm layer, the difference in RSM across N fertilizer treatments was considerable, with that under N_1 (13%) the lowest and that under N_4 (21.4%) the highest. Also, the RSM under N_3, N_4, and N_5 treatments had a slight difference of only 1%. At the 40–50 cm depth, where water absorption by roots was negligible, the RSM across N rates was between 19.4 and 21.6% (Fig. 6).

Fig. 7 Residual soil moisture at different soil depths under I_3 treatment and N rates
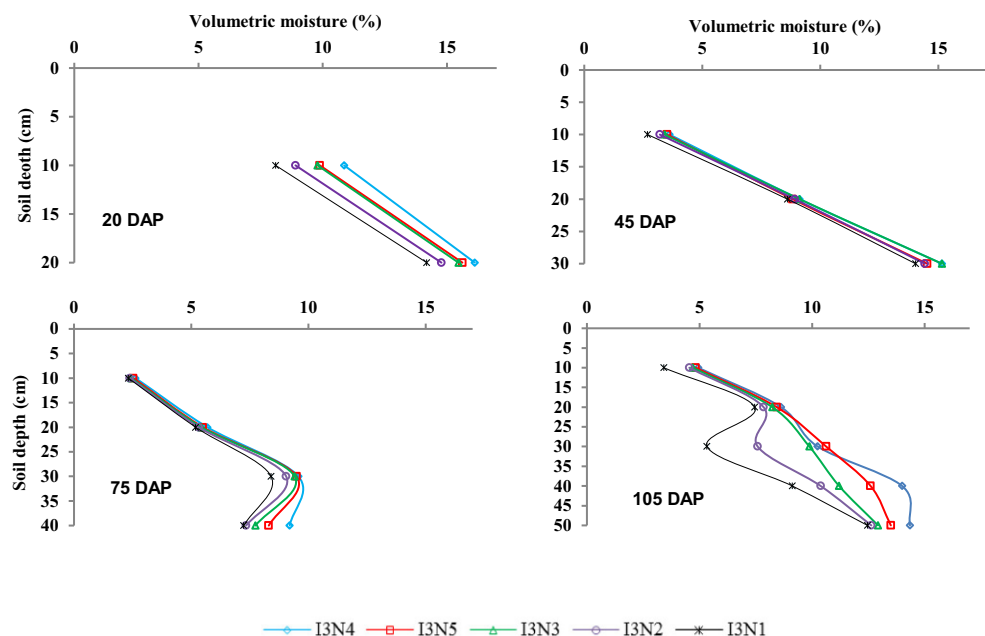
At 20 DAP under I_3 treatment, the RSM (0–10cm) was below the permanent wilting point and the difference among irrigation treatments was only about 2%—the lowest being 8.1% and the highest being 10.8%. The RSM (10–20cm) was slightly higher than that at the 0–10cm depth and the difference among treatments was less than that in the 0–10cm depth. At 45 DAP, the RSM (0–10cm) was very low across fertilizer treatments, being between 2.6 and 3.4%. Irrigation water shortage, high water demand, high root density and rapid growth of the plant caused rapid absorption of water from the soil. As a result, the different N fertilizer treatments did not have much effect on soil moisture storage (Fig. 7).

At 75 DAP, the RSM was very low across N fertilizer treatments, fluctuating in the range of about 2% at the 0–10cm depth, 5% at the 10–20cm depth, and 9% at the 20–30cm depth. Irrespective of N rate, the RSM at the 30–40cm depth was less than that at the 20–30cm depth. Due to the warm air, corn growth and shortage of irrigation water, it can be deduced that the roots absorbed all of the water and soil nutrients, thereby preventing the penetration of moisture into lower depths. At 105 DAP, the RSM across N rates was less than 5–10% at the 0–10 and 10–20cm depths (Fig. 7). At the 20–30 and 30–40cm depths, the N_1 treatment had the lowest and N_4 the highest residual moisture. The RSM across N rates at these two depths was at permanent wilting point. At the 40–50cm depth, it was also at permanent wilting point. As shown in Figs. 5, 6 and 7, the RSM in deeper soil layers was higher than that in the surface soil layers and the rate of its depletion was more pronounced in the surface layers where it reached about the permanent wilting point. Interactively, the best moisture conditions across growth stage and soil depths were at the 150kg/ha N rate. For optimum root development and soil moisture conditions, the I_1N_4 treatment was selected as the best for corn growth in the study area.

Conclusions

The study showed that the root length density (RLD) was significantly affected by irrigation regimes and N rates fertilizer with the peak density at the 20–30cm soil depth. The RLD increased under N_3, N_4 and N_5 treatments across depths and growth stages, due to increases in leaf area index and transfer of more photosynthetic material for root growth early in the growing season. At the last (end-season) sampling time, the highest RLD occurred at the 20–30cm depth, which was the main layer for water absorption. Under I_1 and for all N rates during crop development (45 DAP) and mid-season (75 DAP) stages, although the crop canopy reduced evaporation from surface soil, the warm air and plant demand for more water reduced the moisture level at

surface depths. At the end of the plant's growth cycle, the situation was completely different and the residual moisture (0–10 and 10–20cm) across N rates was at the permanent wilting point. As previously mentioned, at 105 DAP, these two layers had the highest RLD compared to previous growth stages, which explains the moisture depletion in these layers. In this study, the residual soil moisture decreased with reductions in irrigation water and N fertilizer, but with 100% of crop water requirement (I_1), an improved moisture condition was observed in the root zone. The highest RLD was observed in treatments receiving N at 150kg/ha (N_4). It can be concluded from these results, that the N_4 and I_1 treatment combination is recommended for optimum corn farming in this and other areas with similar ecology.

Conflict of interest H. Dehghanisanij and N. Kouhi declare that they have no competing interests.

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