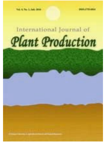

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Effects of deficit irrigation and groundwater depth on root growth of direct seeding rice in a column experiment

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Abstract

Rice is an essential crop in Iran that is grown mostly in areas where depth to groundwater is low. Root growth and water uptake of rice under shallow groundwater has not been thoroughly studied. This experiment was conducted to determine the lowland rice (cv. Ghasrodashti) root distribution above shallow groundwater in relation to deficit irrigation and groundwater depth in cylindrical greenhouse lysimeters. The irrigation treatments were continuous flood irrigation (CFI) and intermittent flood irrigation (4- and 8-day intervals IF-4 and IF-8). The groundwater depths (GWD) were 0.3, 0.45 and 0.6 m from the soil surface. In general, 40-60% of root dry weight was observed in the top 10 cm of soil in CFI treatments and IF-4 with 0.3 m GWD resulted in 20% increase in root dry weight in 10-20 cm layer compared with 0-10 cm. However, the root dry weight in 0-10 cm at 0.60 m GWD was 58% lower in intermittent irrigation compared to CFI. There was no significant difference in mean root length density in IF-4 with 0.3 m GWD compared with CFI. In general, lowland rice showed good ability to develop its root system in shallow groundwater level conditions in order to extract water due to lower soil water content in the intermittent flood irrigations. Simple equations were presented to predict the groundwater contribution to evapotranspiration based on the root length density and root weight density. Therefore, in areas with shallow groundwater depth (up to 0.45 m from the soil surface) and low potential evapotranspiration, application of IF-4 instead of CFI can be useful management especially where water scarcity is a serious problem.

Keywords: Groundwater; Root yield; Root length density; Intermittent flood irrigation; Continuous flood irrigation.

Introduction

Roots play a primary role in absorbing water and nutrients in plants (Seiler, 1998). The importance of plant roots as suppliers of water and minerals for growth has been discussed by many investigators (e.g., Russell, 1977; Barraclough, 1986). However, the extent of their measurements is limited and expensive under field conditions (Zuo et al., 2004). Generally, root studies have lagged behind that of shoot (Tsutsumi et al., 2003; Sarker et al., 2005) mostly because roots are hidden and not easily instrumented or observed due to relatively high cost and labor needed for sampling and analysis. Roots information is scarce compared to the shoots while it is the integrated action of shoots and roots that determines the crop productivity.

Rice is the second-most produced cereal worldwide and it is a staple food for large part of the world population (Gallagher, 1984). For a long time, efforts have been made to characterize the ability of upland rice to uptake water and nutrients with particular focus on the role of the deep root system. As a consequence, size of the root system, distribution of its biomass and root length has been identified as important factors for drought resistance (Kondo et al., 2003; Asch et al., 2005; Dusserre et al., 2009). The root length (or weight) in layers within the soil profile is usually expressed in terms of root length (or weight) per unit volume of soil, referred to as root length (or weight) density. Since water is mostly absorbed passively, root length density, which reflects the development of lateral roots, can be directly related to water uptake ability of the plant. As root length density increases, water uptake usually increases. Furthermore, roots are distributed in such a way that their length and mass will decrease exponentially with depth. Higher root density at deeper soil layers reflects the exploitation of water present at deeper levels (Siopongco et al., 2005).

Drought is a major abiotic stress, affecting 20% of the total rice-growing area in Asia (Pandey and Bhandari, 2008). Improving our understanding of the interactions between root function and drought in rice could have a significant impact on global food security (Gowda et al., 2011). Proper root characteristics have been claimed to be critical for increasing yield under soil-related stresses (Serraj et al., 2004; Lynch, 2007).

As water becomes scarce in arid and semi-arid regions, use of shallow groundwater in many areas plays an important role in crop water supply (Sepaskhah et al., 2003). Crop water use from shallow groundwater is affected by depth to groundwater, groundwater quality, crop stages, irrigation frequency and application depth of irrigation water. Root growth and water uptake under shallow groundwater conditions has not been thoroughly studied and is one of the most important mechanisms of plant growth since it is the conduit between the vegetative portion of the plant and the soil water (Ayars et al., 2006).

Root development in relation to crop growth stage and maximum rooting depth is rarely reported in studies on crop water use from shallow groundwater. Model development and its potential use for better understanding of crop water use from shallow groundwater are limited and there is little data describing the root system and its interaction with the groundwater (Ayars et al., 2006).

Lowland rice plays an important role for rice production in Iran. Although its response to water stress has been considered in many investigations, the relationship between root system and irrigation scheduling under different groundwater depths has not been addressed (Talebnejad and Sepaskhah, 2014). Irrigation strategies and upward flow from shallow groundwater affects the soil water profile. Interaction effects of irrigation frequency and groundwater depth may be influenced on root characteristics in different soil layers above the groundwater situation. Therefore, we conducted this experiment to determine the lowland rice (cv. Ghasrodashti) root distribution above the shallow groundwater as affected by deficit irrigation strategies and groundwater depth.

Materials and Methods

This research was conducted in a greenhouse at the College of Agriculture, Shiraz University in 2009. The soil was silty clay obtained from rice planting area, Kooshkak, which is located in Fars Province, Iran. It was collected from the top 0-0.3 m layer and some of the physico-chemical properties of this soil are shown in Table 1. The soil was air-dried, and crushed to pass through a 2-mm sieve. PVC columns with 200 mm diameter were connected to plastic bottles (90 mm internal diameter and 1500 cc volume) and the groundwater was continually controlled by keeping the water in the bottles at a constant level. Column lengths were 0.37, 0.52 and 0.67 m to accommodate groundwater depths at 0.3, 0.45 and 0.60 m from the soil surface, respectively. Therefore, the top edge of the column was about 7 cm higher than the soil surface to accommodate surface irrigation water. The volume of water supplied from the plastic bottle to maintain the desired groundwater depths for the various treatments was considered as the rate of crop water use from the groundwater. This volume was measured every other day and also before each irrigation event. The connection between the main columns and the plastic bottles were made by plastic tubes with 20 mm diameter. Columns were filled with a 20 mm depth of gravel (average particle diameter of 7 mm). Afterwards, they were filled by air dried soil to target bulk density of 1.23 g cm^{-3}. Gypsum blocks (GB) were placed at specific depths with 10 cm spacing from groundwater for monitoring the soil moisture above the groundwater. They were located in the center of the each soil layer and their wires were emitted from the holes, which were made in the column walls. The outlets were sealed thoroughly. Detail experimental set up presented by Talebnejad and Sepaskhah (2014).

Table 1. Physico-chemical properties of the soil used in the experiment.

Physical property		Chemical property (Saturation extract)	
Sand (%)	5	Ca (mg kg^{-1})	433.7
Silt (%)	49	Cl (mg kg^{-1})	87.3
Clay (%)	46	Na (mg kg^{-1})	13.7
Saturated water content (cm^3 cm^{-3})	0.54	Water soluble K (mg kg^{-1})	47.0
Field capacity (0.033 MPa, cm^3 cm^{-3})	0.35	pH	6.82
Permanent wilting point (1.5 MPa, cm^3 cm^{-3})	0.21	EC (dS m^{-1})	0.5
Bulk density (g cm^{-3})	1.23	Available P for plant (mg kg^{-1})	20.0

Twenty one seeds (local cultivar of Ghasrodashti) were planted in each column on 28 April 2009, in 3 groups/hills (7 seeds in each group). The three seed groups were placed on corner of a triangle with 140 mm spacing in order to be in accordance with the planting pattern in field condition, Therefore, the planting pattern in soil column was similar to the field conditions. After 2 weeks seedlings were thinned to 5 per hill and after 4 weeks they were thinned to 3 per hill similar to the field conditions where seedlings transplanted with 3-4 seedlings in each hill. During the stand establishment period, each column was initially irrigated to field capacity by applying 66 mm of water.

Nitrogen (N) and phosphorus (P) were applied uniformly to all columns at the rate of 163 mg kg^{-1} soil as urea (equivalent to 120 kg N ha^{-1}) and 51.6 mg kg^{-1} soil as triple superphosphate, $Ca(H_2PO_4)_2$ (equivalent to 50 kg P ha^{-1}), respectively. Nitrogen fertilizer was applied at two plant growth stages, i.e., at tiller and heading initiation and all phosphorus was applied at planting.

At the 4-5 leaf stage, irrigation and groundwater depth treatments were initiated. Three irrigation treatments consisted of continuous flooding irrigation (CFI), intermittent flooding at 4-day intervals (IF-4) and intermittent flooding at 8-day intervals (IF-8). The continuous flooding treatments with various groundwater depths were achieved by placing plastic bottle for these treatments at the top of the column wall in order to maintain the soil water at saturation with the standing water depth of 3 cm. A standing water depth of 3 cm of the CFI was maintained by irrigating every other day. The amount of water applied to keep a standing water depth of 3 cm was used as potential crop evapotranspiration in the greenhouse condition. The amount of water application for intermittent flooding treatments was determined by multiplying the amount of water that is used by CFI by a factor of 0.45. Irrigation management for intermittent flooding treatments was chosen on the basis of the root ability to absorb water from shallow groundwater. The amount of irrigation water for IF-4 for all GWD was set to 0.45 of the total water use of CFI for each 4 days period. The ratio of 0.45 was adopted based on the results of Pirmoradian et al. (2004) for rice in field conditions that the ratio of water used in 1-day intermittent irrigation to the continuous flooding was about 0.54 with groundwater depth greater than 1.0 m. Irrigation water for IF-8 was equivalent to 0.45 of summation of water use of continuous flood treatments during first 4 days and the amount of water used for transpiration on the second 4 days. This method was chosen because soil surface was dry after 4 days and the amount of water for evaporation from soil surface was negligible during this period. The rate of evaporation from each treatment was measured from the similar soil filled columns without plants. Then the transpiration rate was determined by difference between the evapotranspiration and evaporation and used for irrigation water calculation for the second 4 days of 8 days interval.

The experimental layout was a 3×3 factorial arrangement with three replications and analysis of variance was performed for this arrangement. Soil water content before each irrigation event was measured by GB in the different layers of the soil above the groundwater. The GB were calibrated in soil filled pots and the calibration curve as a relationship between the soil volumetric water content and GB electrical resistance (ohm) was determined and used in this study to determine the soil volumetric water content (Figure 1).

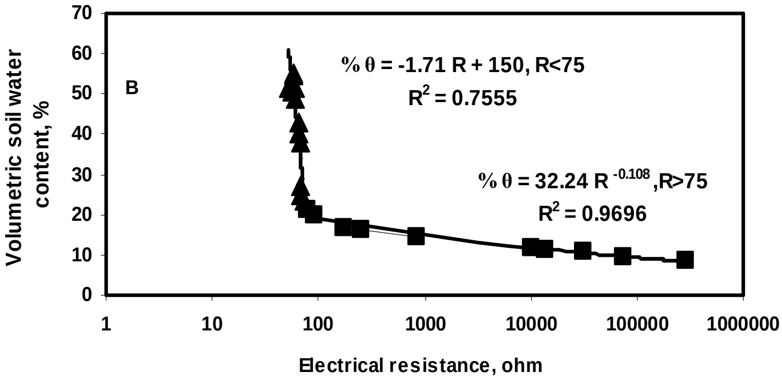

Figure 1. Relationship between volumetric soil water content (θ) and electrical resistence (R) of the gypsum block.

The maximum and minimum greenhouse air temperatures during the growing season were 36±5 and 14±4 °C and the maximum and minimum relative humidity were 45±2 and 33±5%, respectively. The greenhouse was partially shaded and it was not equipped with temperature and humidity controller.

In the field conditions usually there is natural or artificial drainage to control the salt accumulation in soil. However, there was no drainage in the soil columns in our experiment. Although the irrigation water was tap water with an electrical conductivity of only 0.6 dS m^{-1}, upward movement of water from groundwater to the surface layers of the soil and evapotranspiration occurrence resulted in salt accumulation in the root zone. Therefore, during the experimental period the plastic tubes at the bottom of the columns were removed and free drainage condition was performed. Approximately 0.50, 0.30 and 0.23 pore volume of water was applied for salt leaching in GWD of 0.35, 0.50 and 0.65 m, respectively to simulate field condition. The optimum time interval for salt washout was 3, 5 and 7 weeks for 0.3, 0.45 and 0.60 m groundwater depths, respectively in order to reduce the salinity of the groundwater to about 1.0 dS m^{-1} after washing. To determine the time of salt washing, drainage water was sampled occasionally and its electrical conductivity (EC) was measured. When EC reached about 3.0 dS m^{-1} [according to Sepaskhah and Yousofi-Falakdehi (2009), it is the critical EC], salt leaching was performed. Further, it should be noted that ET was determined from water balance in the periods without drainage occurrence.

Plants (3 hills, each with 3-4 plants) were cut at the soil surface on 15 October to 19 November in 2009; 2-3 weeks after stopping irrigation. Plant tops were oven-dried at 65 ˚C for 48-72 h. The soil columns were cut into sections of 10-cm length and the roots of all 3-hills in each soil layer were washed free of soil. The volume of the roots in each soil layer was measured using a graduated cylinder to determine the difference between the volume of water without roots and the volume of water with roots. Sub samples of roots in each layer were chosen to measure the root diameter by micrometer. Root diameter and volume measurements were made less than 12 hours after washing the roots free of soils. Using the root volume and mean root diameter, the root length was calculated and then root length density was determined by dividing root length by the volume of soil in each layer of the soil above groundwater. Finally, the plant roots were dried in an oven at 65 °C for 48-72 h to determine the root dry weight and specific root length was determined by dividing root length by root dry matter.

Results and Discussion

Root to shoot ratio

Shoot and root dry weights were presented in a previous article (Talebnejad and Sepaskhah, 2014). Table 2 shows the root to shoot dry weight ratio (RSR) for different treatments. There was a significant interaction between the effects of GWD and the irrigation treatments on the RSR ($P<0.05$). Root to shoot dry weight ratio increased due to longer soil columns for CFI. There was a significant increase in RSR at 0.3 and 0.45 m GWD (15% and 25%, respectively) for intermittent flood irrigations as compared with CFI. However, RSR decreased by 22% at 0.60 m GWD at intermittent flood irrigations as compared with CFI. Therefore, rice root can adjust its development for intermittent irrigation treatments to tolerate water stress at 0.3 and 0.45 m GWD. However, this adjustment did not occur at 0.60 m GWD. This could be explained by less groundwater contribution to rice water requirement at 0.60 m GWD (Table 3). Maximum RSR (0.206) for intermittent flood irrigation occurred at 0.45 m GWD. In upland conditions, RSR increases (Banba and Ookubo, 1981; Kondo et al., 2000; Singh et al., 2000; Price et al., 2002) compared with root to shoot dry matter ratio in lowland conditions (Azhiri-Sigari et al., 2000; Ba˜noc et al., 2000). This response may be due to mechanical impedance in lowland conditions, which typically feature a hardpan from soil puddling. In the present study

RSR increased for Ghasrodashti lowland rice cultivar under intermittent flood irrigation in which the soil moisture is similar to upland conditions. Therefore, it is indicated that soil moisture conditions play an important role on root characteristics such as root to shoot dry matter ratio.

Table 2. Root to shoot ratio, mean (3 replicates) root length density (cm cm^{-3}), mean (3 replicates) root weight density (g cm^{-3} ×10^{-4}) and mean (3 replicates) specific root length (m g^{-1}) at different groundwater depths and irrigation regimes.

Water table depth (m)	Continuous flooding	Intermittent flood irrigation (4-day interval)	Intermittent flood irrigation (8-day interval)
Root to shoot ratio			
0.30	0.107^{g*}	0.127^{e}	0.120^{f}
0.45	0.160^{c}	0.206^{a}	0.194^{b}
0.60	0.193^{b}	0.159^{c}	0.141^{d}
Mean root length density, cm cm^{-3}			
0.30	11.97^{cd}	12.71^{c}	7.08^{e}
0.45	14.71^{b}	12.99^{c}	12.36^{c}
0.60	17.75^{a}	10.56^{d}	8.16^{e}
Mean root weight density, mg cm^{-3}			
0.30	1.164^{ab}	1.234^{ab}	0.729^{cd}
0.45	1.311^{a}	1.112^{b}	0.856^{c}
0.60	1.237^{ab}	0.652^{de}	0.487^{e}
Mean specific root length, m g^{-1}			
0.30	31.54^{ab}	30.98^{ab}	29.57^{ab}
0.45	24.15^{bc}	25.38^{abc}	32.13^{a}
0.60	21.49^{c}	24.13^{bc}	25.64^{abc}

[*] Means followed by the same letters in row and column for each trait are not significantly different at 5% level of significance.

Table 3. Seasonal groundwater contribution to evapotranspiration, (GC/ET, %) at different groundwater depths and irrigation regimes.

Water table depth (m)	Continuous flooding	Intermittent flood irrigation (4-day interval)	Intermittent flood irrigation (8-day interval)
0.30	0.0	40.3	29.4
0.45	0.0	23.1	16.0
0.60	0.0	15.0	9.0

Soil water content

Figure 2 shows the volumetric soil water content profiles at different groundwater depths at the beginning and the equilibrated conditions at the end of the growing season evaluated under two deficit irrigation regimes. Volumetric soil water content at field capacity, permanent wilting point (PWP) and saturation were also presented in Figure 2. The rather high value for PWP (21%) obtained due to high soil clay content (46%). The CFI treatments were controlled by maintaining the soil water content at saturation with the standing water depth of 3 cm on the soil surface. Therefore, they were not shown in Figure 2.

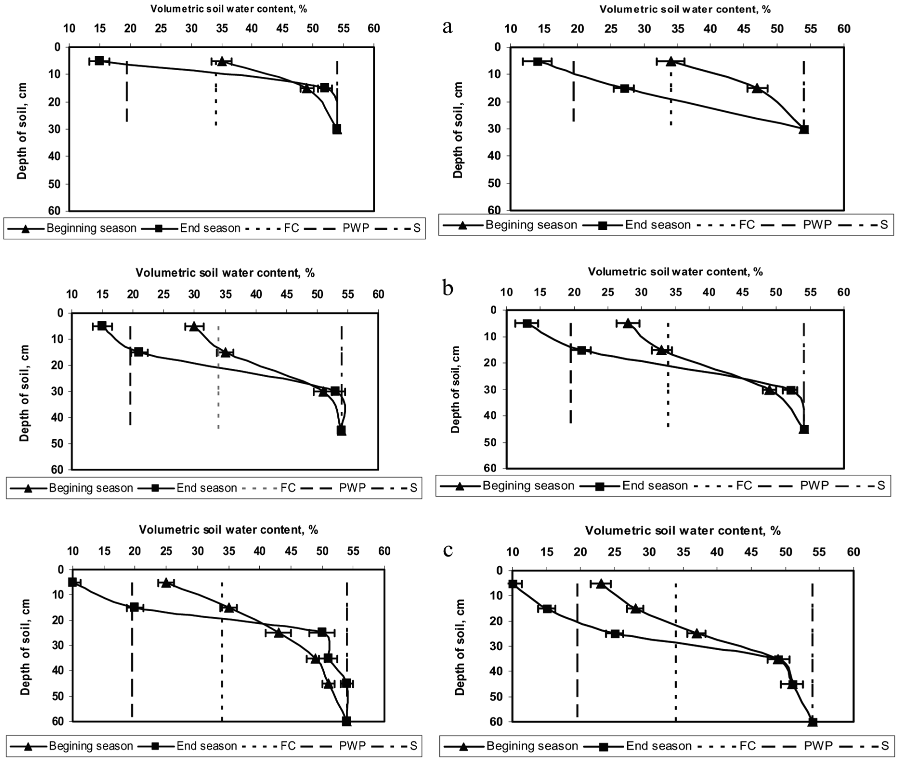

Figure 2. Soil water content profiles above the groundwater for different irrigation treatments: Left side 4-d interval intermittent irrigation Right side 8-d interval intermittent irrigation, (a) 0.3 m (b) 0.45 m (c) 0.60 m. Standard errors were also shown (n=3). FC; Field capacity, PWP: Permanent wilting point, S: Saturation. Note: CFI treatments were not shown because soil was maintained at saturated conditions. Triangle is for the beginning and square is for the end season.

Volumetric soil water content in the 0-10 cm layer for all groundwater depths decreased by the end of growing season for both IF treatments. In IF-4, the volumetric soil water content in the second and third layers, i.e., 0.1-0.3 m, for the 0.3 m GWD increased by the end of growing season. A similar trend was observed in third and forth layers (0.20-0.45 cm) for 0.45 m GWD and also in the third through sixth layers (0.20-0.60 m) for 0.60 m GWD. The increase of volumetric soil water content occurred due to upward groundwater movement to the root zone that resulted in intensified rice shoot growth and root development. At the surface layer, evaporation from soil cracks and water extraction due to the extensive development of lowland rice root system at the surface layer of soil, contributed to a greater soil moisture decrease.

Volumetric soil water contents in 0-0.1 m layer for different GWDs in IF-8 decreased by the end of the growing season. Although volumetric soil water contents in soil layer close to the groundwater level of 0.3 m GWD for IF-4 increased, a decrease was observed in IF-8. Top soil water content showed that increasing irrigation intervals forced the plant to use more water from the soil moisture which could not be replaced by upward movement of water from groundwater. At 0.45 and 0.60 m GWD, the profile of volumetric soil water content in IF-4 was similar to that in IF-8. Obviously interaction effects of irrigation interval, groundwater depth and root development controlled soil water profiles during the growing season.

Root dry weight distribution

Figure 3 shows the vertical root dry weight (RDW) distribution in GWD and irrigation treatments. In CFI treatments, the maximum RDW was observed in the 0-0.1 m layer that is due to the high number of nodal roots that are produced from the nodes at the base of the main stem in flooding conditions. Moreover, the root system continued its development in deeper layers of soil. In the 0.3, 0.45 and 0.60 m of CFI soil columns, 60, 50 and 40% of the total RDW occurred in the top 10 cm of soil layer, respectively. Higher RDW in 0.1-0.2 m and 0.2-0.3 m depth in IF-4 compared with CFI might be due to higher soil aeration in IF-4. The vertical distribution of the RDW is more uniform in deeper layers of soil especially in soil column with 0.60 m length. In the 0.3 m GWD with IF-4 in comparison with CFI; the RDW is 20 and 15% higher in 0.10-0.20 m and 0.20-0.30 m layer, respectively. It showed that rice is capable to produce root in the intermittent flood irrigation condition with presence of shallow groundwater. Therefore, the root has higher water extraction near the groundwater through increasing its accumulated root mass. However, this capability depends on GWD and water stress. In the 0.3 m GWD with IF-8, total RDW is lower than those obtained in IF-4 in all soil layers. Results of several lowland experiments (Hasegawa et al., 1985; Sharma et al., 1987; Mambani et al., 1989; Nabheerong, 1993; Pantuwan et al., 1996; Samson et al., 1995) indicated that 69-94% of roots are located in the top 0.10 m of the soil and very few roots are found below 0.3 m. Deep root penetration would help rice to avoid drought stress; however, root penetration is often restricted by the presence of a hardpan. Although in our experiment no hardpan developed, the majority of RDW occurred in the upper layers of the soil for all groundwater depths.

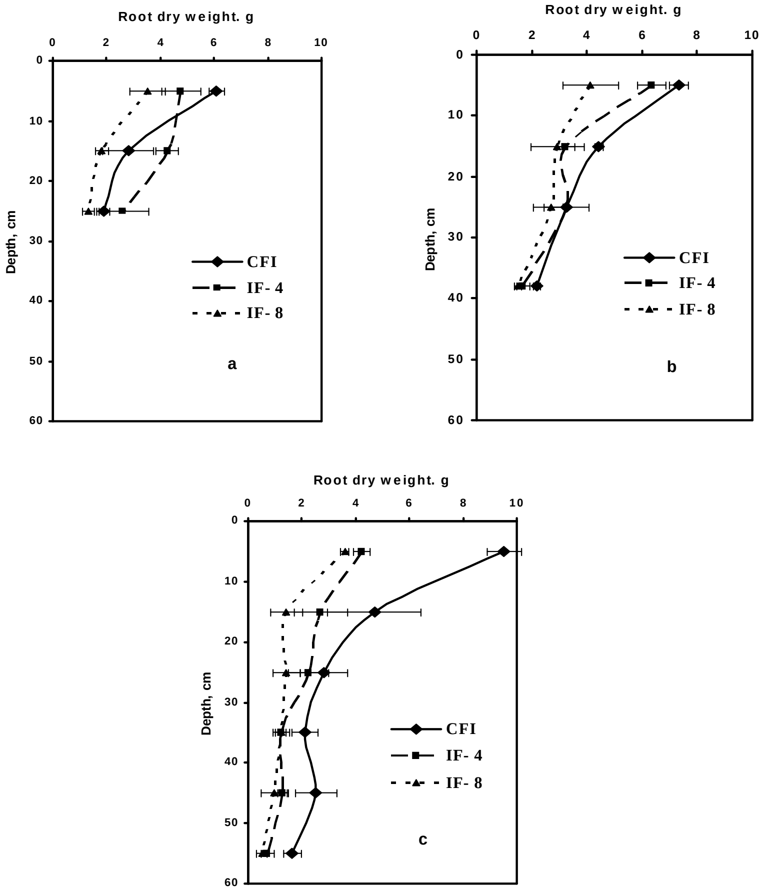

Figure 3. Vertical distribution of root dry weight in different groundwater depths and irrigation treatments: (a) 0.3 m (b) 0.45 m (c) 0.60 m. Standard errors were also shown (n=3), CFI=continuous flood irrigation, FI-4=4-d interval intermittent irrigation, FI-8=8-d interval intermittent irrigation.

Root dry weight for 0.45 m GWD at 0.2 and 0.3 m from the soil surface and for 0.60 m GWD at 0.40 and 0.50 cm from the soil surface were not significantly different between IF-4 and IF-8. In the top 10 cm of soil layer at 0.60 m GWD, the RDW decreased by 58% in intermittent irrigations in comparison with that in CFI; while this reduction was lower at 0.3 m and 0.45 m GWD.

Total root dry weight and soil water contents

Total root dry weights (TRDW) for different treatments were presented in a previous article (Talebnejad and Sepaskhah, 2014). There was a significant interaction between the effects of the GWD and the irrigation treatments on the root dry weight ($P<0.0001$, data not shown in the present article). Figure 4 shows the relationship between TRDW and volumetric soil water content for IF-4 and IF-8. This relationship was obtained by linear regression analysis as follows:

$$TRDW1 = -0.079\theta + 6.13 \tag{1}$$

$R^2=0.53$, $n=13$, $SE=1.15$, $P<0.05$

$$TRDW2 = -0.053\theta + 4.00 \tag{2}$$

$R^2=0.53$, $n=23$, $SE=0.82$, $P<0.05$

Where θ is the mean volumetric soil water content (%) over soil depth and during the growing season and TRDW1 and TRDW2 are the total root dry weight (g column^{-1}) for IF-4 and IF-8, respectively. The covariance analysis indicated that the slope of the linear equations [Equations (1) and (2)] are not statistically different; however, the intercepts are significantly different ($P<0.05$). It is indicated that although the TRDW1 for IF-4 is higher than that for IF-8, the values of TRDW2 increased by decreasing soil water content in order to tolerate water stress. However, the rate of increase (the slope of relationships) is dependent on the irrigation interval (0.079 for IF-4 vs. 0.053 for IF-8) although they are not statistically different ($P<0.05$). Therefore, the slope of relationship was higher for IF-4 than that for IF-8.

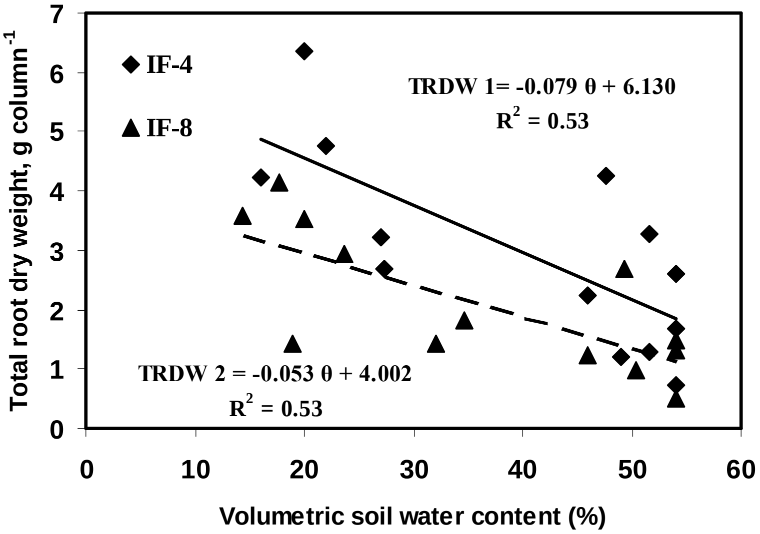

Figure 4. Relationship between total root dry weight (TRDW) and volumetric soil water content (θ). TRDW1 (solid line) and TRDW2 (dash line) are total root dry weight for IF-4 and IF-8, respectively.

Root diameter

Figure 5 shows the root diameter for different soil layers above the groundwater for rice under different irrigation treatments. Maximum root diameter was observed in surface layer. Roots with small diameters occurred in deeper layers of soil adjacent to the groundwater. Root diameter in surface layer (0-0.10 m) was 250 micrometer and in the second layer of soil (0.10-0.20 m) was 200 micrometer. Root diameter in the 0.1 m soil layer adjacent to 0.3 and 0.45 m of GWD was 160 micrometer. Root diameter at 0.60 m GWD decreased to 120 micrometer in CFI and to 95 micrometer in intermittent flood irrigation.

Water management significantly affected the root diameter in 0.60 m GWD especially in deeper layers of soil. The observed differences in root diameter in different soil layers in CFI at 0.60 m GWD may be attributed to the variable physical properties in soil layers such as bulk density. It has been hypothesized that coarse roots have a direct role in drought resistance because roots with large diameter are related to higher penetration ability (Materechera et al., 1992; Nguyen et al., 1997; Clark et al., 2008) and branching (Fitter, 1991; Ingram et al., 1994) and they have greater xylem vessel radii and lower axial resistance to water flux (Yambao et al., 1992). In our research, roots with larger diameter were found for treatments that resulted in more water extraction from groundwater in deficit irrigations such as IF-4 at 0.3 and 0.45 m GWD (Table 3).

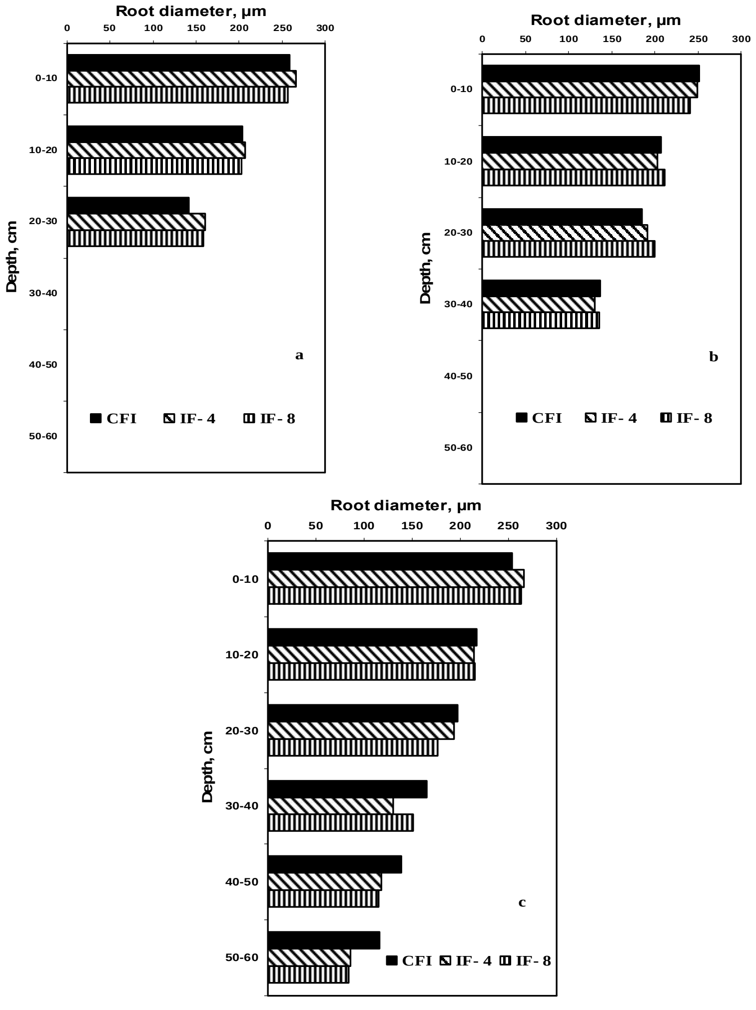

Figure 5. Vertical distribution of root diameter in different groundwater depths and irrigation treatments: (a) 0.3 m (b) 0.45 m (c) 0.60 m groundwater depth. CFI=continuous flood irrigation, FI-4=4-d interval intermittent irrigation, FI-8=8-d interval intermittent irrigation.

Root length density distribution

Figure 6 shows the vertical rice root length density (RLD) distribution for different treatments. In general, shallow soil layers were densely populated by roots. In the middle soil layers, RLD decreased while a moderate increase was observed near the groundwater level. This may be attributed to the closed end of columns and limited space for root distribution at the bottom of the soil column. At the 0.3 m GWD, RLD in 0.10-0.20 m layer was higher for IF-4 than that for CFI. With decreasing water input by using intermittent flood irrigation instead of CFI, rice can extract more water from deeper layers of soil because of better and more developed root system near the groundwater level. The ability of root system to extract water from shallow groundwater is related to the irrigation intervals (Sepaskhah et al., 2003). Therefore, increasing irrigation interval from 4 to 8 days decreased the root length density in 0.10-0.20 m layer at 0.3 m GWD. Irrigation interval did not significantly affect the root development at 0.45 m GWD. In general, application of intermittent irrigation instead of CFI decreased the root length density in all the layers of soil at 0.45 and 0.60 m GWD.

Mean root length density

Table 2 shows the mean RLD for different treatments. It is indicated that mean RLD was increased due to longer soil column for CFI. Like root and shoot dry weight, mean RLD for CFI was statistically similar to that obtained for IF-4 at GWD of 0.3 m. For intermittent flood irrigations mean RLD were higher for 4-d interval especially at 0.3 cm GWD by 44%. For 8-d interval, maximum mean RLD occurred at 0.45 m GWD which was significantly similar to 4-d interval at 0.3 and 0.45 m GWD. In general, the used lowland cultivar showed an increase in its RLD for the intermittent irrigation at shallow groundwater up to 0.45 m depth.

In this experiment, rice evapotranspiration was determined for different treatments by soil water balance. Details are available in Talebnejad and Sepaskhah (2014).

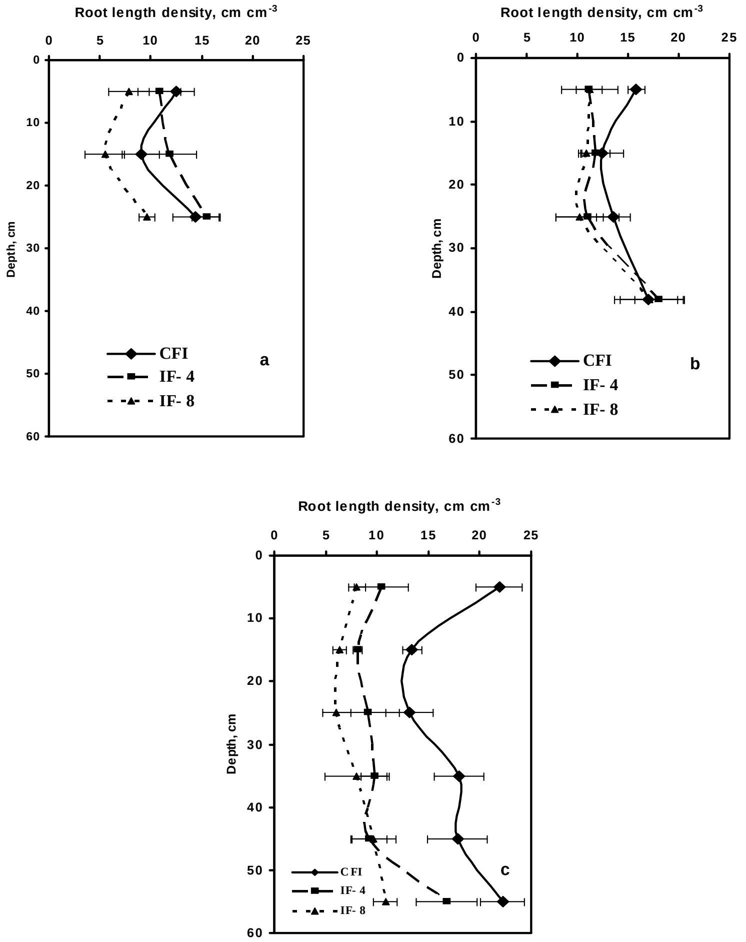

Figure 6. Vertical distribution of root length density in different groundwater depths and irrigation treatments: (a) 0.3 m (b) 0.45 m (c) 0.60 m groundwater depth. Standard errors were also shown (n=3), CFI=continuous flood irrigation, FI-4 = 4-d interval intermittent irrigation, FI-8 = 8-d interval intermittent irrigation.

Figure 7 shows relationship between the evapotranspiration (ET) and RLD. Komashita et al. (2000) demonstrated that water extraction increased with RLD in deeper soil layers in a greenhouse study. Relationship between ET and RLD was obtained by linear regression analysis as follows:

$$ET = 30.05 \times RLD + 186.9 \tag{3}$$

R^2=0.60, n=27, SE=80, P<0.001

Where ET is the evapotranspiration (mm) and RLD is the root length density (cm cm^{-3}). Intercept of Equation (3) indicated that 186.9 mm water evaporated from soil surface before root system development was initiated to produce the shoot dry matter (leaves) for evapotranspiration.

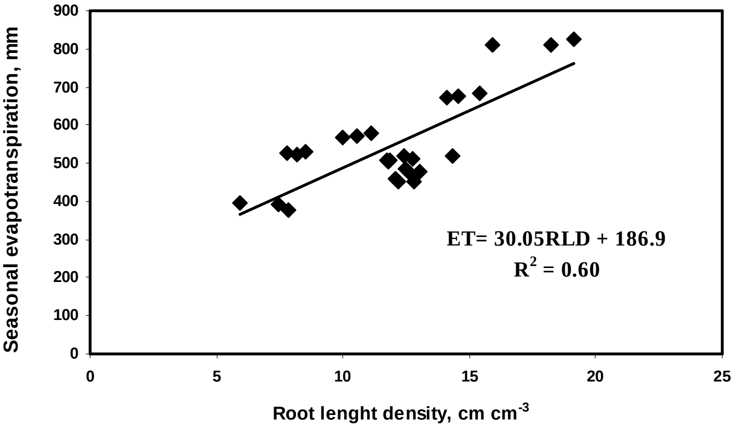

Figure 7. Relationship between seasonal evapotranspiration (ET) and root length density (RLD).

Root weight density and specific root length

There was no significant difference between the mean root weight densities at different GWD for CFI (Table 2). For intermittent flood irrigations, by increasing GWD up to 0.45 m there was no significant difference between the mean root weight densities. However, mean root weight density decreased by increasing GWD from 0.45 m to 0.60 m by 41% and 43% for IF-4 and IF-8 intervals, respectively. Increasing irrigation intervals from 4 to 8 days resulted in significant decrease by 41% and 23% in the mean root weight density at 0.3 and 0.45 m GWD, respectively; however, this decrease at 0.60 m GWD was not statistically significant.

Mean specific root lengths (ratio of root length to root weight) are shown in Table 2. The plants having higher specific root length are assumed to have higher water and nutrient acquisition ability in a particular environment (Habib, 1988). This criterion has inverse relationship to the root diameter. Results of root diameter show that roots with small diameters (higher specific root lengths) occurred in deeper layers of soil adjacent to the groundwater. Mean specific root length decreased generally by increasing GWD, although it was not significant. At 0.45 m GWD, intermittent flood irrigation with 8-d interval resulted in 25% increase in mean specific root length compared with those obtained for CFI. There was not significant difference in mean specific root length for intermittent flood irrigations with different intervals.

Groundwater contribution to ET

The values of ET and groundwater contribution to ET (GC) were presented in a previous article (Talebnejad and Sepaskhah, 2014). The ratio of GC to ET at different GWD and water saving irrigation (WSI) are shown in Table 3. Detail description about these parameters are presented by Talebnejad and Sepaskhah (2014); therefore, in this article the links between root characteristics and GC is emphasized.

The GC in Table 3 is dependent on the mean root weight density (Table 2). It is shown in Tables 2 and 3 that by increasing the RWD the GC were increased. Figure 8 shows relationship between the increase in the root weight density and increase in the groundwater contribution to crop water use. The relationship between the GC and RWD was obtained by regression analysis as follows:

$$GC=125.4\times RWD \tag{4}$$

$R^2=0.62$, $n=18$, $SE=29.0$, $P<0.001$

Where GC is the groundwater contribution (mm) and RWD is the root weight density (g cm^{-3}). Relationship between the GC and RLD for different GWD was obtained by regression analysis as follows (Figure 9):

$$GC1=15.32\times RLD \tag{5}$$

$R^2=0.93$, $n=6$, $SE=0.11$, $P<0.01$

$$GC2,3=7.43\times RLD \tag{6}$$

$R^2=0.55$, $n=12$, $SE=0.18$, $P<0.01$

Where RLD is the root length density (cm cm^{-3}) and GC1 and GC2,3 are the groundwater contribution (mm) at GWD1 (GWC for 0.3 m GWD) and GWD2,3, (GWC for 0.45 m and 0.60 m GWD) respectively. The covariance analysis indicated that the slopes and intercepts of Equations (5) and (6) are significantly different (P<0.05). It is indicated that the GC increased by increasing RLD; however, the rate of increase (slope of the relationship) is dependent on the GWD (15.32 for GWD of 0.3 m and 7.43 for GWD of 0.45 and 0.6 m). Therefore, two different relationships obtained for different irrigation intervals (Figure 9). Ayar et al. (2006) reviewed the potential of shallow groundwater use in irrigated agriculture. They emphasized that the root system is the least quantified aspect of the groundwater contribution and it is one of the most important components in the groundwater contribution to the crop water use. In this research, these relationships for rice [Equation (5) and (6)] have been presented.

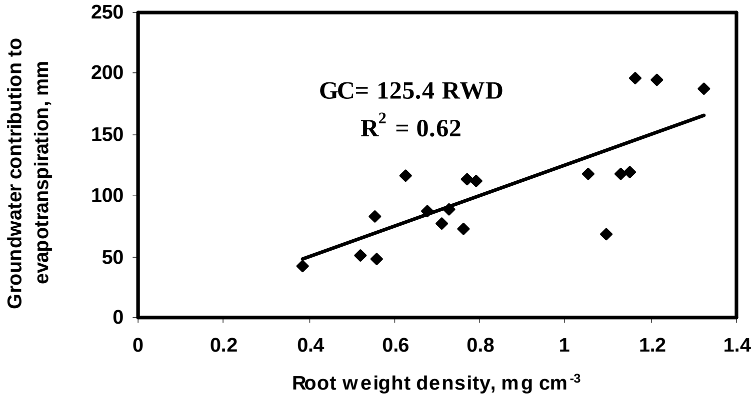

Figure 8. Relationship between groundwater contribution to evapotranspiration (GC) and root weight density (RWD).

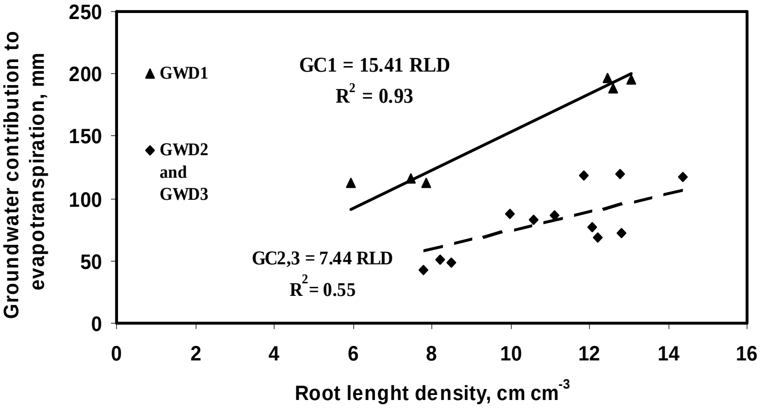

Figure 9. Relationship between groundwater contribution to evapotranspiration (GC) and root length density (RLD). GC1 is groundwater contribution to ET for GWD1 (solid line) and GC2,3 is groundwater contribution to ET for GWD2 and GWD3 (dash line).

Conclusions

In general, 40-60% of root dry weight was observed in the 0-0.10 cm layer for CFI treatments at all three groundwater depths (0.3-0.6 m). At 0.3 m GWD, IF-4 resulted in 20% increase in root dry weight in 0.10-0.20 cm layer. However, in the surface layer of the soil at 0.60 m GWD the root dry weight has been decreased by 58% for intermittent irrigation in comparison with that for CFI. However, there was no significant difference in mean root length density for IF-4 with 0.3 m GWD compared with CFI. For intermittent flood irrigation with 4-d interval, the used lowland rice cultivar increased root length density in order to uptake more water from shallow (0.3 m) GWD. Maximum root to shoot dry weight ratio (0.206) occurred for intermittent flood irrigations at 0.45 m GWD. Simple equations were demonstrated to predict the groundwater contribution to crop evapotranspiration from root length density and root weight density. In general, lowland rice showed good ability to develop its root system near shallow groundwater level in order to extract water under lower soil water content for the intermittent flood irrigations. Therefore, in areas with shallow GWD (up to 0.45 m from the soil surface) application of IF-4 instead of CFI can be a useful management especially in areas that water scarcity is a serious problem. As the depth of puddling is about 0.2-0.3 m in field conditions; therefore, the lowland rice cultivars seems to adopt its root growth behavior to its traditional cultivation practice.

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