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ORIGINAL PAPER

Barley (*Hordeum vulgare* L.) Response to Partial Root Drying Irrigation, Planting Method and Nitrogen Application Rates

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Abstract

Barley (*Hordeum vulgare* L.) is an important crop in many areas of the world. Drought and scarce resource of irrigation water are serious concerns in agricultural production in Iran and other arid and semi-arid regions. The objective of this study is to investigate the interaction effects of partial root drying (PRD) irrigation, planting method and different nitrogen application rates on yield, water and nitrogen use efficiencies and economical nitrogen and water use for barley in 2011–2012 cropping season. The experiment was designed as split–split plot that arranged in randomized complete blocks with irrigation strategy as the main plot, planting method as the subplot and nitrogen levels as the sub-subplot in three replications. The irrigation strategies consisted of ordinary furrow irrigation (OFI) and variable alternate furrow irrigation (VAFI) as a PRD technique. The planting methods included of on-ridge planting (ORP) and in-furrow planting (IFP) methods. The nitrogen levels were 0 (N_0), 90 (N_1) and 180 (N_2) kg N ha^{-1} as urea. The results indicated that using VAFI method, 25% reduction in irrigation water depth was occurred compared with OFI, with no significant yield reduction. Furthermore, in IFP method, yield increased 13% compared with ORP. The maximum profits, water economic productivity, water use efficiency and water productivity were obtained in VAFI with IFP and nitrogen application rate of 180 kg/ha. Nitrogen use efficiency in VAFI compared with OFI was increased due to higher nitrogen absorption by plant. Thus, it is indicated that in areas with water limiting, it is preferable to recommend VAFI, IFP and 180 kg N ha^{-1} as best management practice for barley farm in the study region.

Keywords Variable alternative furrow irrigation · Deficit irrigation · Planting pattern · Water productivity · Nitrogen use efficiency

Introduction

Freshwater shortage is one of the important limitations in arid and semi-arid regions for agricultural production. Therefore, efficient irrigation methods, i.e., partial root zone drying (PRD) should be used to mitigate the water shortage (Sepaskhah and Ahmadi 2010). Variable alternate furrow irrigation (VAFI) is a PRD irrigation. In this irrigation, every other furrows are irrigated in each irrigation event and the irrigated furrow is remained dry in the next irrigation event. By VAFI irrigation water is saved with minimum reduction in crop yield (Sepaskhah and Kamgar-Haghighi 1997; Li et al. 2011; Samadi and Sepaskhah 1984; Sepaskhah and Ghasemi 2008).

In furrow irrigation, by planting on the ridge, soil surface evaporation results in water loss due to less shading occurs on the wetted area in furrow; whereas, in-furrow planting results in lower surface evaporation and water saving due to shading on the wetted area (Zhang et al. 2007; Li et al. 2010; Buttar et al. 2006; Shabani et al. 2013).

Nitrogen is the key nutrition in crop production and it is lost by water leaching and contaminates the groundwater (Raun and Johnson 1999; Cerrato and Blackmer 1990). Furthermore, there is significant interaction effect between irrigation regimes, water use and nitrogen application rate in crop production and productivity that should be considered (Huang et al. 2003). Water soluble nitrate is easily leached and contaminated the groundwater that should be managed properly. Many studies indicated that nitrogen absorption is increased and nitrogen leaching is decreased in maize field under alternate furrow irrigation (Skinner et al. 1999; Sepaskhah and Tafteh 2012; Tafteh and Sepaskhah 2012).

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PRD combined with optimum nitrogen application rate and in-furrow planting could be desirable practice in case of limited water supply conditions; however, the optimum level of nitrogen application rate in PRD and in-furrow planting should be determined.

The objectives of this study was to investigate the interaction effects of alternate every other furrow irrigation (PRD), planting\methods (in-furrow and on-ridge) and nitrogen application rates on barley yield, water use efficiency and nitrogen use efficiency.

Materials and Methods

Description of the Study Area

This study was conducted at the research station of the Agricultural College of Shiraz University, Shiraz, Iran during the 2011–2012 cropping season. The station is located in Badjgah valley at 29°56′N latitude, 52°02′E longitude and 1810 m above sea level. The mean monthly weather data during the cropping season have been reported in Table 1 and Fig. 1. The physico-chemical properties of the soil and water used for irrigation have been characterized following the procedures explained in Sparks et al. (1996) and presented in Table 2. The soil data has been adopted from Barzegari et al. (2017).

Experimental Setup and Procedure

The response of barley to the interaction effects of three factors, namely irrigation techniques, planting pattern and nitrogen fertilizer levels were investigated. The experiment was designed in split–split-plot with three replications and treatments were arranged as randomized complete blocks. The two different irrigation treatments were ordinary furrow irrigation (OFI) and variable alternate furrow irrigation (VAFI). They were assigned as main plot treatments. While the planting method treatments, on-ridge planting (ORP) and in-furrow planting (IFP) of seeds, were allocated as the sub plot. Nitrogen fertilizer, which has three levels namely 0, 90 and 180 kg N ha^{-1}, were assigned as sub-subplot treatment.

Table 1 Monthly mean weather data during the growing season in 2011–2012

Month	Mean daily temperature (°C)	Mean daily relative humidity (%)	Wind speed (mile d^{-1})	Daily sunshine hour (h)
November	11.1	35.6	60.1	8.1
December	4.6	52.7	28.5	7.2
January	4.4	58.3	54.5	7.2
February	4.0	55.5	72.5	6.5
March	5.9	42.8	88.9	8.7
April	11.1	43.4	65.2	7.3
May	17.2	35.0	58.0	8.7
June	21.7	26.1	57.2	10.1

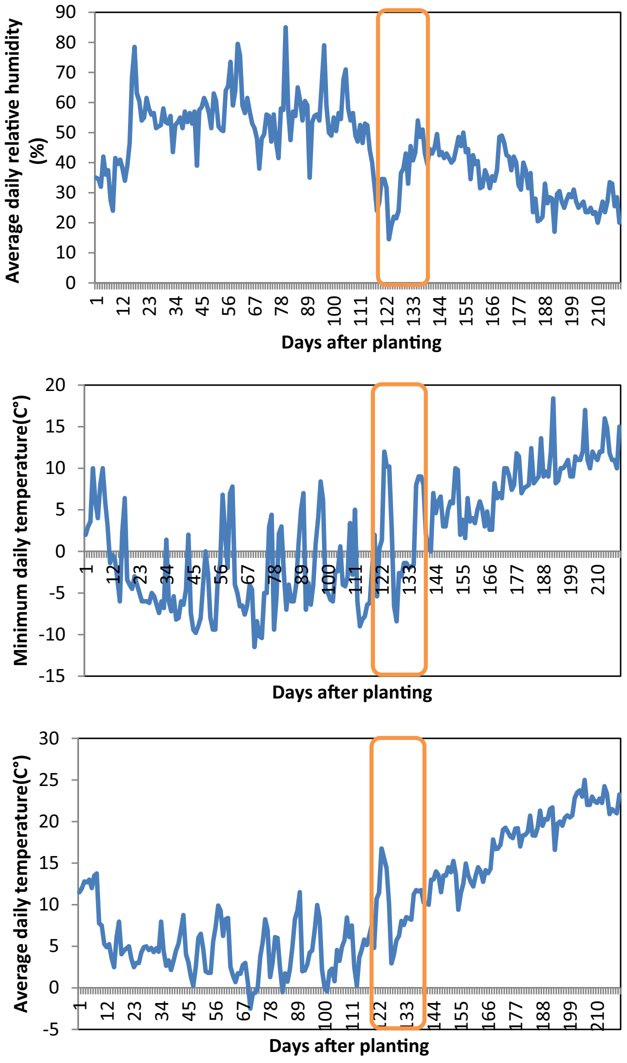

Fig. 1 Variations of the weather parameters during the growing season

Barley (cv local Bahman) was seeded on 13 November of 2011 in 36 water balance lysimeters (2.25 m^2), which was preceded by sugar beet. Each lysimeter has similar dimensions of 1.5 m × 1.5 m × 1.1 m. A layer of 0.05 m gravel was placed at the bottom of each unit and soil layer with thickness of 0.90 m was placed on top of the gravel layer. A drain tube has been fixed into each lysimeter to drain the drainage water from the bottom to individual sumps. Before planting, three furrows and four ridges were made in each lysimeter. Local cultivar of barley were

Table 2 Physico-chemical properties of the soil and water at experimental site

Characteristics	Unit	Soil depth (cm)				Irrigation water
		0–30	30–60	60–90	0–90	
Sand	%	35	23	21	–	–
Silt	%	35	38	39	–	–
Clay	%	30	39	40	–	–
Bulk density	g cm^{-3}	1.39	1.44	1.47	–	–
Field capacity	cm^3 cm^{-3}	0.32	0.34	0.36	–	–
Permanent wilting point	cm^3 cm^{-3}	0.11	0.14	0.16	–	–
Electrical conductivity	dS m^{-1}	–	–	–	0.64	0.72
pH	–	–	–	–	7.54	7.58
Cl^-	(mmol l^{-1})	–	–	–	1.2	0.9
Na^+	(mmol l^{-1})	–	–	–	1.0	0.62
K^+	(mmol l^{-1})	–	–	–	0.03	0.03
Ca^{2+}	(mmol l^{-1})	–	–	–	4.5	4.0
Mg^{2+}	(mmol l^{-1})	–	–	–	2.1	3.0
HCO_3^-	(mmpl l^{-1})	–	–	–	4.0	4.0
SO_4^{2-}	(mmol l^{-1})	–	–	–	2.4	2.5

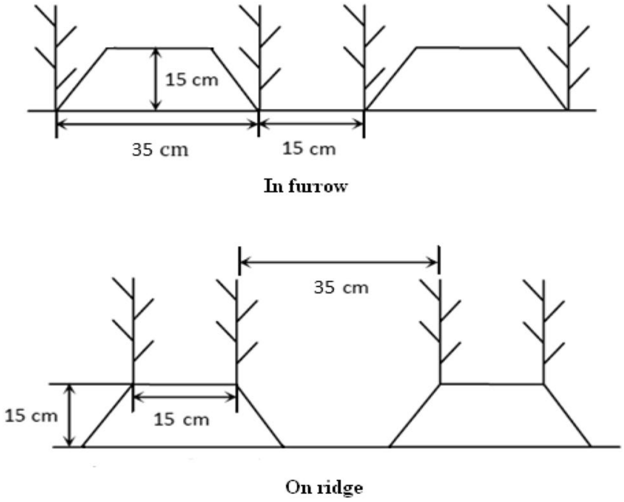

Fig. 2 Schematic diagram of the planting methods

hand-seeded at a rate of 200 kg ha^{-1} in 6 rows, which were 0.15 m apart both in furrows and on ridges. The size of furrows and rides was 0.35 m (Fig. 2). Recommended rate of phosphorous, 46 kg P_2O_5 ha^{-1}, was applied as basal application from triple superphosphate. Nitrogen (N) fertilizer was applied based on the treatment arrangement from urea twice per growing season. Half of N was applied at 3 weeks after planting and the remaining half was added at 15 weeks after planting at stem elongation stage as side dressing. Urea was used in the irrigated furrows before irrigation to avoid ammonia volatilization. Weeds were controlled by hand four times during the growing season.

Crop Water and Irrigation Requirement

Reference evapotranspiration (ET_o) during the growing season was calculated using modified Penman–Monteith equation for semi-arid environments (Razzaghi and Sepaskhah 2012).

Crop irrigation requirement was determined by monitoring the soil water status in different treatments at 10 days irrigation interval that is in accordance with the optimum water depletion fraction for barley and local farmers practice. Soil water contents at depths of 0.30, 0.60 and 0.90 m were measured before each irrigation events using neutron scattering method. The access tube of neutron meter was installed at the bottom of middle furrow in an OFI and at the bottom side of the middle furrows in a VAFI treatments. Soil water content at depth of 0–0.15 m was determined using gravimetric sampling method. Soil water contents in the root zone determined through neutron scattering and gravimetric methods were used to calculate the amount of irrigation water needed. The irrigation water depth was calculated using the following equation:

$$d = \sum_{i=1}^{n} (\theta_{fci} - \theta_i)\,\Delta z_i, \qquad (1)$$

where d is the irrigation water depth (m), θ_{fci} and θ_i are the volumetric soil water content (m^3 m^{-3}) in layer i at field capacity and before irrigation, respectively, Δz is thickness of soil layer (m) and n is the number of soil layers.

The root depths of barley at different growing stages were estimated by Eq. (2) (Borg and Grimes 1986):

$$Z_r = R_{DM}\left[0.5 + 0.5\sin\left(\frac{3.03D_{as}}{D_{tm}} - 1.47\right)\right], \qquad (2)$$

where Z_r is the root depth (m), R_{DM} is the maximum root depth, 0.9 m as the maximum soil depth in the lysimeter, D_{as} is the number of days after planting and D_{tm} is the number of days for maximum root depth. The gross irrigation water requirement was calculated using an irrigation application efficiency of 70%. The calculated gross irrigation water requirement was fully applied to an OFI regime and to all three furrows; whereas, only two-third of gross irrigation water requirement was applied to VAFI regime, which were dry in the preceding irrigation cycle. The amount of applied irrigation water to each lysimeter was measured using a volumetric flow meter. Three initial irrigations with total amounts of 74 and 69 mm for OFI and VAFI, respectively were applied as full irrigation (OFI) to induce uniform seed germination and plant stands, and uniform distribution of the applied nitrogen fertilizer. The first irrigation, which was 34 mm was conducted after seeding and was followed by two other irrigations, which were about 40 and 35 mm for OFI and VAFI, respectively for the purpose of dissolving and uniformly distributing the applied nitrogen from urea. During fall and winter, the crop water requirement was mostly provided by precipitation until early spring.

The following equation was employed to calculate the water balance during the cropping season for calculating crop evapotranspiration) (Jensen 1974):

$$ET = I + P - D \pm \left(\sum_{i=1}^{n} (\theta_1 - \theta_2) \Delta S_i \right), \tag{3}$$

where ET is the crop evapotranspiration (mm), I is the irrigation depth (mm), P is the precipitation (mm), D is the deep percolation (mm) from the bottom of root zone, n is the number of soil layers, ΔS is the thickness of each soil layer (300 mm for three different layers) and θ_1 and θ_2 are the volumetric soil water contents before each wetting event ($cm^3\ cm^{-3}$).

Micro-lysimeters were used to measure evaporation (E) from the soil surface. Small PVC cylinders with dimensions of 10 cm diameter and 30 cm height filled with the same field soil and buried into the surface soil. The micro-lysimeters were weighted between irrigation and rainfall events to determine the soil evaporation.

Data Collection

The crop has been harvested on June 9 and June 19 of 2012 from the in-furrow and on-ridge treatments, respectively from the four inner rows of the lysimeters. Mowing was conducted just above ground level, dried at 80 °C until a constant weight and threshed manually. The grains and straws were weighted using balance and the results were converted into kg ha^{-1} for statistical purposes. Grain protein concentrations of each treatment was calculated from the determination of their N concentrations using Kjeldahl method and multiplying them by 5.3 (Sanchez-Mata et al. 2003). Protein yield was determined by multiplying the protein concentration fraction by the grain yield (kg ha^{-1}). N concentration in straw was determined by measuring the N concentration in a mixture of stems and leaves by Kjeldahl method. Straw nitrogen uptake was determined by multiplying the nitrogen concentration fraction in straw by the straw yield (kg ha^{-1}) and total nitrogen uptake was determined as sum of the straw and grain nitrogen uptake.

Water Use Efficiency

Water use efficiency (WUE) was calculated as a ratio of seed yield of barley produced to unit of crop water use [Eq. (4)]:

$$WUE = \frac{Y}{ET}, \tag{4}$$

where WUE is the water use efficiency in kg m^{-3}, Y is the grain yield in kg ha^{-1} and ET is the crop evapotranspiration in $m^3\ ha^{-1}$. The water productivity (WP) also determined as the ratio of grain yield to applied irrigation water (IW) as follows:

$$WP = Y/IW. \tag{5}$$

Nitrogen Use Efficiency

The apparent N recovery (NUE) for different levels of N was calculated by making use of the total N uptake by grain and straw, and the amount of applied N fertilizer, as shown in Eq. (6).

$$NUE = \frac{N_{ui} - N_{uc}}{N_{fi} - N_{fc}}, \tag{6}$$

where NUE is the apparent N recovery or nitrogen use efficiency, N_{ui} and N_{uc} are the total N uptake by grain and straw in different N treatments and control, respectively (kg ha^{-1}), and N_{fi} and N_{fc} are the applied N fertilizer in different N treatments and control, respectively (kg ha^{-1}).

To describe the utilization of N inputs in relation to the level of N applied, nitrogen yield efficiency (NYE) or agronomic nitrogen efficiency has been used (Fageria and Baligar 2005). The NYE in different N treatments was calculated using the applied N fertilizer and grain yield as indicated in Eq. (7) (Craswell and Godwin 1984).

$$NYE = \frac{Y_i - Y_c}{N_{fi} - N_{fc}}. \tag{7}$$

The physiological N efficiency (NPE) was determined using Eq. (8).

$$NPE = \frac{Y_i - Y_c}{N_{ui} - N_{uc}}, \tag{8}$$

where Y_i and Y_c are the grain yield in different N treatments and control, respectively (kg ha^{-1}).

Economic Analysis

For the purpose of economic analysis, information about the total production cost and gross income from unit area was collected and analysed. Total production cost consisted of fixed and variable costs. Fixed cost included the costs related to land preparation, planting, farm maintenance and harvesting according to the recommendation of Jehade-Agriculture Organization of Fars province for 2011–2012 production year. While variable costs for the different irrigation and fertilizer treatments consisted of costs related to water, fertilizer, labour and transportation. Gross income was calculated as a product of total yield from unit area and unit price of barley. The net income was determined as a difference between the gross income and total production cost. The net income divided by the total amount of applied irrigation water was considered as economic productivity of water. The differences between the net incomes from the different nitrogen treatments applied and the zero nitrogen treatment divided by the total amount of nitrogen was considered as economic nitrogen productivity.

Statistical Analysis

Analysis of variances (ANOVA) for all of the parameters measured and determined were performed using SAS software. Duncan multiple range test at 5% level of probability was used to find differences among treatment means. The interaction effects between irrigation strategies, planting methods and fertilizer levels were evaluated.

Results and Discussions

Irrigation Water Use

The cumulative irrigation, rainfall and ET_o of barley have illustrated in Fig. 3. The seasonal reference evapotranspiration (ET_o) was 944 mm. Total rainfall was 335 mm during the barley growing season that mostly occurred in late fall, winter and early spring. The seasonal applied irrigation water for different treatments have presented in Table 3. It was 750 mm for OFI that is similar to that is used in another study as reported by Sepaskhah (1978). The PRD irrigation reduced the applied irrigation water by 25% compared with the full irrigation (OFI). Similarly, different experimental results from various crops have indicated that irrigation water may be reduced by approximately 30–50% in PRD irrigation without significant yield loss (Sepaskhah and Ahmadi 2010). According to Table 3, the applied irrigation water in PRD treatments was higher than the half of the irrigation water applied in OFI. This finding was similarly reported by Sepaskhah and Tafteh (2012), Tafteh and Sepaskhah (2012), and Shahrokhnia and Sepaskhah (2016) which resulted due to the fact that the mean soil water content in the rooting zone in the PRD irrigation is lower than that in OFI.

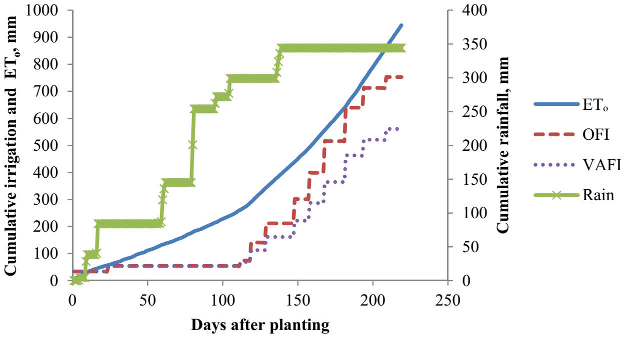

Fig. 3 Variations in cumulative irrigation water, potential evapotranspiration (ET_o), and rainfall during the growing season

Table 3 Seasonal water balance components (mm) at different irrigation methods

Component	Irrigation method	
	Ordinary furrow	Variable alternate furrow
Rainfall	335	335
Reference ET_o	944	944
Net irrigation	552	416
Gross irrigation	753	561
Drainage water	336	225
Evapotranspiration	682	614
Surface evaporation	226	192

Seasonal barley evapotranspiration (ET) in different treatments were determined by water balance method [Eq. (1)] that is illustrated in Table 3. The values of ET varied between 614 and 682 mm for different irrigation treatments. The PRD irrigation reduced the barley ET and surface evaporation about 10 and 16%, respectively, compared with the full irrigation treatments whereas irrigation water was reduced 25% (Table 3). Therefore, VAFI is more efficient in using the irrigation water Similarly, the PRD mechanism led to 20% decline in rapeseed evapotranspiration in study of Sepaskhah and Tafteh (2012) at the same site that were reported due to the reduced soil surface evaporation in alternate furrow irrigation. This reduction was 16.5% for safflower as reported by Shahrokhnia and Sepaskhah (2016). Furthermore, 10–26% reductions in maize water consumption have reported by Liang et al. (2013) under variable alternate furrow irrigation strategy.

Yield

Grain

The grain yield of barley for different treatments is presented in Table 4. The results showed that grain yield was not reduced significantly by changing irrigation regimes under ORP with different N application rates: however, it was reduced significantly by VAFI under IFP with N application rates of 90 and 180 kg ha^{-1} (10%) whereas, the irrigation water depth was reduced 25% (Table 4). The highest grain yield (8.13 Mg ha^{-1}) was obtained in the OFI with in-furrow planting method and 180 kg N ha^{-1} treatment. Furthermore, the minimum grain yield (3.76 Mg ha^{-1}) was produced in VAFI with on-ridge planting method and non-fertilized treatment.

Furthermore, VAFI under IFP with N application rates of 90 and 180 kg ha^{-1} resulted in significantly higher grain yield compared with those in OFI under ORP. Similar results were obtained in the studies of Istanbulluoglu et al. (2009), Movahhedy-Dehnavy et al. (2009), Abd El-Lattief (2013), Ghamarnia and Sepehri (2010) and Shahrokhnia and Sepaskhah (2016) in which safflower seed yield was significantly decreased by imposing different deficit irrigation strategies in ordinary and alternate furrow irrigation. As noted above, in our study, no significant grain yield decrement was resulted by about 25% decrease in applied irrigation water by PRD irrigation strategy that shows a satisfactory result in application of this technique. This occurred due to the fact that in PRD (VAFI) irrigation the chemical signal from root to plant top resulted in higher reduction in leaf transpiration and lower reduction in photosynthesis ending to higher leaf scale water productivity (Sepaskhah and Ahmadi 2010).

Compared with ORP, in-furrow planting showed positive influence on producing grain yield higher than those in on-ridge planting in all irrigation methods and 90 and 180 kg N ha^{-1} treatments; moreover, the in-furrow and on-ridge planting methods were not effective in yield increase for non-fertilized treatments. In other words, a yield enhancement of 15% was occurred under various nitrogen supported plots in in-furrow planted crops with shorter growing season and 40 mm less applied water compared with those in on-ridge planting. This difference was occurred due to early spring low air temperature (Fig. 1) that adversely affected the flowering in on-ridge planting. Similarly, there are researches indicated that in-furrow planting has increased crop yield (Yarami and Sepaskhah 2015; Shabani et al. 2013; Quanqi et al. 2012; Shahrokhnia and

Table 4 Grain yield (Mg ha^{-1}), biomass (Mg ha^{-1}), grain protein concentration (%) and grain protein yield (kg ha^{-1})

Irrigation treatment	Planting method						Mean
	In-furrow planting			On-ridge planting			
	Nitrogen (kg ha^{-1})						
	0	90	180	0	90	180	
Grain yield, Mg ha^{-1}							
OFI	4.14 e[a]	7.28 b	8.13 a	4.16 e	5.76 d	6.57 c	6.01 A
VAFI	3.89 e	6.46 c	7.34 b	3.76 e	5.45 d	6.85 c	5.63 A
Mean	6.21 A			5.42 B			
Biomass yield, Mg ha^{-1}							
OFI	10.08 e[a]	15.95 b	18.20 a	10.20 e	12.12 d	13.85 c	13.40 A
VAFI	8.95 f	13.99 c	16.71 b	8.59 f	12.07 d	14.33 c	12.44 B
Mean	13.98 A			11.86 B			
Grain protein concentration, %							
OFI	7.46 g[a]	9.02 e	11.71 c	6.91 h	9.16 e	11.46 c	9.29 B
VAFI	8.45 f	10.13 d	13.27 a	8.36 f	10.03 d	12.20 b	10.41 A
Mean	10.01 A			9.69 B			
Grain protein yield, kg ha^{-1}							
OFI	308.5 f	657.9 d	952.8 a	287.2 f	526.9 e	753.3 c	581.1 A
VAFI	329.4 f	654.2 d	974.6 a	308.1 f	540.0 e	835.4 b	606.9 A
Mean	646.2 A			541.8 B			

OFI ordinary furrow irrigation, *VAFI* variable furrow irrigation

[a] Means follow with the same letters are not different significantly at 5% probability level by Duncan multiple range test

Sepaskhah 2016) due to providing an appropriate soil temperature condition, higher accessible soil water content for plants and better frost avoidance. Meanwhile, in the study of Shabani et al. (2013) yield was increased by 5.3 and 13.7% for two consecutive years in in-furrow planted rapeseed that were relatively close to our results.

Different application rates of nitrogen showed that barley is a responsive crop to nitrogen. This is in agreement with other research findings reported by Banziger et al. (1994), Dordas and Sioulas (2008), Abbadi et al. (2008) and Shahrokhnia and Sepaskhah (2016). Application of nitrogen as 90 and 180 kg N ha^{-1} resulted in significant increase about 42 and 69% in grain yield compared with control treatments (0 kg N ha^{-1}) in on-ridge planting. These increases were 71 and 93%, respectively in in-furrow planting. These results indicated that nitrogen application rates in in-furrow planting method is more effective in grain yield increase. The different applied nitrogen levels showed statistically significant effects on barley grain yield, whereas the increase rate of grain yield obtained by application of 180 kg N ha^{-1} were lower in comparison with 90 kg N ha^{-1} rate as compared with control (0 kg N ha^{-1}). Therefore, application of more than 180 kg N ha^{-1} may have no significant influence on barley grain yield which is in accordance with the results obtained by Shahrokhnia and Sepaskhah (2016) for safflower. Furthermore, Dordas and Sioulas (2008) reported that application of 200 kg N ha^{-1} compared with 100 kg N ha^{-1} did not produce significant seed yield increase in safflower seed yield.

Biomass

The biomass yield of barley (straw + grain) in different treatments was presented in Table 4. Irrigation regimes, planting method and nitrogen application rates showed significant effects on biomass yield. Results showed, the combination of OFI irrigation regime, in-furrow planting method and 180 kg N ha^{-1} treatment produced maximum biomass; whereas the minimum biomass was obtained in VAFI plots with on-ridge planting method and non-fertilized treatments. According to Table 4, VAFI treatments reduced the mean biomass by 7% compared with that obtained in OFI plots. As noted above, biomass yield decrement (about 7%) in our study was resulted by about 25% decrease in applied irrigation water by PRD irrigation strategy that shows a satisfactory result in application of this technique.

Barley biomass was significantly influenced by in-furrow planting method that produced higher biomass (18%) than that for on-ridge planting method (Table 4). Biomass yield for in-furrow planting method showed significant differences between OFI and VAFI irrigation treatments (11.5%, data not shown); whereas, this increase was about 3.4% (non significant, data not shown) in on-ridge planting. The findings in Table 4 showed that the positive effect of in-furrow planting method was more achievable under OFI conditions for biomass production than that for VFAI (22 vs. 13%).

Biomass was significantly influenced by different nitrogen application rates in both planting methods. Nitrogen application rates from 0 to 90 kg N ha^{-1} led to increase of 57% in biomass in in-furrow planting. Furthermore, in this method, 83% increase in biomass achieved by nitrogen use of 180 kg N ha^{-1} compared with 0 kg N ha^{-1}. Corresponding increase in biomass were 29 and 50% in on-ridge planting. Therefore, the nitrogen effect on biomass increase was higher in in-furrow planting. Similarly, N fertilization increased crop biomass such as safflower compared with the control in the study of Dordas and Sioulas (2008) and winter wheat reported by Sepaskhah and Hosseini (2008).

Yield Quality

Grain Protein Concentration and Protein Yield

Protein concentration in barley grain is an important issue in this investigation because of its application in livestock feed. Barley grain protein concentration (GPC) and protein yield (PY) are presented in Table 4. In general, application of PRD irrigation technique, in-furrow planting method and 180 kg N ha^{-1} resulted in the most favourable protein yield (PY) with respect to less water consumption and higher yield production.

Irrigation regimes, nitrogen application rates and planting method showed significant influence on GPC. In addition, PY was not statistically affected by irrigation strategies. In contrary, it was influenced by planting method and nitrogen application rates. Moreover, no interaction effects on PY were observed among treatments except N application rate of 180 kg ha^{-1} and ORP that VAFI enhanced the PY significantly by 11%.

The mean value of GPC was significantly increased by PRD irrigation (VAFI) by 12.1% compared with full irrigation regime (Table 4). Consequently, less water consumption led to higher protein accumulation in barley grain. This is due to the fact that water stress shortens the cycle of grain filling and since proteins are initial source compounds in grains; therefore, the chance to reserve carbohydrates is limited (Sabbagh et al. 2012). Enhancement of grain protein concentration by imposing PRD (VAFI) regime has been reported by other researchers such as Sepaskhah and Tafteh (2012), Sepaskhah and Hosseini (2008) that are in agreement with our results.

In-furrow planting method showed significant influence in GPC and PY. The values of GPC and PY were increased for in-furrow planting method by 3.3 and 19.3%, respectively. In fact, the enhancement of PY was related to higher grain yield that was produced by in-furrow planted barley.

The highest barley GPC and PY was obtained in N_2 treatments due to higher grain nitrogen accumulation and grain yield, respectively. Indeed, N_1 and N_2 treatments showed higher GPC as 23.4 and 56.5% compared with N_o, respectively. This increase for GPC was higher in N_2 than that in N_1. On the other hand, PY was higher in N_1 and N_2 treatments by about 93 and 184% compared with that in N_o, respectively. Furthermore, the GPC in N_2 treatments was 26.9% higher than that in N_1. GPC and PY were also increased by N application rates as reported by Nasr et al. (1978), Haby et al. (1982) and Dordas and Sioulas (2008) for safflower.

Biomass Nitrogen Uptake

The biomass nitrogen uptake (BNU) of barley is presented in Table 5. There was no significant difference in BNU in different irrigation regimes. However, in ORP and N application rate of 180 kg ha^{-1} there was significantly higher BNU in VAFI. In-furrow planting method resulted in significantly higher BNU (22%) compared with ORP. By increasing N application rates the BNU was increased significantly. In N application rates of 90 and 180 kg ha^{-1} the BNU was significantly higher in in-furrow planting than that in on-ridge planting. Similar results were reported for safflower by Shahrokhnia and Sepaskhah (2017). Therefore, it is indicated that in-furrow planting is more effective in N uptake. Nitrogen fertilization by 90 and 180 kg ha^{-1} led to 119 and 192% increase in BNU, respectively compared with 0 N application rate that represent the substantial influence of nitrogen on barley BNU.

Water and Nitrogen Use Efficiencies

Water Use Efficiency

Water use efficiency (WUE) of barley was in range of 0.7–1.2 kg m^{-3} (Table 6). The highest WUE in our study

Table 5 Biomass nitrogen uptake (kg ha^{-1})

Irrigation treatment	Planting method						Mean
	In-furrow planting			On-ridge planting			
	Nitrogen (kg ha^{-1})						
	0	90	180	0	90	180	
Biomass N uptake, kg ha^{-1}							
OFI	64.3 f[a]	45.1 d	215.1 a	60.0 f	111.7 e	61.3 c	126.3 A
VAFI	70.9 f	143.0 d	209.3 a	66.3 f	117.9	176.7 b	130.7 A
Mean	141.3 A			115.6 B			

OFI ordinary furrow irrigation, *VAFI* variable furrow irrigation

[a] Means follow with the same letters are not different significantly at 5% probability level by Duncan multiple range test

Table 6 Water use efficiency (WUE), and water productivity (WP) in different treatments

Irrigation treatment	Planting method						Mean
	In-furrow planting			On-ridge planting			
	Nitrogen (kg ha^{-1})						
	0	90	180	0	90	180	
WUE, kg m^{-3}							
OFI	0.73 d[a]	1.16 ab	1.19 a	0.70 d	0.91 c	0.94 c	0.94 A
VAFI	0.75 d	1.13 ab	1.20 a	0.72 d	0.95 c	1.11 b	0.98 A
Mean	1.03 A			0.89 B			
WP, kg m^{-3}							
OFI	0.40 g[a]	0.70 c	0.77 b	0.38 g	0.53 f	0.60 d	0.56 B
VAFI	0.46 f	0.76 b	0.86 a	0.41 g	0.60 d	0.76 b	0.64 A
Mean	0.66 A			0.55 B			

OFI ordinary furrow irrigation, *VAFI* variable furrow irrigation

[a] Means follow with the same letters are not different significantly at 5% probability level by Duncan multiple range test

was achieved by in-furrow planting method and both nitrogen supported treatments about 1.17 kg m^{-3}. In general, 16% of yield increment was recorded due to planting of barley in in-furrow method compared with on-ridge method using the same amount of water. Furthermore, PRD irrigation treatments showed statistically similar WUE in comparison with OFI. Similar results were obtained from studies of Sepaskhah and Tafteh (2012), Liu et al. (2006) and Lovelli et al. (2007). They reported that WUE of rapeseed and potato was not affected by PRD. Conversely, the least WUE in our study was about 0.7 kg m^{-3} that obtained from full irrigation (OFI) accompanied by on-ridge planting method and non-fertilized treatments. Moreover, in-furrow planting method increased WUE about 16% compared with on-ridge planting method. This increase is significant and is in agreement with the results obtained from studies of Shabani et al. (2013) and Quanqi et al. (2012) for rapeseed and wheat, respectively. Furthermore, application of 90 kg N ha^{-1} led to about 55 and 31% increase in WUE of barley compared with non-fertilized treatment in in-furrow and on-ridge planting methods, respectively. Whereas, about 61.5 and 44.3% increase in WUE was observed in 180 kg ha^{-1} nitrogen application rates. The difference in WUE between 90 and 180 nm application rates were not statistically significant.

In general, the highest WP was obtained in VAFI, in-furrow planting and 180 kg N ha^{-1}.

Water productivity (WP) in VAFI is higher than that in OFI and this increase is about 14% that is statistically significant. In-furrow planting resulted in 20% increase in WP compared with that in on-ridge planting that is statistically significant. By application of N, WP is increased and this increase was statistically significant in different N application rates. Similar results are reported by Singh and Kumar (1981). They observed that N application resulted in 9 and 8% higher water use in wheat and barley with 90 and 100% increase in yield, respectively. Table 6 indicated that there is no significant difference between WP of OFI-180 kg N ha^{-1} and VAFI-90 kg N ha^{-1}. Therefore, in PRD irrigation regimes lower N is required to obtain equal WP to OFI. It is indicated that WP can be improved by irrigation method and N application management.

Nitrogen Efficiencies

NUE can demonstrate the amount of N that is acquired by crops and also their efficiency in taking up soil nitrogen. The NUE of barley ranged between 0.40 and 0.71 kg kg^{-1} for different treatments (Table 7). The highest NUE (ranging between 0.66 and 0.71 kg kg^{-1}) was obtained in nitrogen application rates of 90–180 kg ha^{-1} accompanied by in-furrow planting method; whereas, 90 and 180 kg ha^{-1} nitrogen application rate and on-ridge planting method in OFI resulted in least NUE values (between 0.4 and 0.42 kg kg^{-1}). In ORP with high rates of nitrogen (180 kg N ha^{-1}), NUE values were significantly higher in PRD irrigated crops compared with the well watered crops. This issue showed that PRD irrigation have somewhat recovered the negative effect of higher nitrogen application rates on barley NUE. NUE was significantly increased by in-furrow planting method by about 42% compared with on-ridge planting. In other words, obtaining higher seed yield from in-furrow planted crops took up more amount of N from the soil and resulted in higher NUE than on-ridge planting method. Application of 180 kg N ha^{-1} increased NUE by about 6% that was not statistically significant. In general, application of 90 kg N ha^{-1} with in-furrow planting method and VAFI for barley was optimum. This might be due to higher accessibility of nitrogen in furrows and VAFI that have led to higher N uptake by barley. In contrast, it has been shown that high N application decreased NUE in various crops (Lopez-Bellido et al. 2005; Dawson et al. 2008), that is mainly due to the low capability of crops to utilize total applied N (Gholamhoseini et al. 2013).

Table 7 Nitrogen use efficiency (NUE), nitrogen physiologic efficiency (NPE) and nitrogen yield efficiency (NYE)

Irrigation treatment	Planting method				Mean
	In-furrow planting		On-ridge planting		
	Nitrogen (kg ha^{-1})				
	90	180	90	180	
NUE, kg kg^{-1}					
OFI	0.660 a[a]	0.670 a	0.403 c	0.423 c	0.539 B
VAFI	0.693 a	0.710 a	0.510 bc	0.587 ab	0.625 A
Mean	0.683 A		0.481 B		
NPE, kg kg^{-1}					
OFI	26.49 de[a]	39.04 a	23.87 e	30.74 c	30.03 A
VAFI	24.99 e	35.64 ab	28.74 cd	32.32 bc	30.42 A
Mean	31.54 A		28.92 A		
NYE, kg kg^{-1}					
OFI	22.19 bc[a]	31.27 a	13.43 d	17.73 cd	21.15 A
VAFI	18.45 cd	28.51 ab	17.64 cd	18.96 cd	20.89 A
Mean	25.11 A		16.94 B		

OFI ordinary furrow irrigation, *VAFI* variable furrow irrigation

[a] Means follow with the same letters are not different significantly at 5% probability level by Duncan multiple range test

Barley NPE was in range of 23.9–39.0 kg kg^{-1} for different treatments (Table 7). The highest value of NPE (ranged between 35.6 and 39.0 kg kg^{-1}) was obtained in treatments with 180 kg N ha^{-1} and in-furrow planting. Furthermore, there was no significant difference between NPE in full irrigation (OFI) and VAFI treatments. Conversely, application rate of 180 kg N ha^{-1} resulted in higher NPE than that obtained in 90 kg N ha^{-1} and it

Table 8 Economic water productivity (EWP, Rls m^{-3}) and economic nitrogen productivity (ENP, 1000 Rls kg^{-1} N) in different irrigation regimes, planting methods and nitrogen treatments

Irrigation treatment	Planting method						Mean
	In-furrow planting			On-ridge planting			
	Nitrogen (kg ha^{-1})						
	0	90	180	0	90	180	
EWP, Rls/m^3							
OFI	214 g[a]	2170 d	2626 bc	115 g	788 f	1114 f	1171 B
VAFI	752 f	2978 b	3864 a	338 g	1717 e	2577 c	2038 A
Mean	2101 A			1108 B			
ENP, 1000 Rls/kg N							
OFI	–	153.2 a[a]	96.7 c	–	55.7 e	42.3 f	87.0 B
VAFI	–	128.0 b	90.9 c	–	85.4 c	70.3 d	93.7 A
Mean	117.2 A			62.9 B			

OFI ordinary furrow irrigation, *VAFI* variable furrow irrigation

[a] Means follow with the same letters are not different significantly at 5% probability level by Duncan multiple range test

was higher in in-furrow planting. In contrary, Rostamza et al. (2011) and Mokhtassi-Bidgoli et al. (2013) reported that nitrogen utilization efficiency was decreased with higher N availability. There was no significant difference between NPE in in-furrow planting and on-ridge planting methods; however, application of 90 kg N ha^{-1} in ORP significantly increased NPE in VAFI by 20% compared with that in OFI.

NYE of barley was in range of 13.4–31.3 kg kg^{-1} (Table 7). These values are higher than those reported by Dordas and Sioulas (2008) for safflower as 2.2–5.4 kg kg^{-1} in application rates of 100 and 200 kg N ha^{-1} for different cultivars. Similar to NPE, the maximum values of NYE (31.3 and 28.5 kg kg^{-1} for OFI and VAFI, respectively) in our study were obtained in the treatments with 180 kg N ha^{-1}. Moreover, full irrigation treatments (OFI) and in-furrow planting method produced statistically similar NYE in comparison with PRD irrigation strategy and in-furrow planting. On the other hand, application rate of 180 kg N ha^{-1} led to 39.9% higher NYE compared with 90 kg N ha^{-1}. In contrary, Dordas and Sioulas (2008) and Fageria and Baligar (2005) reported that agronomic efficiency (NYE) of safflower was higher in lower N application rate compared with higher N application rate. Consequently, the NYE of safflower decreased when higher N rates were applied due to the fact that the increase in seed yield becomes lower with increase in the rate of N application. This is in agreement with other studies found that NYE was higher at lower N application rates and decreased at higher N application rates (Fageria and Baligar 2005). This is due to the fact that capability of barley to N uptake has increased in higher N application rate.

Economical Water and Nitrogen Productivity

Economic water and nitrogen productivity (EWP, ENP) for different treatments are shown in Table 8. The maximum EWP was obtained in VAFI, in-furrow planting and 180 kg N ha^{-1} that is recommended for the study area. VAFI increased ENP by 8% compared with that for OFI that is statistically significant. VAFI increased EWP by 74% compared with that for OFI that is statistically significant. Also, in-furrow planting increased EWP by 90% compared with that for on-ridge planting that is statistically significant. Furthermore, increasing nitrogen application rate increased the EWP significantly. For VAFI the optimum nitrogen application rate is 180 kg ha^{-1} especially in in-furrow. Also, in-furrow planting increased ENP by 86% compared with on-ridge planting that is statistically significant. Difference between ENP for the 90 and 180 kg N ha^{-1} was statistically significant and it was decreased by 33% in 180 kg N ha^{-1} compared with that in 90 kg N ha^{-1} in in-furrow planting. This decrease was 21% in on-ridge planting. Furthermore, it is indicated that in-furrow planting, the values of ENP in both irrigation regimes are not statistically different in 180 kg N ha^{-1}. Therefore, by using less water in VAFI in in-furrow planting and N application rate of 180 kg ha^{-1} equal ENP was obtained compared with OFI.

Conclusions

This investigation showed that the variable alternate furrow irrigation (VAFI) as a PRD irrigation technique resulted in 25% decrease in applied irrigation water for barley with no significant grain yield reduction. Furthermore, in-furrow planting method resulted in 15% enhancement in barley grain yield compared with that in on-ridge planting due to the better soil conditions (temperature and moisture) that is provided by this technique. Moreover, application of nitrogen as 90 and 180 kg N ha^{-1} resulted in significant increase about 42 and 69% in grain yield compared with control treatments (0 kg N ha^{-1}) in on-ridge planting. These increases were higher as 71 and 93%, respectively in in-furrow planting. Therefore, in in-furrow planting and VAFI, increase in grain yield by higher N application rate was obtained with equal nitrogen use efficiencies.

In general, PRD irrigation strategy increased barley grain protein concentration and water productivity, but it showed no effects on protein yield and water use efficiency and harvest index. In addition, in-furrow planting method enhanced barley grain yield, biomass, total nitrogen uptake, WUE, WP, protein concentration, protein yield, NUE and NYE; whereas, it did not influence the barley NPE. Furthermore, different N fertilization rates increased different barley traits. Application of 180 kg N ha^{-1} dominantly increased NYE and NPE in in-furrow planting in comparison with application nitrogen rate of 90 kg ha^{-1}.

Finally, it is concluded that PRD irrigation (VAFI) can be an effective strategy in irrigation water saving for barley in areas with limited water resources. On the other hand, in-furrow planting method can be an appropriate alternative for barley due to its favourable influence on WP, EWP and WUE and other barley traits, especially in semi-arid and arid regions. In addition, application of 180 kg N ha^{-1} as urea can be recommended for improvement of most barley traits such as yield production, WP, EWP, WUE and high nitrogen use efficiencies.

Finally, it is indicated that in areas with water limiting, it is preferable to recommend VAFI, in-furrow planting and 180 kg N ha^{-1} as best management practice for barley farm in the study region.

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