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Effects of Alternate Furrow Irrigation and Nitrogen Application Rates on Yield and Water-and Nitrogen-Use Efficiency of Winter Wheat (*Triticum aestivum* L.)

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Effects of Alternate Furrow Irrigation and Nitrogen Application Rates on Yield and Water- and Nitrogen-Use Efficiency of Winter Wheat (*Triticum aestivum* L.)

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Abstract : A study was conducted in Bajgah (deep water table condition) and Kooshkak (shallow water condition) areas in Fars province in I.R. of Iran to investigate the effects of different nitrogen application rates, deficient irrigation by alternate furrow irrigation (AFI) method and their interaction on the yield and water- and nitrogen use efficiency of winter wheat. The experimental design was split plot with three main plots as irrigation treatments [ordinary furrow irrigation (OFI), fixed alternate furrow irrigation (FAFI) and variable alternate furrow irrigation (VAFI)] and four subplots as nitrogen application rates (0, 90, 180 and 270 kg ha^{-1}) repeated three times. The amount of irrigation water for each irrigation event was considered equal to readily available water of soil in the root zone, and the time of irrigation was determined by the cumulative evapotranspiration (according to Penman-FAO method). The total amounts of irrigation water were 439.0 and 256 mm for OFI and AFI, respectively in the Bajgah area, and 367 and 226 mm, respectively, in the Kooshkak area. Total seasonal rainfalls were 409.0 and 470.5 mm in the Bajgah and Kooshkak, respectively. The results indicated that the interaction between irrigation method and nitrogen application rate was statistically significant for total biomass but not for grain yield and other traits. In terms of grain production, VAFI was superior to FAFI in the Bajgah and Kooshkak areas. VFAI in Bajgah and Kooshkak resulted in 42 and 39% reduction in irrigation water use and 22 and 13% reduction in grain yield, respectively, compared with OFI. Based on the grain yield, nitrogen use efficiency, apparent nitrogen recovery and water use efficiency, it was concluded that VAFI with application of 180 kg N ha^{-1} is appropriate in the experimental areas. Based on the grain yield and protein content, VAFI with application of 270 kg N ha^{-1} was also appropriate due to 21-35% greater production of total protein, although nitrogen use efficiency, and apparent nitrogen recovery decreased by 20 and 16%, respectively, compared with 180 N ha^{-1}. Further, water-use efficiency in VAFI with 180 kg N ha^{-1} was 0.89 and 0.85 kg m^{-3} in the Bajgah and Kooshkak areas, respectively, which were values not significantly different from those obtained in VAFI with a nitrogen application rate of 270 kg ha^{-1}. Therefore, VAFI with a nitrogen application rate of 180 kg ha^{-1} is a recommendable practice in the study areas.

Key words : Alternate furrow irrigation, Nitrogen application, Nitrogen use efficiency, Water use efficiency, Winter wheat (*Triticum aestivum* L.).

Water is an important factor for crop production especially for wheat (*Triticum aestivum* L.) in arid and semi-arid regions. Thus, application of appropriate methods for irrigation is essential in these areas. Alternate furrow irrigation (AFI) is an appropriate procedure for management of deficit irrigation in these regions. In this irrigation, deep percolation and soil surface evaporation are reduced and less water is used (Benjamin et al., 1997; Sepaskhah and Kamgar-Haghighi, 1997; Sepaskhah and Khajehabdollahi, 2005). Mintesinot et al. (2004) reported that the water-use efficiency and yield of maize (*Zea mays* L.) were higher in AFI than in the ordinary furrow irrigation (OFI) in vertisols. This increase might be due to cracking of vertisols. Sepaskhah and Khajehabdollahi (2005) showed that the yield of maize in AFI with irrigation at 4-day intervals was similar to yield with ordinary furrow irrigation at 7-day intervals.

Nitrogen plays an important role in plant growth (Weinhold et al., 1995). Uhart and Andrade (1995) indicated that the grain yield of maize was reduced by reduced application of nitrogen. It is important to use an optimum amount of water and nitrogen for best management of crop production in arid and semi-arid regions, because the application of an excess amount of water causes nitrogen leaching (Artiola, 1991). Howard et al. (1999) reported that nitrogen application to non-irrigated furrows resulted in reduced nitrogen leaching. Furthermore, Kirda et al. (2005) reported that N fertilizer was recovered at a higher rate in AFI than in OFI with 10% yield reduction in maize. They also indicated that AFI is as effective as OFI with 50% saving of irrigation water, but it should be regarded as an environmentally friendly irrigation practice due to its association with reduced mineral N residue left in the soil. Tavakoli and Oweis

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Table 1. Physical properties of soils in two experimental areas.

Depth Cm	Particle size distribution			Organic matter %	$CaCO_3$ %	Texture
	Sand %	Silt %	Clay %			
			Badjgah*			
0-30	35	35	30	2.0	17.0	cl***
30-54	23	38	39	–	19.6	cl
54-112	21	39	40	0.70	28.0	c
112-158	19	46	25	–	30.4	sicl
158-180	33	51	16	0.5	37.5	sil
			Kooshkak**			
0-25	19	36	45	1.83	37.5	c
25-42	21	29	50	1.28	44.0	c
42-70	16	32	52	0.98	44.5	c
70-100	21	21	58	0.84	39.0	c
100-120	13	34	53	0.70	44.5	c
120-160	12	35	53	0.60	44.7	c

*, Abtahi et al. (1991).
**, Mahjoory (1975).
***, cl= clay loam, sicl = silty clay loam, sil= silt loam, c=clay.

(2004) reported that with irrigation, the response of winter wheat to nitrogen significantly increased up to 60 kg N ha^{-1}. They also stated that by limited irrigation (1/3 of full irrigation) wheat yield was significantly increased and the water use efficiency (WUE) was maximized. Furthermore, nitrogen use efficiency (NUE) was greatly increased by supplemental irrigation.

AFI at regular irrigation intervals resulted in decreased crop yield in summer crops, i.e., dry beans (*Phaseolus vulgaris* L.) (Samadi and Sepaskhah, 1984), Maize (*Zea mays* L.) (Sepaskhah and Khajehabdollahi, 2005; Sepaskhah and Parand, 2006), sorghum (*Sorghum bicolor* L.) (Ghasemi and Sepaskhah, 2003) and sugarbeet (*Beta vulgaris* L.) (Sepaskhah and Kamgar-Haghighi, 1997). However, in winter crops, AFI may result in effective use of rainfall and reduce the nitrogen loss with least yield reduction.

The objectives of this research were to investigate the interaction of AFI and OFI with nitrogen application rate on yield, and WUE and NUE in winter wheat.

Materials and Methods

1. Experimental design

This study was conducted in Bajgah and Kooshkak areas in Fars province, Islamic Republic (I.R.) of Iran in the growing season of 2003–2004 with different climates, soils, and groundwater depths. This growing season was a representative season for the region with the same average rainfall and mean annual air temperature. Table 1 shows the physico-chemical properties of soils in these areas. The Bajgah soil is a clay loam (Fine, mixed, mesic, Typic Calcixerepts) with a deep water table in the Bajgah Agricultural Experiment Station of Shiraz University located 16 km north of Shiraz (29˚, 36'N, 52˚, 32'E, 1810 m MSL). The Kooshkak soil is a clay (Fine carbonic, mesic, Aquic Calcixerepts) with a shallow water table in Kooshkak Agricultural Experiment Station of Shiraz University located 75 km north of Shiraz (30˚, 4'N, 52˚, 35'E, 1609 m MSL).

The experimental design was split plot with three main plots (each with net area of 270 m^2) as irrigation treatments (ordinary furrow irrigation, OFI, fixed alternate furrow irrigation, FAFI, and variable alternate furrow irrigation VAFI), and four subplots (54 m^2 each) with different nitrogen application rates (0, 90, 180, and 270 kg N ha^{-1}), replicated three times. In OFI, water was applied to every furrow at each irrigation event, in FAFI, water was applied to fixed alternate furrows throughout the growing season, and in VAFI irrigation water was applied to alternate furrows which were dry in the preceding irrigation cycle. Each subplot consisted of three furrow beds of wheat (*Triticum aestivum* L.) and V-shaped furrows 30 m long with 0.6 m spacing between furrows. The slope of furrows was about 0.002 m m^{-1} and they were diked to prevent runoff. The subplots were separated 1.2 m by two planted furrow beds acting as guard areas for each subplot.

The field was prepared by the local standard procedure used by farmers. During the land preparation triple superphosphate at a rate of 150 kg ha^{-1} and urea as a half of the nitrogen treatment were mixed with the soil. After the land preparation, seeds

Table 2. The amounts of rainfall and irrigation water in different treatments at each irrigation event in the Bajgah and Kooshkak areas.

Days after Planting	Bajgah			Kooshkak		
	Rainfall* mm	Ordinary furrow mm	Alternate furrow mm	Rainfall mm	Ordinary furrow mm	Alternate furrow mm
0	0.0	77.8	77.8	0.0	82.0	82.0
40	57.0	66.7	33.4	120.0	0.0	0.0
116	301.0	55.6	27.8	268.0	60.0	30.0
156	45.5	66.7	33.4	73.5	66.8	33.4
174	5.5	77.8	38.9	9.0	77.8	38.9
191	0.0	94.4	47.2	0.0	83.3	41.7
Total	409.0	438.4	258.5	470.5	369.9	226.0

* The rainfall values are cumulative amounts between the consecutive irrigation dates.

of Alamoot cultivar was broadcasted at a rate of 250 kg ha^{-1} and buried in the soil using a furrower with 0.6 m spacing. Therefore, the winter wheat grew on the beds between the furrows. Seeding dates were 17 November, and 21 November in 2003 in the Bajgah and Kooshkak areas, respectively. The second half of the nitrogen treatment was applied on 13 March 2004 when the height of plants was about 30 cm. The top dressing of nitrogen was applied to every furrow in OFI and to the furrows which should be irrigated in AFI.

Irrigation water was obtained from the wells with electrical conductivity (EC) of 0.5 dS m^{-1} and 1.2 dS m^{-1} in the Bajgah and Kooshkak areas, respectively. Water table levels in the Bajgah and Kooshkak areas were deeper than 25 m and about 2.0 m, respectively. The mean air temperatures during the growing season in the Bajgah and Kooshkak areas were 9.6°C and 12.2°C, respectively. In the Bajgah area, volumetric soil water contents at field capacity and permanent wilting point at a depth of 0–30 cm were 0.335 and 0.168 cm^3 cm^{-3}, respectively. In Kooshkak area, volumetric soil water contents at field capacity and permanent wilting point at a depth of 0–30 cm were 0.39 and 0.213 cm^3 cm^{-3}, respectively. These values at depth of 30–90 cm were 0.42 and 0.282 cm^3 cm^{-3}, respectively.

Irrigation water was applied when readily available water of soil in the root zone was equal to the cumulative potential evapotranspiration (ET_p) of wheat. The readily available water was determined as follows:

$$RAW=(\theta_{fc}-\theta_{pwp})D\times p \qquad (1)$$

where: RAW is the readily available water of soil in mm; θ_{fc} and θ_{pwp} are the volumetric water content of soil at field capacity and permanent wilting point in m^3 m^{-3}, respectively; D is the root depth in mm and p the coefficient of readily available water (dimensionless). The effective rainfall was considered in determining the time of irrigation, which delayed the time of the next irrigation. The crop ET_c of wheat was determined by multiplying the crop coefficient by reference crop potential evepotranspiration (ET_o). The values of ET_o in Bajgah and Kooshkak areas were calculated by Penman-FAO (Doorenbos and Pruitt, 1977) method using the meteorological data obtained from weather stations in the areas. The Penman-FAO method was used as recommended by Sepaskhah (1999) for the local conditions. The amount of water for each irrigation event was considered as cumulative ET_c in the respective duration and the water was applied with a flexible hose and measured with a volumetric flow meter. The amount of irrigation water at each irrigation event was considered equal to the cumulative ET_c during the interval between two consecutive irrigations. The first irrigation was similar in all irrigation treatments (7.78 cm in the Bajgah and 8.20 cm in the Kooshkak) for uniform and vigorous seed germination and vegetation stands. Table 2 shows the amounts of irrigation water applied each irrigation event in OFI and AFI in Bajgah and Kooshkak areas.

The water content of soil in the root zone at 90 cm depth was measured by soil sampling and gravimetry before each irrigation. The soil samples were obtained in depths of 30, 60 and 90 cm in the middle of each subplot in each replication. The method of soil sampling was as reported by Sepaskhah and Parand (2006). The actual crop evapotranspiration during each irrigation interval was estimated by soil water balance equation as described in detail by Sepaskhah and Khajehabdollahi (2005). In the present investigation, the water table depth in the Kooshkak area was about 2.0 m, therefore, the groundwater contribution to the crop water use was negligible (Sepaskhah et al., 2003). Deep percolation mostly occurred after rainfall in late autumn and winter. The amount of deep percolate was considered as the amount of excess rainfall compared with the amount of water that could be stored in the root zone.

The grain and total biomass yields at harvest were determined on 9.0 m^2 area for treatments at the middle of each subplot. The grain was separated and

Table 3. Total dry matter of winter wheat in different irrigation treatments in the Bajgah and Kooshkak areas.

Nitrogen application rate (kg ha^{-1})	Total dry matter (t ha^{-1}) Ordinary furrow	Variable alternate furrow	Fixed alternate furrow	Mean
		Bajgah		
0	6.01f*	5.16f	5.13f	5.43C
90	12.02bcd	10.78de	9.39e	10.73B
180	16.99a	13.34bc	10.86cde	13.73A
270	17.45a	13.76b	11.75bcde	14.32A
Mean	13.12A	10.76AB	9.28B	
		Kooshkak		
0	4.40f	4.60f	4.67f	4.56D
90	10.13de	9.50e	9.95de	9.86C
180	13.54b	10.80cd	10.05de	11.46B
270	14.77a	11.50c	10.84cd	12.37A
Mean	10.71A	9.10B	8.88B	

* Values followed by the same letters (lower- and upper-case letters, separately) in each column and row are not different at 5% level of probability by LSD test.

weighed. The amount of soil nitrogen at different depths (0–30, 30–60 and 60–90 cm) before planting and at harvest time, and the amount of nitrogen in grain and straw were determined. The average soil nitrogen before planting was 21.8 and 20.2 kg ha^{-1} in the Bajgah and Kooshkak areas , respectively. The average soil nitrogen at harvest in the Bajgah area was 6.5, 63.6, 132.0 and 205.4 kg ha^{-1} for nitrogen application rates of 0, 90, 180 and 270 kg ha^{-1}, respectively. These values in the Kooshkak area were 4.6, 64.4, 140.4 and 207.2 kg ha^{-1}, respectively.

2. Nitrogen efficiency

Nitrogen contents of grain and straw at the harvest were determined by the Kjeldahl method (Chapman and Pratt, 1961). The protein content of grain (as percent) was estimated by multiplying the nitrogen content of grain as percent by 6.25.

By using the total nitrogen uptake by grain and straw and the amount of applied nitrogen as fertilizer the apparent N recovery for different nitrogen treatments were calculated as follows:

$$N_{ap}=(N_{ui}-N_{uc})/(N_{fi}-N_{fc}) \quad (2)$$

where N_{ui} and N_{uc} are the total nitrogen uptake by grain and straw in different nitrogen treatments and control, respectively in kg ha^{-1}, and N_{fi} and N_{fc} are the applied nitrogen as fertilizer in different nitrogen treatments and control, respectively, in kg ha^{-1}. Further, by using the applied nitrogen as fertilizer and grain yield, the NUE in different nitrogen treatments were calculated as follows:

$$N_{ue}=(Y_i-Y_c)/(N_{fi}-N_{fc}) \quad (3)$$

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

Results and Discussion

Although the present experiments were conducted for only one year, the results at multiple sites were analyzed. The 30-year mean air temperatures in Bajgah and Kooshkak areas are 14.1 and 15.6°C, respectively and the mean annual rainfall in these areas are 420 and 440 mm, respectively. The mean air temperatures and annual rainfalls in the year of study were 14.4°C and 15.9°C and 409 mm and 470 mm, respectively. Therefore, the climate condition of the experiment year is a representative of the region.

1. Total dry matter and grain yield

(1) Total dry matter

Bajgah: There was no significant difference in total dry matter (TDM) between the plants in OFI and those in VAFI but there was a difference between those in OFI and FAFI (Table 3). There was no significant difference in TDM between the plants with 180 and those with 270 kg N ha^{-1}, but it was significantly lower in 90 and 0 kg N ha^{-1}. The interaction between irrigation treatment and nitrogen application rate on the total dry matter was statistically significant. At higher nitrogen application rates (180 and 270 kg ha^{-1}) TDM was significantly heavier in OFI than in AFI, but there was no significant difference in TDM between the plants in OFI and those in VAFI at lower nitrogen application rates (90 and 0 kg ha^{-1}).

Koosahkak: A significantly heavier TDM was obtained in OFI than in VAFI and FAFI (Table 3). The heaviest TDM was obtained at a nitrogen application rate of 270 kg ha^{-1}, and TDM was significantly decreased by decreasing the nitrogen application rates (Table 3). The interaction between irrigation

Table 4. Grain yield of winter wheat in different irrigation treatments in Bajgah and Kooshkak areas.

Nitrogen application rate kg ha^{-1}	Grain yield (t ha^{-1}) Ordinary furrow	Variable alternate furrow	Fixed alternate furrow	Mean
		Bajgah		
0	2.54gh*	2.01h	1.74h	2.10C
90	4.95bcd	3.52fg	2.50gh	3.66B
180	6.13a	4.62cde	3.82ef	4.86A
270	5.99ab	5.09abc	3.95def	5.01A
Mean	4.90A	3.81AB	3.00B	
		Kooshkak		
0	1.60f	1.73f	1.55f	1.63C
90	3.96bc	3.19de	3.05e	3.40B
180	4.69a	3.86bcd	3.61bcde	4.05A
270	4.72a	4.28ab	3.53cde	4.18A
Mean	3.74A	3.26AB	2.93B	

* Values followed by the same letters (lower- and upper-case letters, separately) in each column and row are not different at 5% level of probability by LSD test.

treatment and nitrogen application rate on TDM was statistically significant. As a result, there was no significant difference in TDM between the plants in OFI and those in AFI at the nitrogen application rate of less than 180 kg ha^{-1}. In general, TDM was lower in Kooshkak than that in Bajgah area due to the smaller amount of applied water and smaller number of plants per unit area (158 and 122 m^{-2} in Bajgah and Kooshkak, respectively). It seems that the presence of shallow water table in Kooshkak with a moderately heavy texture soil did not contribute to the water use of winter wheat (Table 1) (Sepaskhah et al., 2003; Sepaskhah and Parand, 2006). Therefore, a smaller amount of irrigation water in Kooshkak area resulted in lower TDM production.

(2) Grain yield

1) Irrigation

There was no significant interaction between irrigation treatment and nitrogen application rate on grain yield in the two areas. There was no significant difference in grain yield between the plants in OFI and those in VAFI (Table 4), nor between those in FAFI and VAFI at the 5% level of probability (Table 4). However, there was a significant difference in the grain yield between the plants in OFI and those in FAFI at the 5% level both in the Bajgah and Kooshkak areas as shown in Table 4. The effects of AFI and OFI on grain yield were similar to those obtained with soybean (*Glycine max* L.) (Crabtree et al., 1985), sugarbeet (*Beta vulgaris* L.) (Sepaskhah and Kamgar-Haghighi, 1997) and sorghum (*Sorghum bicolor* L.) (Ghasemi and Sepaskhah, 2003). The reduction of grain yield in VAFI was 22% with a 42% reduction of water use in the Bajghah area, and was 13% with a 39% reduction of water in the Kooshkak area.

Furthermore, there was no significant difference in the grain yield between the plants in OFI and those in VAFI with 270 kg N ha^{-1}, while the grain yield in OFI with 180 and 90 kg N ha^{-1} was significantly higher than that in VAFI. In terms of grain yield production, it is concluded that VAFI with an appropriate amount of N application rate is a preferable irrigation water management in areas with a scarce amount of irrigation water and rainfall of about 400 mm in the cold growing season of winter wheat (late fall to early spring). At present, some farmers in a few regions tend to use VAFI. In a drought situation where the farmers are short in irrigation water supply, some farmers in the Fars province who irrigate their farms by siphon and furrow irrigation tend to apply VAFI. In these situations, the proper application rate of N should be used.

2) Effect of Nitrogen

There was no significant difference in grain yield between the plants with 180 and those with 270 kg N ha^{-1}, but there was a significant difference among the plants on soil applied 0, 90 and 180 kg N ha^{-1} (Table 4). The grain-yield increase resulting from a 50% increase in nitrogen application rate from 180 and 270 kg ha^{-1} was only 2.7% and 3.0%, in the Bajgah and Kooshkak areas, respectively. The results showed that 180 kg N ha^{-1} is appropriate for winter wheat in both experimental areas.

Although the total biomass was high in OFI with high N application rates (180 and 270 kg ha^{-1}), as shown in Table 3, the grain yield was not as high as expected (Table 4). This might be due to the low dry-matter transfer from leaves to the grains, which occurred as a result of low leaf water potential due to high air temperature. This might also be explained by

Table 5. 1000-Grain weight of winter wheat in different treatments in Bajgah and Kooshkak areas.

	Weight (g)			
Nitrogen application rate (kg ha^{-1})	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow	Mean
		Bajgah		
0	34.5cd*	31.3ef	29.3f	31.7C
90	35.7bc	32.7de	29.8f	32.7C
180	39.4a	37.5ab	36.3bc	37.8A
270	38.1ab	34.7cd	32.9de	35.2B
Mean	36.9A	34.1B	32.1B	
		Kooshkak		
0	34.7cde	32.8f	30.8g	32.7D
90	37.0b	34.3def	33.1ef	34.8C
180	39.3a	37.8ab	37.3b	38.1A
270	37.8ab	36.5bc	35.1cd	36.4B
Mean	37.2A	35.3AB	34.0B	

* Values followed by the same letters (lower-and upper-case letters, separately) in each column and row are not different at 5% level of probability by LSD test.

Table 6. Protein content of grain in winter wheat in different treatments in Bajgah and Kooshkak areas.

	Protein content (%)			
Nitrogen application rate (kg ha^{-1})	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow	Mean
		Bajgah		
0	13.87a*	14.71a	15.89a	14.82B
90	13.91a	15.29a	17.74ab	15.65AB
180	14.32a	15.69a	17.90ab	15.97AB
270	18.32b	19.67b	18.59b	18.86A
Mean	15.10A	16.34A	17.53A	
		Kooshkak		
0	12.89a	12.69a	13.27a	12.29B
90	13.16a	13.68a	13.51b	13.45AB
180	13.50a	13.70a	14.71b	13.97AB
270	14.61b	14.95b	15.03bc	14.86A
Mean	13.54A	13.75A	14.13A	

* Values followed by the same letters (lower- and upper-case letters, separately) in each column and row are not different at 5% level of probability by LSD test.

the lack of a significant difference in 1000-grain weight in OFI with 180 and 270 kg N ha^{-1}, as presented in the following section.

2. Grain weight and protein content

(1) Grain weight

There was no interaction between irrigation treatment and nitrogen application on 1000-grain weight in the two areas. In the Bajgah area, the 1000-grain weight at a nitrogen application rate of 180 kg ha^{-1} was maximum, and there was no significant difference between the plants in OFI and those in AFI (Table 5). However, in general, 1000-grain weight was higher in plants in OFI than in those in AFI.

In the Kooshkak area, the 1000-grain weight was also heaviest at a nitrogen application rate of 180 kg ha^{-1} and there was no significant difference between the plants in OFI and those in AFI at this nitrogen application rate (Table 5). There was no significant difference in the 1000-grain weight between the plants in OFI and those in AFI. The 1000-grain weight in the Bajgah and Kooshkak areas was 34.4 and 32.2 g, respectively. No significant difference was observed in the 1000-grain weight at N application rates of 180 and

Table 7. The amount of irrigation water, evapotranspiration (ET) and deep percolate at different irrigation treatments in the Bajgah and Kooshkak areas.

Location	Irrigation treatment	Applied water (mm)	ET, (mm)	Deep percolate (mm)
Bajgah	Ordinary furrow	439	397	314
(Annual rainfall,	Variable alternate	256	308	276
409 mm)	Fixed alternate	256	299	278
Kooshkak	Ordinary furrow	370	445	262
(annual rainfall,	Variable alternate	226	384	261
407.5 mm)	Fixed alternate	226	379	264

270 kg ha^{-1} (Table 5).

(2) Protein content of grain

There was no significant interaction between irrigation treatment and nitrogen application rates on protein content of grain in the two areas. Protein content of grain was significantly higher at a 270 kg ha^{-1} nitrogen application rate in either irrigation treatment (Table 6). The irrigation treatment did not affect the protein content of grain significantly in the two areas. However, at 180 kg N ha^{-1} the protein content of grain increased about 10% in AFI and even more in FAFI. Such an increase was not observed in the Kooshkak area (Table 6). In general, the protein content of grain in the Kooshkak area was lower than that in the Bajgah area due to the lower ability of root to take up nitrogen under a shallow water table condition.

At 270 kg N ha^{-1}protein content of grain was 23 and 10% higher than that at 180 kg N ha^{-1}, in the Bajgah and Kooshkak areas, respectively, but the grain yield was only 9 and 11% higher in the Bajgah and Kooshkak areas, respectively. This indicated that application of 270 kg N ha^{-1} is preferred in VAFI (21–35% higher production of total protein). However, nitrogen use efficiency (NUE) and apparent nitrogen recovery was decreased, though not significantly, by 20 and 16%, respectively, compared with 180 kg N ha^{-1}. Therefore, VAFI at 180 kg N ha^{-1} is recommended in the experimental areas for the combined effects on grain yield, higher NUE and apparent nitrogen recovery.

3. Water use and water use efficiency

(1) Water use

Table 2 shows the amounts of irrigation water in each treatment. The amount of water in AFI was 41 and 39% lower than that in OFI in the Bajgah and Kooshkak areas, respectively. In general, the amount of applied water in Kooshkak was smaller due to the lower number of irrigation events since the second irrigation in Kooshkak was coincided with the sufficient amount of rainfall. This water saving irrigation can be practiced in conditions similar to those in the experimental areas.

The values of actual evapotranspiration (ET) in the Kooshkak area were higher than those in the Bajgah area (Table 7) due to the higher annual mean air temperature (15.9°C vs. 14.4°C during the year of experiment). In general, the values of ET in AFI were lower than those in OFI due to the smaller amount of applied water in non-rainy periods. Furthermore, in the Bajgah area there was more deep percolation in OFI (Table 7) due to the very low water table depth and free drainage conditions while in the Kooshkak area a shallow water table depth resulted in less deep percolation in OFI. However, the amount of deep percolate in AFI was similar in these areas.

(2) Water-use efficiency

Water-use efficiency (WUE) was calculated as the ratio of grain yield to the sum of irrigation water and seasonal rainfall. The highest WUE was obtained in VAFI at all nitrogen application rates (Table 8). WUE was higher in AFI than in OFI. The WUE was higher in VAFI with 180 kg N ha^{-1} in the Bajgah and Kooshkak areas which were 0.89 and 0.85 kg m^{-3}, respectively (Table 8). Other investigators such as Stewart et al. (1983); Hooker (1985); Sepaskhah and Kamgar-Haghighi (1997); Tavakoli and Oweis (2004) reported a higher WUE in deficient irrigation than in full irrigation. The reasons for the higher WUE are less deep percolation, low soil surface evaporation and saving more water in soil in AFI.

Application of nitrogen up to 180 kg ha^{-1} tended to increase WUE and application of 270 kg ha^{-1} was not essential. There was also a significant difference in WUE between the plants in OFI and those in VAFI, but there was no significant difference in WUE between the plants in FAFI and those in VAFI in the Bajgah and Kooshkak areas. Furthermore, there was a significant difference in WUE among the plants with 0, 90 and 180 kg ha^{-1} at the 5% level, but not between those with 180 and 270 kg ha^{-1}. This application of 270 kg N ha^{-1} is not essential. Therefore, VAFI with 180 kg N ha^{-1} is more appropriate (Table 8).

Table 8. Water-use efficiency of winter wheat grain based on sum of applied water and seasonal rainfall in different treatments at Bajgah and Kooshkak areas.

Nitrogen application rate (kg ha^{-1})	Water use efficiency (kg m^{-3})			
	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow	Mean
		Bajgah		
0	0.29g*	0.39fg	0.34fg	0.34C
90	0.56de	0.69cd	0.49ef	0.58B
180	0.70cd	0.89ab	0.75bc	0.78A
270	0.68cd	0.97a	0.77bc	0.81A
Mean	0.56B	0.74A	0.59AB	
		Kooshkak		
0	0.22g	0.38f	0.34f	0.31C
90	0.54e	0.71cd	0.67cd	0.64B
180	0.63de	0.85ab	0.80ab	0.76A
270	0.64de	0.92a	0.78abc	0.78A
Mean	0.51B	0.72A	0.65A	

* Values followed by the same letters (lower- and upper-case letters, separately) in each column and row are not different at 5% level of probability by LSD test.

Table 9. Apparent nitrogen recovery of winter wheat (kg kg^{-1}) in different treatments at Bajgah and Kooshkak areas.

Nitrogen application rate (kg ha^{-1})	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow	Mean
		Bajgah		
90	0.66a*	0.57ab	0.25b	0.50A
180	0.50ab	0.45ab	0.29b	0.42B
270	0.50ab	0.38ab	0.30ab	0.40B
Mean	0.56A	0.47A	0.28A	
		Kooshkak		
90	0.58a	0.35bc	0.41b	0.45A
180	0.39b	0.30bc	0.27bc	0.32B
270	0.29bc	0.25bc	0.20c	0.25B
Mean	0.42A	0.30A	0.29A	

* Values followed by the same letters (lower- and upper-case letters, separately) in each column and row are not different at 5% level of probability by LSD test.

4. Nitrogen content of straw and nitrogen use efficiency

(1) Nitrogen content of straw

There was no significant interaction between irrigation treatment and nitrogen application rate on nitrogen content of straw. Nitrogen content of straw was not significantly influenced by the irrigation treatment and nitrogen application rate (data are not shown). In general, the nitrogen content of straw was lower in the Kooshkak area than in the Bajgah area due to the lower ability of root to take up nitrogen under a shallow water table condition.

(2) Nitrogen use

1) Apparent N recovery

In the two areas, there was no significant difference in apparent N recovery (N_{ap}) among irrigation treatments, but was significantly higher with 90 kg N ha^{-1} (Table 9). There was no difference in the value of N_{ap} between the plants on soil applied 180 kg N ha^{-1}and those on soil applied 270 kg N ha^{-1}.

2) Nitrogen use efficiency

There was a significant interaction between irrigation treatment and nitrogen application rates on nitrogen use efficiency (NUE) in the Bajgah area. NUE in VAFI was not significantly different from that in OFI (Table 10). This is because almost all of the deep percolation occurred as a result of excess rainfall in winter (Tables 2 and 7) However, in FAFI, NUE was lower (Table 10) mainly due to the lower grain yield, since there was no significant difference in the deep

Table 10. Nitrogen use efficiency of winter wheat (kg kg^{-1}) in different treatments at Bajgah and Kooshkak areas.

Nitrogen application rate (kg ha^{-1})	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow	Mean
		Bajgah		
90	26.74a*	16.78bc	8.48e	17.33A
180	19.93b	14.52cd	11.57de	15.34A
270	12.75d	11.43de	8.20e	10.79B
Mean	19.81A	14.24AB	9.42B	
		Kooshkak		
90	26.19a	16.15b	16.61b	19.65A
180	17.17b	11.81c	11.44c	13.47B
270	11.54c	9.43cd	7.33d	9.43C
Mean	18.30A	12.46B	11.79B	

* Values followed by the same letters (lower- and upper-case letters, separately) in each column and row are not different at 5% level of probability by LSD test.

percolation among different irrigation treatments. The NUE at 180 kg N ha^{-1} was not significantly different from that at 90 kg N ha^{-1}, but was higher than that at 270 kg N ha^{-1}. It appeared that VAFI and the nitrogen application rate at 180 kg ha^{-1} are appropriate to increase NUE in the Bajgah area (Table 10).

There was no significant interaction between irrigation treatment and nitrogen application rate on NUE in the Kooshkak area. The NUE in the Kooshkak area was significantly lower in AFI than in OFI (Table 10) mainly due to the lower grain yield. Furthermore, NUE decreased significantly with the increase in nitrogen application rate. In general, NUE in the Kooshkak area was lower than that in the Bajgah area (Table 8) due to the smaller amount of applied water and consequently lower grain yield. It should be noted that almost all of the deep percolation occurred in winter during the high rainfall occurrence. The deep percolation leached away the half of the nitrogen fertilizer applied at planting time in autumn, but the other half of nitrogen fertilizer was applied in early spring after the main rainfall occurrence.

Based on the results of the present study, it is concluded that VAFI with application of 180 kg N ha^{-1} is more appropriate for the experimental areas.

Conclusions

The interaction between irrigation method and nitrogen application rate was statistically significant for total biomass but not for grain yield and other traits. The results indicated that in terms of grain production VAFI is superior to FAFI in the Bajgah and Kooshkak areas. VAFI is a water saving irrigation in the Bajgah and Kooshkak areas (with rainfall about 400 mm during cold growing season, late fall to early spring) with 42 and 39% reduction in irrigation water use and 22 and 13% reduction in grain yield, respectively. Furthermore, based on the grain production, it was concluded that VAFI with 180 kg N ha^{-1} is appropriate for winter wheat in the two experimental areas. Irrigation treatment did not influence the grain protein in the two areas. However, at a nitrogen application rate of 180 kg ha^{-1} protein content of grain was about 10% higher in VAFI and FAFI than in OFI. In the experimental areas, VAFI with 180 kg N ha^{-1} was the appropriate treatment to obtain apparent N recovery similar to that in other treatments. However, in the Bajgah area, these treatments were appropriate resulting in similar NUE. High water-use efficiency was obtained in VAFI with 180 kg N ha^{-1} (appropriate treatment), which were 0.89 and 0.85 kg m^{-3} in the Bajgah and Kooshkak areas, respectively. These values were not significantly different from those in VAFI with 270 kg N ha^{-1}. Application of 270 kg N ha^{-1} in VAFI was also appropriate (21–35% higher production of total protein), although NUE and apparent nitrogen recovery were only 20 and 16%, respectively, lower than those in VAFI with 180 kg N ha^{-1}. Therefore, VAFI with nitrogen application at a rate of 180 kg ha^{-1}, is a recommendable practice in the present study areas.

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* In Persian.