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

Ali Reza Sepaskhah and Seyedeh Narges Hosseini

(Department of Irrigation, Shiraz University, Shiraz, 71886-55794 I.R. of Iran)

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). Mentesinot 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
(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 winter 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 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.
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 9.6ºC and 12.2ºC, respectively. In the Bajgah area, volumetric soil water contents at field capacity and permanent wilting point in m\(^3\) 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 0.355 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:

\[
RAW = (\theta_c - \theta_{pwp})\cdot D \cdot p
\]

where: RAW is the readily available water of soil in mm; \(\theta_c\) and \(\theta_{pwp}\) 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 evapotranspiration (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.

| Days after Planting | 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.
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:

\[
N_{\text{app}} = \frac{(N_{\text{gi}} - N_{\text{ci}})}{(N_{\text{fi}} - N_{\text{fc}})} \tag{2}
\]

where \(N_{\text{gi}}\) and \(N_{\text{ci}}\) are the total nitrogen uptake by grain and straw in different nitrogen treatments and control, respectively in kg ha\(^{-1}\), and \(N_{\text{fi}}\) and \(N_{\text{fc}}\) 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:

\[
N_{\text{UE}} = \frac{(Y_{\text{gi}} - Y_{\text{ci}})}{(N_{\text{fi}} - N_{\text{fc}})} \tag{3}
\]

where, \(Y_{\text{gi}}\) and \(Y_{\text{ci}}\) 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 15.6ºC, 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 14.4ºC and 15.9ºC 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\(^{-1}\)).

      **Kooshkak:** 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

| Nitrogen application rate (kg ha\(^{-1}\)) | Bajgah | Kooshkak |
|------------------------------------------|--------|---------|
|                                          | Ordinary furrow | Variable alternate furrow | Fixed alternate furrow | Mean |
| 0                                        | 6.01f   | 5.16f   | 5.13f   | 5.43C |
| 90                                       | 12.02bcd| 10.78de | 9.39c   | 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   |       |

* 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 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.

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

| Nitrogen application rate kg 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                   | 2.50gb                 | 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.
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 270 kg ha\(^{-1}\), as presented in the following section.

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

| Nitrogen application rate (kg ha\(^{-1}\)) | Ordinary furrow | Variable alternate furrow | Fixed alternate furrow | Mean |
|------------------------------------------|----------------|--------------------------|-----------------------|------|
| Bajgah                                  |                |                          |                       |      |
| 0                                       | 34.5cde        | 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.

| 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                   | 17.33A                |      |
| Kooshkak                                 |                |                          |                       |      |
| 0                                       | 12.89a         | 12.69a                   | 13.27a                | 12.99B|
| 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.
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 (15.9ºC vs. 14.4ºC 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) | Ordinary furrow | Variable alternate furrow | Fixed alternate furrow | Mean |
|-----------------------------------|----------------|--------------------------|------------------------|------|
| Bajgah                            |                |                          |                        |      |
| 0                                 | 0.29g*         | 0.39g                   | 0.34g                  | 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          | 0.355bc                  | 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          | 0.50A                    | 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
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 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.

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.

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.

**Acknowledgements**

This research was supported in part by Grant no. 85-GR-AGR 42 of Shiraz University Research Council and Center of Excellence for On-Farm Irrigation Water Management.

**References**

Abtahi, A., Karimian, N.A. and Solhi, M. 1991. Semi-detail soil survey report for Bajgah area in Fars province. Research Report, Soil Science Department, Shiraz University. 1-77*.

Ariola, J.F. 1991. Non uniform leaching of nitrate and solute in a furrow irrigation sludge-amended field. Commun. Soil Sci. Plant Anal. 22 : 1013-1030.

Benjamin, J.G., Porter, L.K., Duke, H.R. and Ahuja, L.R. 1997. Corn growth and nitrogen uptake with furrow irrigation and fertilizer bands. Agron. J. 89 : 609-612.
Chapman, H.D. and Pratt, P.F. 1961. Methods of Analysis for Soils, Plants and Waters. University of California, Division of Agricultural Sciences. 1-309.

Crabtree, R.J., Yassin, A.A., Kargougou, I., and Mcnew, R.W. 1985. Effects of alternate-furrow irrigation : Water conservation on the yields of two soybean cultivars. Agric. Water Manage. 10 : 253-264.

Doorenbos, J. and Pruitt, W.O. 1977. Crop water requirements. FAO Irrigation and Drainage Paper. No. 24. Rome, Italy. 1-144.

Ghasemi, M.M. and Sepaskhah, A.R. 2003. Economic evaluation of every-furrow irrigation for sorghum with real and subsidized irrigation water prices. J. Sci. Technol. Agric. Natur. Resour. 7 : 1-11*. 

Hooker, M.L. 1985. Grain sorghum yield and yield component response to timing and number of irrigation. Agron. J. 77 : 810-812.

Howard, S., Hanson, J.D. and Benjamin, J.G. 1999. Nitrogen uptake and partitioning under alternate- and every furrow irrigation. Plant Soil 210 : 11-20.

Kirda, C., Topcu, S., Kaman, H., Ugler, A.C., Yazici, A., Cetin, M. and Derici, M.R. 2005. Grain yield response and N-fertilizer recovery of maize under deficit irrigation. Field Crop Res. 93 : 132-141.

Mahjoory, R.A. 1975. Clay mineralogy, physical and chemical properties of some soils in arid regions of Iran. Soil Sci. Soc. Am. Proc. 39 : 1157-1164.

Mintesinot, B., Verplancke, H., van Ranst, E. and Mitiku, H. 2004. Examining traditional irrigation methods, irrigation scheduling and alternate furrow irrigation on vertisols in northern Ethiopia. Agric. Water Manage. 64 : 12-27.

Samadi, A. and Sepaskhah, A.R. 1984. Effects of alternate furrow irrigation on yield and water use efficiency of dry beans. Iran Agric. Res. 3 : 95-115.

Sepaskhah, A.R. and Kamgar-Haghighi, A.A. 1997. Water use and yields of sugarbeet grown under every-other-furrow irrigation with different irrigation intervals. Agric. Water Manage. 34 : 71-79.

Sepaskhah, A.R. 1999. A review on methods for calculating crop evapotranspiration In : Proceeding of the 7th National Conference on Irrigation and Evaporation Reduction. Shahid Bahonar University, Kerman, Islamic Republic of Iran. 1-10*.

Sepaskhah, A.R., Kanooni, A. and Ghasemi, M.M. 2003. Estimating water table contribution to corn and sorghum water use. Agric. Water Manage. 58 : 67-79.

Sepaskhah, A.R. and Khajchabdollahi, M.H. 2005. Alternate furrow irrigation with different irrigation intervals for maize (Zea mays L.). Plant Prod. Sci. 8 : 592-600.

Sepaskhah, A.R. and Parand, A.R. 2006. Effects of alternate furrow irrigation with supplemental every-furrow irrigation at different growth stages on the yield of maize (Zea mays L.). Plant Prod. Sci. 9 : 415-421.

Stewart, B.A., Musick, J.T. and Dusek, D.A. 1983. Yield and water use efficiency of grain sorghum in a limited irrigation-dryland farming system. Agron. J. 75 : 629-634.

Tavakoli, A.R. and Oweis, T.Y. 2004. The role of supplemental irrigation and nitrogen in producing bread wheat in the highlands of Iran. Agric. Water Manage. 65 : 225-236.

Uhart, S.A. and Andrade, F.H. 1995. Nitrogen deficiency in maize. 1. Effects on crop growth, development to dry matter partitioning, and kernel set. Crop Sci. 35 : 1376-1383.

Weinhold, B.J., Todd, P.T. and Richman, G.A. 1995. Yield and nitrogen efficiency of irrigated corn in North Great Plains. Agron. J. 87 : 842-846.

* In Persian.