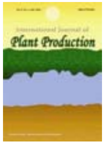

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Yield and nitrogen leaching in maize field under different nitrogen rates and partial root drying irrigation

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Abstract

Irrigation water is limiting for crop production in arid and semi-arid areas. Furthermore, excess nitrogen (N) application is a source of groundwater contamination. Partial root drying irrigation (PRD) can be used as water saving technique and a controlling measure of groundwater N contamination. The objectives of this investigation were to evaluate the effect of ordinary furrow irrigation (OFI), variable alternate furrow irrigation (VAFI) and fixed alternate furrow irrigation (FAFI) and different N application rates (0, 100, 200, and 300 kg ha^{-1}) on maize yield and yield quality, drainage water, N leaching, uptake and N use efficiency (NUE). Results indicated that the interaction between irrigation treatments and N application rates was statistically significant for all treatments applied in this investigation. Maize grain yield was reduced by alternate furrow irrigation due to high sensitivity of maize to water stress, however, in case of water shortage, VAFI is superior to FAFI. In the study region, N application of 200 kg ha^{-1} is optimum for maize grain yield to obtain optimum grain yield, NUE and N-yield efficiency. Drainage water and total leached nitrate decreased for VAFI and FAFI as compared to OFI and their amount were lowest for FAFI (drainage water) and in VAFI (total leached nitrate), respectively. Total leached nitrate bellow the root zone increased in response to the increase in total available nitrogen for water applications higher than crop ET. N loss was reduced for FAFI and VAFI for N application rates of 200 and 300 kg ha^{-1}. Only for FAFI and VAFI, the N uptake decreased and the soil residual N increased as compared with OFI. Thus, in order to avoid N loss, the amount of N fertilizer should be reduced in proportion to the amount of soil water available for plant uptake under deficit irrigation. Furthermore, it was indicated that leaf level stress sensitivity index (LLSSI) was higher for VAFI and it was about 2.5 times of OFI.

Keywords: Alternate furrow irrigation; Nitrogen leaching; Deficit irrigation; Water quality.

Introduction

Irrigation water is limiting for crop production in arid and semi-arid regions in Iran. Therefore, partial root drying (PRD) irrigation is used in these areas (Samadi, and Sepaskhah, 1984; Sepaskhah and Kamgar-Haghighi, 1997; Sepaskhah and Khajehabdollahi, 2005; Sepaskhah and Parand, 2006; Sepaskhah and Hosseini, 2008; Sepaskhah and Ahmadi, 2010). PRD is a modified form of deficit irrigation which involves irrigating only one part of the root zone in each irrigation event, leaving another part to dry to certain soil water content before rewetting by shifting irrigation to the dry side. In PRD irrigation deep percolation and surface evaporation are decreased, therefore, less water is used (Benjamin et al., 1997; Sepaskhah and Ahmadi, 2010). Furthermore, it is reported that water productivity (WP) in PRD irrigation is higher for maize (Mintesinot et al., 2004; Sepaskhah and Khajehabdollahi, 2005; Sepaskhah and Parand, 2006) and wheat (Sepaskhah and Hosseini, 2008).

Nitrogen (N) is one of the main plant nutrients affecting plant growth (Weinhold et al., 1995). It is reported that grain yield of maize (Uhart and Andrade, 1995) and wheat (Sepaskhah and Hosseini, 2008) was increased by application of N. Optimum amount of water and N should be used for a better management of crop production. Excess application of water and N resulted in N leaching in a semi-arid area (Gheysari et al., 2009). Howard et al. (1999) indicated that N application to non-irrigated furrows in PRD irrigation resulted in lower N leaching. Furthermore, Kirda et al. (2005) reported that N recovery of fertilizer was higher in PRD furrow irrigation with 10% yield reduction in maize. Based on the grain yield of wheat, N use efficiency (NUE), apparent N recovery and water productivity (WP), it was concluded that PRD irrigation with application of 180 kg N ha^{-1} was appropriate for a semi-arid area (Sepaskhah and Hosseini, 2008). It is indicated that PRD furrow irrigation is an environmentally friendly irrigation practice due to its association with reduced mineral N residue left in the soil for maize (Kirda et al., 2005) and wheat (Sepaskhah and Hosseini, 2008).

On the other hand, N loss contaminates the surface and subsurface water (Barton and Colmer, 2006). Subsurface water contamination by nitrate (NO_3^-) is usually associated with an excess use of N fertilizer (Asadi et al., 2002; Jalali, 2005). In semi-arid regions over-irrigation is the main cause of N leaching (Jalali, 2005). Therefore, application of N at a rate less than optimal and/or using PRD irrigation can reduce NO_3^- leaching (Sexton et al., 1996).

Nitrate leaching was investigated under different irrigation and fertilizer management practices in semi-arid and arid conditions (Tamini and Mermoud, 2002; Darwish et al., 2003; Rajput and Patel, 2006). Results of N leaching indicated that it is affected by different methods of irrigation. Ahmadi et al. (2011) reported that under limited water conditions and applying water-saving irrigation strategies (PRD), sandy loam and coarse sand soils are better growth media such that N is more available for potatoes.

In semi-arid and arid climates, PRD irrigation is used due to the shortage of water that does not meet the evapotranspiration (ET) requirements of a crop. Therefore, an application of N fertilizer based on full irrigation conditions could result in N over use and could increase the potential for N losses to the groundwater (Tarkalson et al., 2006). Therefore, there is a need to quantify the nitrate leaching potential as a result of N fertilizer application under PRD and full irrigation in semi-arid conditions.

The objectives of this study were to investigate the interaction between furrow irrigation method variations (full and PRD furrow irrigation) and nitrogen application rates and its effect upon yield, yield quality, water productivity, nitrogen use efficiency and NO_3^- leaching for maize in a semi-arid region.

Methods and Materials

Experimental site

This study was conducted in Bajgah area in Fars province, Iran in the growing season of 2009. This was a drought year with an annual rainfall of 175 mm (44% of mean annual rainfall). The physico-chemical properties of soil are shown in Table 1. The 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, 32° 32' E, 1810 MSL). The chemical analysis of the soil water extract and irrigation water is shown in Table 2. There was no salinity and sodium hazards by using the irrigation water. This experiment was conducted in a cluster of water balance lysimeters consisting of 36 square units (12×3) with dimensions of 1.5 m long, 1.5 m wide, and 1.1 m depth each. A gravel layer of 0.05 m was placed at the bottom of each lysimeter and a soil layer 1.0 m thick was placed on top. Therefore, soil surface was 0.05 m below the edge of each lysimeter. In each lysimeter a drainage tube was installed under the gravel filter to drain the drainage water. These drains were conducted to different sumps in order to collect the drainage water. The spacing between the lysimeters was 0.3 m. The wall and bottom of the units were made in concrete and coated with water proof bitumen.

Table 1. Physico-chemical properties of the experimental soil.

Physical properties						
Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk density (g cm^{-3})	Field capacity* (cm^3 cm^{-3})	Permanent wilting point* (cm^3 cm^{-3})
0-15	30	35	35	1.25	0.32	0.11
15-30	30	35	35	1.32	0.36	0.12
30-50	39	38	23	1.36	0.36	0.14
50-70	40	39	21	1.42	0.39	0.16
70-100	40	39	21	1.42	0.39	0.16

Chemical properties				
Depth (cm)	pH	Organic matter (%)	Calcium carbonate (%)	Cation exchange capacity (cmol kg^{-1})
0-15	8.0	2.0	17.0	48.0
15-30	8.0	2.0	17.0	48.0
30-50	8.2	-	9.6	-
50-70	8.0	0.7	28.0	44.0
70-100	8.0	0.7	28.0	44.0

* Field capacity and permanent wilting point are volumetric soil water content at soil water matric potential of 0.033 and 1.5 MPa, respectively.

Table 2. Chemical analysis of soil saturation extract and irrigation water.

Properties	Unit	Saturation extract	Irrigation water
pH		7.49	7.20
Electrical conductivity	dS m^{-1}	1.10	0.76
Chloride	meq L^{-1}	1.18	0.40
Calcium	meq L^{-1}	2.10	0.28
Magnesium	meq L^{-1}	3.85	0.79
Sodium	meq L^{-1}	1.01	0.35
Potassium	meq L^{-1}	0.20	0.01
Bicarbonate	meq L^{-1}	0.29	0.07
Phosphorous	meq L^{-1}	0.013	0.003
Nitrate	meq L^{-1}	-	0.11

Experimental design and measurement methodologies

The experimental design was complete randomized design with factorial arrangement and three replications. The experimental treatments consisted in: four levels of nitrogen (0, 100, 200, and 300 kg N ha^{-1}) and three variations of the furrow irrigation methods (ordinary furrow irrigation-OFI, fixed alternate furrow irrigation-FAFI, and variable alternate furrow irrigation-VAFI). OFI is considered as full irrigation and FAFI and VAFI are considered as partial root drying (PRD) irrigations. In OFI, water was applied to every furrow at each irrigation event; in FAFI, water was applied to fixed alternate furrows through the growing season while in VAFI water was applied to alternate furrows which were dry in the preceding irrigation cycle. Each lysimeter contained three V-shaped furrows and four ridges planted with maize (*Zea mays* L.) with 1.5 m long and 0.5 m between furrows.

The soil in each unit was tilled by hoe. During the soil preparation triple superphosphate at a rate of 46 kg P ha^{-1} and urea as 50% of the total N amount were mixed with the soil. The remaining N (50% of each treatment) was applied 60 days after seed emergence. Top dressing of N was applied to every furrow in OFI and to the irrigated furrows in FAFI and VAFI. After soil preparation, the seeds of Single Cross 704 maize cultivar were planted on top of the four furrow ridges (four rows) with spacing between rows of 0.5 m and seeding spacing along the row of 0.15 m with density of 13 seeds per m^2. Seeding date was 18 June in 2009.

Mean air temperature during the growing season was 22.1 ºC. During 1 to 2 weeks after emergence, plants were thinned to the desired spacing on each row. Weeds were removed by hand weeding in 2-week intervals. Pests were controlled twice by using appropriate pesticides in 2-week intervals.

Irrigation water was applied in 7-day interval, and soil water in the root zone was raised to the field capacity by following equation:

$$d_n=\Sigma_{i=1}^{n}(\theta_{fci}-\theta_i)\Delta z \qquad (1)$$

Where d_n is the net irrigation depth (m), θ_{fci} and θ_i are the volumetric soil water contents in layer *i* at field capacity and before irrigation, respectively ($m^3\ m^{-3}$), Δz is the soil layer thickness (m) and n is the number of soil layers. Then, the gross irrigation water was determined by using an irrigation application efficiency of 70%. The irrigation water was applied with a flexible hose and the volume was measured with a volumetric flow meter. The first, second and third irrigation events were similar in all irrigation treatments (a total amount of about 150 mm) for uniform and vigorous seed germination and vegetation stands. Figure 1 shows the amounts of crop evapotranspiration (ET_p), irrigation water applied for each irrigation event of OFI, FAFI, and VAFI. Root zone depth was estimated by the following equation (Borg and Grimes, 1986):

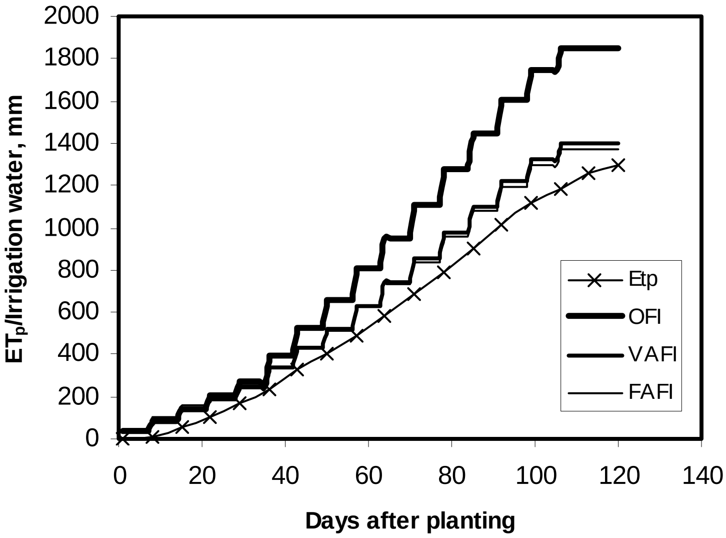

Figure 1. Cumulative crop evapotranspiration (ET_p), and irrigation depths for ordinary furrow irrigation (OFI), variable alternate furrow irrigation (VAFI) and fixed alternate furrow irrigation (FAFI) at different days after planting (DAP).

$$z_r=R_{DM}[0.5+0.5\mathrm{SIN}(3.03D_{AS}/D_{TM}-1.47)] \quad (2)$$

Where z_r is the root depth, m, R_{DM} is the maximum root depth, 1.0 m, D_{AS} is the number of days after planting, D_{TM} is the number days after planting for maximum root depth, 80 d.

The measured traits were analyzed by MSTATC software, and the means were compared by Dunckan's multiple range test.

Soil water and soil nitrogen measurements

The soil water content at the depths of 0.15, 0.3, 0.5, 0.7, and 1.0 m was measured with a neutron probe before each irrigation event. The access tube was installed at the end of the central furrow in OFI and in the central and lateral furrows in the AFI. The soil water content in furrow to be irrigated was used in Eq. (1) to determine the irrigation depth.

The crop evapotranspiration for the irrigation intervals (ET, mm) was estimated by the water balance procedure using the following equation (Jensen, 1973):

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

Where I is the irrigation amount (mm), P is the percipitation (mm), D is the deep percolation (mm) at the bottom of the root zone, n is the number of layers, ΔS is the thickness of each soil layer (mm) and θ_1 and θ_2 are the volumetric soil water contents (cm^3 cm^{-3}) before two consecutive irrigations.

Initial soil NO_3-N was determined in soil samples at the depths of 0-0.3, 0.3-0.6, and 0.6-0.9 m before the N application (14 June, 2009) using the method presented by Chapman and Pratt (1961). The residual soil NO_3-N was determined at the same depths after harvest (17 October, 2009).

After each irrigation event, the drainage water was collected and its total volume was measured by the volumetric method. The drainage water was kept in the refrigerator, and the NO_3^- concentration was determined by a spectrophotometer. Nitrate leaching with each irrigation event was determined by multiplying the water volume by the nitrate concentration.

Plants from the two central ridges were harvested, and the number of cobs per plant and seeds per cub were determined. Seeds were separated from cobs and weighed and the 1000-grain weight was determined. Furthermore, the oven-dried weight of straw was determined. Samples from grains and straw were used to determine the N concentration in mg kg^{-1} by Kejldahl procedure (Bremner and Mulvaney, 1982). The seed protein content (as percentage) was determined by multiplying the N content of seed by 6.25 (Chapman and Pratt, 1961).

Data treatment

Water productivity and nitrogen efficiency

Water productivity (WP) was determined by the ratio of grain yield to the applied irrigation water. By using the total N uptake by grain and straw and the amount of applied N as fertilizer, the apparent N recover for different N treatments were calculated as follows (Pirmoradian et al., 2004):

$$N_{ap}=(N_{ui}-N_{uc})/(N_{fi}-N_{fc}) \quad (4)$$

Where N_{ap} is the apparent N recovery, 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 as fertilizer in different N treatments and control, respectively, kg ha^{-1}. By using the N applied with the fertilizer and the seed yield, the N_{ye} in different N treatments was calculated as follows:

$$N_{ye}=(Y_i-Y_c)/(N_{fi}-N_{fc}) \quad (5)$$

Where N_{ye} is the N-yield efficiency (NYE), Y_i and Y_c are the grain yield in different N treatments and control, respectively, kg ha^{-1}.

Photosynthesis measurement

After the start of irrigation treatments on 9 July and until leaf senescence on 7 October stomatal resistance (r_s) and net photosynthesis rate (A_n) were measured on fair weather days (mostly sunny). Measurements of r_s and A_n were made in three plots of each irrigation treatment during three different days at tasseling, cob formation and grain denting stages. Measurements of gas exchange parameters were made using a LC_i analyzer (Li-Cor Inc, Nebraska, USA). Within each plot, one fully expanded leaf from the top of the plant was chosen for the measurements. Furthermore, the vapor pressure deficit (VPD) in leaves was determined by using the saturated vapor pressure in leaf measured by the LC_i analyzer and actual air vapor pressure determined from air temperature and relative humidity measured in a nearby weather station. Then, the relationship between the ratio of A_n to r_s and VPD was determined by a linear regression analysis. The slope of this line was considered as leaf level stress sensitivity index (LLSSI) (Ahmadi et al., 2010).

Results and Discussion

Water use

Seasonal water balance components (mm) for the different irrigation treatments are shown in Table 3. There was no rainfall during the growing season. In relation to full irrigation, in alternate furrow irrigation (AFI) evapotranspiration (ET) decreased about 20%. This might be mostly due to the reduced surface evaporation. Drainage water decreased by 57 and 40% for FAFI and VAFI, respectively. Furthermore, the ratio of drainage water to crop ET was 0.19 for OFI that is close to 0.3, i.e., 1 minus irrigation application efficiency. This ratio is 0.11 and 0.15 for FAFI and VAFI, respectively. Therefore, it is indicated that deep percolation in AFI is reduced about 42% and 21% for FAFI and VAFI, respectively compared with OFI. This water saving should be added to the reduction in surface evaporation in AFI.

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

Component	Irrigation method		
	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow
Rainfall	0.0	0.0	0.0
Net irrigation	1296.0	957.0	982.0
Gross irrigation	1852.0	1367.0	1402.0
Drainage water	251.0	108.0	152.0
Evapotranspiration	1291.0	1021.0	1043.0

Straw dry matter and grain yield

Grain and straw yields are shown in Table 4. Results of the statistical analysis of grain and straw yields were similar. There was a statistically significant interaction between N application rates and irrigation methods ($P<0.05$). In VAFI and FAFI, the grain and straw yields were statistically similar at N application retaes of 200 and 300 kg ha^{-1}, however, they were statistically lower at N application rates of 0 and 100 kg ha^{-1}. In OFI, the yields were increased as a function of N application rates. The yields were decreased in OFI, VAFI and FAFI, respectively at all N application rates.

In general, it is indicated that under water shortage, if VAFI is going to be used, the lower N application rate is appropriate to be used (i.e., 200 kg ha^{-1}), while under full irrigation condition, higher N application rate (i.e., 300 kg ha^{-1}) is appropriate.

Table 4. Grain and straw yields, 1000-grain weight and grain protein content of maize in different irrigation and N treatments.

Nitrogen application rate, kg ha^{-1}	Irrigation method		
	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow
Grain yield, kg ha^{-1}			
0	4326[f*]	2087[h]	1390[i]
100	6969[c]	3337[g]	2314[h]
200	10553[b]	6419[cd]	5747[e]
300	11274[a]	6468[cd]	5987[e]
Straw yield, kg ha^{-1}			
0	8652[e]	4175[g]	2781[h]
100	12672[b]	6068[f]	4208[g]
200	17589[a]	10699[c]	9578[de]
300	17345[a]	9950[cd]	9211[de]
1000-grain weight, g			
0	258.9[bc]	217.4[e]	215.4[e]
100	280.1[b]	228.9[de]	223.7[e]
200	326.9[a]	260.1[bc]	248.6[cd]
300	334.6[a]	280.9[b]	275.7[b]
Grain protein content, %			
0	6.70[f]	8.56[de]	7.94[e]
100	7.32[ef]	9.18[d]	10.04[c]
200	7.32[ef]	10.35[c]	10.97[c]
300	10.97[c]	14.01[a]	12.96[b]

[*] Means followed by the same letters in each parameter are not significantly different at 5% level of probability.

1000-grain weight

1000-grain weights are shown in Table 4. There was a statistically significant interaction between N application rates and irrigation methods ($P<0.05$). For all N application rates, 1000-grain weights were statistically similar in VAFI and FAFI, however, they were statistically lower than those in OFI. In general, 1000-grain weights were statistically similar in N application rates of 0-100 kg ha^{-1} and 200-300 kg ha^{-1} and they were higher at N application rates of 200-300 kg ha^{-1}than those at 0-100 kg ha^{-1} N application rates.

Grain protein content

Grain protein contents are shown in Table 4. There was a statistically significant interaction between N application rates and irrigation methods ($P<0.05$). In general, grain protein content was significantly higher in VAFI and FAFI ($P<0.05$) compared with OFI. This is due to the water stress effects on increasing the protein content in grain as reported for maize, potato and tomato crops (Wang et al., 2009; Wang et al., 2010).

As it is expected, the grain protein content increased with the N application rate, however, the effect of N application rate was enhanced in VAFI and FAFI. Maximum grain protein content in OFI was obtained at 300 kg ha^{-1} N application rate, while this amount of grain protein content was occurred at 200 and 100 kg ha^{-1} of N application rate for VAFI and FAFI, respectively.

Water productivity

Ratio of grain yield to applied irrigation water is considered as water productivity (WP). Results are presented in Table 5. There was a statistically significant interaction between N application rate and irrigation methods ($P<0.05$). For all N application rates, the highest WP occurred in OFI and its value was significantly higher in VAFI than in FAFI. N application rate increased WP up to 300 kg ha^{-1} in OFI. However, in VAFI and FAFI, WP increased significantly up to N application rate of 200 kg ha^{-1}. Therefore, under water shortage, by using VAFI, N application rate of 200 kg ha^{-1} is adequate for higher WP.

Table 5. Water productivity, nitrogen use efficiency, and nitrogen-yield efficiency in different irrigation and N treatments.

Nitrogen application rate, kg ha^{-1}	Irrigation method		
	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow
Grain yield water productivity, kg m^{-3}			
0	0.330^{f*}	0.212^{g}	0.153^{h}
100	0.542^{e}	0.342^{f}	0.243^{g}
200	0.811^{b}	0.652^{c}	0.601^{d}
300	0.872^{a}	0.661^{c}	0.632^{cd}
Nitrogen use efficiency, kg kg^{-1}			
100	0.68^{b}	0.36^{e}	0.30^{f}
200	0.74^{a}	0.67^{bc}	0.66^{bc}
300	0.63^{c}	0.57^{d}	0.58^{d}
Nitrogen-yield efficiency, kg kg^{-1}			
100	26.4^{b}	12.5^{e}	9.2^{f}
200	31.1^{a}	21.7^{c}	21.8^{c}
300	23.2^{c}	14.6^{d}	15.3^{d}

[*] Means followed by the same letters in each parameter are not significantly different at 5% level of probability.

Nitrogen efficiencies

Apparent N recovery or N use efficiency (NUE), and N-yield efficiency (NYE) are shown in Table 5. There was a statistically significant interaction between N application rate and irrigation methods ($P<0.05$). Results of NUE and NYE were similar. Highest NUE and NYE were obtained in OFI and N application rate of 200 kg ha^{-1}. Furthermore, in VAFI and FAFI, the highest NUE and NYE was occurred at N application rate of 200 kg ha^{-1}, although it was lower than that in OFI. In general, NUE and NYE were significantly decreased in VAFI and FAFI compared with OFI. Therefore, it is indicated that in terms of NUE and NYE, the N application rate of 200 kg ha^{-1} is the optimum rate for the study region for both OFI and AFI irrigations.

Nitrogen balance

Results of N balance analysis are presented in Table 6. The N added by the irrigation water was higher in OFI due to higher volume of applied water (Table 3). Plant N uptake was calculated from the N concentration in grain and straw yield. Nitrogen losses (except for N in drainage water) are presented in Table 6. They include N uptake by weeds, stored N in root and denitrification. Soil residual N increased as the N application rate increased. This increase was about 13.0, 4.0, and 4.0 times at N application rate of 300 kg ha^{-1} compared with 0 application rate in OFI, FAFI, and VAFI, respectively. These differences are due to the fact that higher N uptake and leaching occurred in OFI and these values were lower for VAFI and FAFI. Furthermore, these differences were partly due to the increase of soil residual N before planting as a result of N application rate difference in previous experiment in the same lysimeters.

Nitrogen losses increased as the N application rate increased up to 300 kg ha^{-1}. for the same irrigation treatments, low N losses (45 kg ha^{-1}) were reported by Sepaskhah and Hosseini (2008) for winter wheat at N application rate of 270 kg ha^{-1}. This difference might be due to not considering N in the irrigation water nor the weeds uptake. Also, there was a higher N uptake by wheat (Sepaskhah and Hosseini, 2008).

Table 6. Nitrogen balance components in different treatments of irrigation and nitrogen application.

Nitrogen application rate, kg ha^{-1}	Residual N before planting kg ha^{-1}	Residual N after harvest kg ha^{-1}	Leached N kg ha^{-1}	N loss kg ha^{-1}
Ordinary furrow irrigation				
0	70.2	11.3	4.16	3.25
100	95.9	41.2	5.59	29.91
200	113.6	55.0	9.11	50.30
300	173.4	138.1	12.26	81.86
Variable alternate furrow irrigation				
0	75.8	50.2	2.13	2.39
100	90.0	105.2	2.33	25.47
200	120.0	130.2	4.72	30.91
300	160.2	190.2	5.46	71.04
Fixed alternate furrow irrigation				
0	65.7	60.2	1.44	1.69
100	81.9	121.5	2.11	25.59
200	124.8	140.1	3.66	46.71
300	199.4	238.3	5.81	79.25

Nitrogen leaching

Average seasonal nitrate concentration in drainage water and total leached nitrate from 1.0 m soil depth are shown in Table 7. There was a statistically significant interaction between N application rate and irrigation methods ($P<0.05$) for these variables. For all irrigation treatments, nitrate concentration in drainage water increased as N application rate increased. At N application rates of 0 kg h^{-1}, nitrate concentration in drainage water was not significantly different for the different irrigation treatments. However, at N application rates of 100-200 kg ha^{-1}, nitrate concentration in drainage water was significantly lower for VAFI. For the N application rate of 300 kg ha^{-1} nitrate concentration in drainage water was significantly increased in OFI, VAFI, and FAFI, respectively. In FAFI, top-dress N was applied at two fixed furrows and irrigated during the growing season. Therefore, higher nitrate concentration in drainage water at this irrigation method was due to the lower amount of drainage water that resulted in higher nitrate concentration. However, at VAFI, top-dress N was applied at two fixed furrows and N was not applied in the middle furrow, while irrigation was applied alternately to the central furrow with no N application. Therefore, nitrate concentration of drainage water was lower in VAFI.

Table 7. Nitrogen concentration of drainage water and total leached nitrogen in different treatments.

Nitrogen application rate, kg ha^{-1}	Irrigation method		
	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow
Nitrogen concentration, mg L^{-1}			
0	6.78^{fg*}	5.50^{h}	5.25^{h}
100	8.91^{e}	5.86^{gh}	7.51^{f}
200	14.52^{c}	12.47^{d}	13.75^{c}
300	19.67^{b}	14.45^{c}	21.45^{a}
Total leached nitrogen, kg ha^{-1}			
0	16.64^{e*}	5.76^{g}	8.52^{f}
100	22.35^{c}	8.43^{f}	9.31^{f}
200	36.42^{b}	14.63^{e}	18.90^{d}
300	49.06^{a}	23.24^{c}	21.82^{c}

[*] Means followed by the same letters in each parameter are not significantly different at 5% level of probability.

Results indicated that due to the strategies of N application and irrigation water application in furrows in VAFI, nitrate concentration in drainage water is decreased. Furthermore, results showed that as less water is applied in VAFI, less drainage water and lower nitrate concentration in drainage water was found. Similar results were reported by other investigators (Cameira et al., 2003; Vazquaz et al., 2006; Gheysari et al., 2009).

For all irrigation treatments, total leached nitrate significantly increased as N application rate increased (Table 7). In general, total leached nitrate significantly decreased in VAFI compared with OFI and FAFI, except at N application rate of 300 kg ha^{-1} that total leached nitrate reduction was continued in VAFI and FAFI compared with OFI. Therefore, it is indicated that total leached nitrate was lowest at VAFI that is in comparison with recommended irrigation strategy at water shortage conditions. Total leached nitrate in our study was higher than those reported by Gheysari et al. (2009) for maize. This might be due to higher seasonal drainage during the growing season in our study (i.e., 251 mm, 108 mm, and 152 mm in OFI, VAFI, and FAFI, respectively) compared with those obtained by Gheysari et al. (2009) (i.e, 67 mm, and 21 mm at soil depth of 0.60 m and irrigation treatment of 1.0 and 1.13 SMD, soil moisture deficit).

Interaction of water and N on nitrate leaching

The interaction between water and N on the total nitrate leaching below the root zone (1.0 m) was shown by fitting the following equation:

$$(NO_3\text{-}NL)=48.0-874.4\ (DR/ET) + 0.053\ (TAN) + 3627.2\ (DR/ET)^2 \qquad (6)$$

R^2=0.91, SE=4.50, n=12, P=0.0002

Where $NO_3\text{-}NL$ is the total leached nitrate, kg ha^{-1}, *DR/ET* is the ratio of drainage water to crop ET and *TAN* is the total available N (initial soil N + irrigation water N + N fertilizer), kg ha^{-1}. The contour of total leached NO_3-N as a function of TAN and DR/ET is shown in Figure 2. Total leached NO_3-N increased non-linearly (quadratic) by increasing applied irrigation water (higher DR/ET). However, it increased linearly by TAN. Therefore, total leached NO_3-N was enhanced by increasing TAN. Overall, these results indicated that interactive effects of water and TAN on nitrate leaching were dependent on the depth of applied water and TAN. These results showed that the highest leached N during the growing season occurred at higher irrigation water and N application. Our results are similar to those reported by other investigators (Cameira et al., 2003; Vazquez et al., 2006; Gheysari et al., 2009).

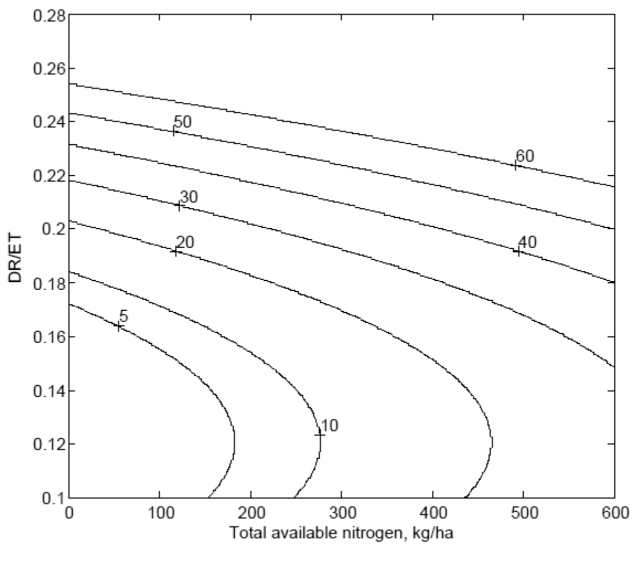

Figure 2. Total nitrogen leaching (kg ha^{-1}) at soil depth of 1.0 m as a function of total available nitrogen and the ratio of drainage water to actual evapotranspiration (DR/ET).

Ratio of DR/ET is equivalent to $1/E_a$-1 in which E_a is the irrigation water application efficiency (fraction) with assumption of irrigation water loss being mainly due to deep percolation. Therefore, at a given value of E_a, the ratio of DR/ET can be estimated, then, the leached NO_3-N at a given value of TAN can be determined from Figure 2.

Relationship between plant N uptake and total applied nitrogen

Linear relationships between the plant N uptake and the total available nitrogen for different irrigation treatments were obtained by regression analysis as follows:

$$NU=45.3+0.48TAN, \quad R^2=0.97 \quad \text{for OFI} \tag{7}$$

$$NU=11.5+0.42TAN, \quad R^2=0.96 \quad \text{for FAFI} \tag{8}$$

$$NU=-25.2+0.49TAN, \quad R^2=0.96 \quad \text{for VAFI} \tag{9}$$

Where *NU* is the plant N uptake, kg ha^{-1} and *TAN* is the total available N, kg ha^{-1}. These equations are valid in the range of 100-500 kg TAN ha^{-1}. The fitted equations indicated that the ratio of NU to TAN is similar for different irrigation treatments, however, the intercepts are increased by irrigation methods with a highest value occurred for OFI, indicating higher NU in this irrigation compared with other irrigation treatments. This is occurred due to the fact that an increased in soil water availability in OFI increased crop N uptake. In general, it is indicated that applying N fertilizer without considering water availability could increase either N losses or soil residual N as shown in Table 7.

Gas exchange in maize leaf

Photosynthesis rates (A_n) at three different growth stages of maize are shown in Table 8. Results indicated that there was no significant differences between N application rates, however, different methods of irrigation were statistically significant ($P<0.05$). In tasseling and cob formation stages, AFI showed significantly lower A_n ($P<0.05$) compared with OFI. However, FAFI resulted in significantly lower A_n ($P<0.05$) than those obtained in OFI and VAFI. Furthermore, the values of A_n were highest in cob formation stage.

Table 8. Photosynthesis rate (micromole m^{-2} s^{-1}) at different growth stages of maize in different irrigation and N treatments.

Nitrogen application rate, kg ha^{-1}	Irrigation method		
	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow
Tasseling			
0	22.19[a*]	17.72[b]	17.14[b]
100	21.57[a]	17.79[b]	17.04[b]
200	21.72[a]	18.00[b]	17.14[b]
300	21.95[a]	18.20[b]	17.33[b]
Cob formation			
0	32.20[a]	19.70[b]	19.10[b]
100	31.60[a]	19.80[b]	19.00[b]
200	31.70[a]	20.00[b]	19.10[b]
300	32.00[a]	20.00[b]	19.30[b]
Grain denting			
0	21.20[a]	14.70[a]	11.10[c]
100	20.60[a]	14.80[b]	11.00[c]
200	20.70[a]	15.00[b]	11.10[c]
300	21.00[a]	15.20[b]	11.30[c]

[*] Means followed by the same letters in each parameter are not significantly different at 5% level of probability.

Our results for maize in semi-arid area were in contradiction with those obtained for potatoes in a humid area (Denmark) as reported by Ahmadi et al. (2010). They indicated that irrigation treatments of partial root drying irrigation (PRD) resulted in similar A_n as full irrigation. This difference is due to the fact that maize is a sensitive crop to water stress especially when water stress is occurred in reproductive stage (Sepaskhah and Parand, 2006).

Leaf stomatal resistance (r_s) at three different growth stages of maize are presented in Table 9. There was significant interaction effects between N application rates and irrigation methods for r_s ($P<0.05$). The values of r_s significantly decreased ($P<0.05$) as N application rates increased in VAFI and FAFI, unless at 200 and 300 kg N ha^{-1} that they were not significantly different ($P<0.05$). The values of r_s were lowest at cob formation stage. At tasseling and cob formation stages, differences in the values of r_s were significant ($P<0.05$) compared with OFI, with no significant difference in these two irrigation methods. However, at grain denting stage, the values of r_s were significantly increased on OFI, VAFI and FAFI, respectively.

Table 9. Leaf stomatal resistance (m^2 s $mole^{-1}$) at different growth stages of maize in different irrigation and N treatments.

Nitrogen application rate, kg ha^{-1}	Irrigation method		
	Ordinary furrow	Variable alternate furrow	Fixed alternate furrow
		Tasseling	
0	10.10[e*]	16.00[a]	15.80[a]
100	9.50[ef]	14.30[b]	15.50[a]
200	8.60[fg]	12.00[d]	13.00[cd]
300	7.90[g]	12.70[cd]	13.80[c]
		Cob formation	
0	5.16[e]	16.04[a]	12.93[a]
100	4.99[e]	11.79[b]	12.66[a]
200	4.63[e]	10.09[d]	10.85[cd]
300	4.39[e]	10.61[cd]	11.40[bc]
		Grain denting	
0	10.94[g]	23.02[d]	36.17[a]
100	10.36[gh]	20.00[e]	34.80[a]
200	9.24[gh]	16.20[f]	26.43[c]
300	8.54[h]	17.33[f]	28.82[b]

[*] Means followed by the same letters in each parameter are not significantly different at 5% level of probability.

Our results for maize in semi-arid area were in contradiction to those obtained for potatoes in a humid region (Denmark) as reported by Ahmadi et al. (2010). They indicated that irrigation treatment of PRD resulted in similar leaf stomatal conductance as full irrigation. This difference is due to the fact that maize is a sensitive crop to water stress especially when water stress is occurred in reproductive stage (Sepaskhah and Parand, 2006).

Relationship between photosynthesis rate (A_n) and stomatal conductance (g_n) ratio A_n/g_n and vapor pressure deficit (VPD) for different irrigation treatments are shown in Figure 3. It is indicated that higher A_n/g_n ratio was occurred under higher evaporative demands (i.e., higher VPD). The slope of this relationship (i.e, leaf level stress sensitivity index, LLSSI) was proposed by Ahmadi et al. (2010) as an index to determine the plant physiological stress that can be used in order to assess the sensitivity of the plant to VPD variation and its effects on A_n/g_n under environmental stress. Higher value of the slope indicates a higher tolerance to water stress. Values of the slope are 134.4, 350.6 and 359.1 for OFI, FAFI and VAFI, respectively. These indicated that the highest tolerance to water stress occurred in VAFI. The values of slope for FAFI and VAFI were not statistically different, however, their values were statistically higher than that for OFI ($P<0.05$).

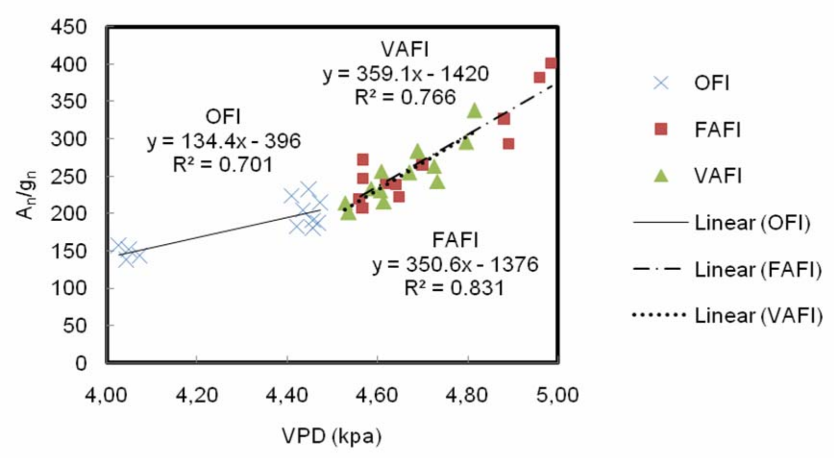

Figure 3. Relationship between photosynthesis rate to stomatal conductance ratio (A_n/g_n) and vapor pressure deficit (VPD).

Conclusions

Results indicated that the interaction between irrigation treatments and N application rates was statistically significant for all the experiments performed in this investigation. Results indicated that maize grain yield was reduced by alternate furrow irrigation due to high sensitivity of maize to water stress, however, in case of water shortage, VAFI is superior to FAFI. In the studied region, N application of 200 kg ha^{-1} is optimum to obtain optimum grain yield, NUE and N-yield efficiency. Drainage water and total leached nitrate decreased for VAFI and FAFI compared to OFI and their amount were lowest in FAFI (for drainage water) and in VAFI (for total leached nitrate), respectively. Total leached nitrate to the soil depth below the crop root zone increased in response to the increase in total available nitrogen for water application higher than crop ET. N losses were reduced for FAFI and VAFI at N application of 200 and 300 kg ha^{-1}. Only in FAFI and VAFI, N uptake decreased and soil residual N increased as compared with OFI. Thus, in order to avoid N losses, the amount of N fertilizer should be reduced in proportion to the amount of soil water available for plant uptake under deficit irrigation. Furthermore, it was indicated that leaf level stress sensitivity index (LLSSI) was higher for VAFI and it was about 2.5 times of OFI.

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