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Distribution and loss of water and nitrate under alternate and conventional furrow fertigation

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Abstract

Alternate furrow irrigation and surface fertigation have been known as techniques to control water and fertilizer losses. The main goal of this field study was to characterize the combined effect of these techniques on water and nitrate losses and on soil water and nitrate concentration. Two types of alternate furrow irrigation, *i.e.,* variable alternate furrow irrigation (AFI) and fixed alternate furrow irrigation (FFI), as well as conventional furrow irrigation (CFI) were considered in the experiments. Results evidenced higher infiltration at irrigated furrows under AFI and FFI as compared to CFI. Increased lateral water movement under alternate irrigation resulted in lower water and nitrate losses via runoff and deep percolation. Water application efficiency for the CFI, FFI and AFI strategies amounted to 61.3%, 71.8% and 77.0% in the first fertigation and 36.4%, 58.8% and 60.7% in the second fertigation, respectively. Nitrate runoff for the CFI, FFI and AFI strategies amounted to 32.4%, 31.2% and 25.7% in the first fertigation and 44.3%, 35.1% and 32.7% in the second fertigation, respectively. Soil water content and nitrate concentration at the upstream part of the experimental field were larger than at the middle and downstream parts for all three irrigation regimes. Overall, alternate furrow fertigation, particularly AFI, stands as a simple and practical management practice for water and fertilizer conservation in agricultural fields.

Additional key words: alternate furrow irrigation; fertigation; water and nitrate losses.

Resumen

Distribución y pérdidas de agua y nitrato bajo fertirriego por surcos alterno y convencional

El riego por surcos alternos y el fertirriego por superficie se han venido utilizando por separado como técnicas con capacidad demostrada para controlar las pérdidas de agua y fertilizantes. El principal objetivo del ensayo descrito en este trabajo fue caracterizar el efecto del uso conjunto de estas técnicas en las pérdidas de agua y nitratos, en el agua en el suelo y en la concentración de nitrato en el suelo. En el ensayo se consideraron dos tipos de fertirriego por surcos alternos, variable (AFI) y fijo (FFI), así como el riego por surcos convencional (CFI). Los resultados evidenciaron una mayor infiltración en los surcos AFI y FFI que en los surcos CFI. El aumento del movimiento lateral del agua en el riego alterno resultó en menores pérdidas de agua y nitrato por escorrentía y percolación profunda. La eficiencia de aplicación del agua para las estrategias CFI, FFI y AFI fue de 61,3%, 71,8% y 77,0% en el primer fertirriego, y de 36,4%, 58,8% y 60,7% en el segundo fertirriego, respectivamente. Las escorrentías de nitrato en las estrategias CFI, FFI y AFI fueron de 32,4%, 31,2% y 25,7% en el primer fertirriego y de 44,3%, 35,1% y 32,7% en el segundo fertirriego, respectivamente. El contenido de agua en el suelo y la concentración de nitrato en el extremo aguas arriba del campo experimental resultó mayor que en la parte media o en el extremo aguas abajo en las tres estrategias ensayadas. El fertirriego por surcos alternos (AFI en particular) resulta una técnica de manejo simple y práctica para conservar agua y fertilizantes en la agricultura de regadío.

Palabras clave adicionales: fertirriego; pérdidas de agua y nitrato; riego por surcos alternos.

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Abbreviations used: AFI (variable alternate furrow irrigation); CFI (conventional furrow irrigation); EC_e (electrical conductivity of the soil saturated extract); FFI (fixed alternate furrow irrigation).

Introduction

Inappropriate irrigation system design and management and the use of traditional irrigation methods have been reported to cause large water losses in agricultural fields (Wang *et al.,* 1996; Howell, 2001). Irrigation system upgrade and replacement can mitigate water shortages or lead to increased irrigated area to cope with rapid population growth (Rijsberman, 2006). Alternate furrow irrigation is an irrigation management strategy in which one out of two adjacent furrows is irrigated. By facilitating horizontal (lateral) water movement, alternate furrow has potential to reduce water losses via deep percolation and runoff. A number of researchers have reported that using alternate furrow irrigation reduces irrigation water use, often decreases crop yield, and results in an increase in water productivity (Stone *et al.*, 1982; Kang *et al.*, 2000a; Horst *et al.,* 2007; Slatni *et al.*, 2011). These traits make alternate furrow irrigation convenient and economical in arid and semi-arid regions. Two strategies have been defined for alternate furrow irrigation: 1) Variable alternate furrow irrigation (AFI), in which one of the two adjacent furrows is alternatively irrigated in consecutive events; and 2) Fixed alternate furrow irrigation (FFI), in which one of the two adjacent furrows (always the same) is irrigated in all events.

Alternate furrow irrigation has been found to retain fertilizer in the soil for plant uptake, thus leading to lower nitrate leaching, as compared to conventional furrow irrigation (CFI) (Mitchell *et al.*, 1994; Benjamin *et al.*, 1998; Skinner *et al.*, 1999). Ashraf & Saeed (2006) reported that salt accumulation in the root zone was smaller in FFI than in CFI. Sepaskhah & Afshar-Chamanabad (2002) determined infiltration characteristics of soils for various values of inflow discharge. They showed that infiltration in FFI was higher than in CFI. Horst *et al.* (2007) examined two irrigation treatments in a cotton field: 1) alternate *vs.* conventional furrow irrigation; and 2) surge *vs.* continuous flow. They reported highest irrigation performance (in terms of water productivity and application efficiency) for alternate furrow and surge flow. Slatni *et al.* (2011) reported that large irrigation depths applied by CFI resulted in large deep percolation losses compared to AFI and FFI at a blocked-end furrow irrigated field. The highest and lowest irrigation application efficiencies were obtained for the FFI and CFI treatments, respectively.

Chemical pollution by nitrate and phosphorus in water bodies is increasing due to the extensive, uncontrolled application of fertilizers. Agricultural fertilizers currently stand as the main non-point source of water pollution. Nitrate pollution in groundwater was detected in 49 out of the 50 states of the USA in 1992 (Ongley, 1996). Different authors have identified optimum surface fertigation techniques resulting in minimum fertilizer losses and maximum distribution uniformity of fertilizer (Playán & Faci, 1997; Abbasi *et al.*, 2003; Sabillon & Merkley, 2004; Burguete *et al.*, 2009). In addition, surface fertigation has been reported to lead to specific advantages as compared to the mechanical application of fertilizers. Among them: low energy and labor requirements; potential for small and frequent fertilizer applications; and reduction in soil compaction and crop damage resulting from machine traffic (Perea *et al.*, 2010).

Several researchers have documented N transport following standard fertilization practices (not fertigation) in combination with alternate furrow irrigation (Benjamin *et al.*, 1998; Skinner *et al.*, 1999; Crevoisier *et al.*, 2008). However, no references have been found in the literature about fertigation in alternate furrow irrigation. Fertigation performance under alternate furrow irrigation and its practical implementation constitute an interesting research challenge. Previous findings on separate advantages of alternate furrow irrigation and surface fertigation lead to hypothesize that alternate furrow fertigation has great potential to reduce water and nitrate losses, thus protecting the environment and making a significant contribution to sustainable agriculture.

Furrow fertigation models were first used by Boldt *et al.* (1994), who presented a mechanistic model for the overland part of this problem. Overland models have evolved in the last decades with the application of specific methods for the solution of the saint-Venant and the Cross-sectional average dispersion equation (Burguete *et al.*, 2009; Perea *et al.*, 2010). Wohling & Schmitz (2007) and Wohling & Mailhol (2007) presented a simulation model coupling an overland furrow irrigation model and a 2D soil water model and a crop growth model. The coupled model was successfully validated for conventional furrow irrigation.

The objectives of this paper were twofold: 1) to characterize alternate furrow (AFI and FFI) and conventional furrow (CFI) fertigation in terms of water and nitrate losses and the spatial and temporal distribution of soil water and nitrate; and 2) to produce and disseminate an experimental data set which can be used as a standard case study to support the development and validation of furrow fertigation models. Such models will permit to generalize the results of this research, identifying practical fertigation rules for the specific conditions of conventional and alternate furrow irrigation.

Material and methods

A field experiment was conducted at the experimental station of the College of Agriculture and Natural Resources, University of Tehran, Karaj, Iran. The region is characterized by a Mediterranean continental climate, with an average annual rainfall of 265 mm and an average annual temperature of 16 °C. Physical and chemical soil properties for the upstream, middle and downstream sections of the experimental field are presented in Table 1. Soil texture was assessed using the USDA classification system (Soil Survey Staff, 1951). Field capacity and wilting point were determined using pressure plates at reference suctions of 0.03 and 1.5 MPa, respectively. The electrical conductivity of the saturated extract (EC_e) was determined according to the methodology proposed by the U S Salinity Laboratory Staff (1954). Soil depth was limited to 0.60 m due to the presence of a gravel layer. Maize (*Zea mays*, single cross 704, Iranian Seed and Plant Improvement Institute) was sown in June 10, 2010. A small fraction of the N fertilizer requirements (10% of 200 kg N ha^{-1}) was applied the day before sowing using a mechanical broadcaster. Three N dressings (each of them amounting to 30% of the fertilizer requirements) were applied at the vegetative (seven leaves, July 7), flowering (August 9) and grain filling (August 30) growth stages using surface fertigation. Only fertigations 1 and 2 were investigated in this research. Plant height was 0.3 and 1.0 m, at the time of first and second fertigation events, respectively. Nitrogen fertilizer was applied in the form of granulated ammonium nitrate. In this study, only nitrate transport in water and soil was considered.

Three furrow irrigation treatments, CFI, AFI and FFI, were investigated. A statistical design oriented towards the use of ANOVA techniques would have been desirable to assess the relationship between fertigation performance and the experimental treatments. The large area of the experimental units and the high sampling intensity prevented the use of replications. As a consequence, the experimental results do not permit to establish firm, statistically sound differences between treatments. Similar conditions were reported by Slatni *et al.* (2011) when analyzing the effect of CFI, AFI and FFI on irrigation performance and crop yield.

Measurements were conducted on a single furrow per treatment. Each experimental furrow was surrounded by two irrigated guard furrows (Fig. 1). The experiment required 14 contiguous furrows (3, 5, and 6 furrows for the CFI, FFI, and AFI strategies, respectively). Furrow spacing was 0.75 m, the furrow length was 86 m, and the longitudinal slope was 0.0093. The same amount of water and fertilizer was applied to all irrigated furrows. Thus, the water and fertilizer application rate per unit area was twice as much for conventional irrigation than for the two alternate irrigation treatments.

Table 1. Physical and chemical soil properties determined at the upstream, middle and downstream sections of the experimental field

Depth (m)	Texture	Bulk density (Mg m^{-3})	Field capacity (–)	Permanent wilting point (–)	Organic matter (%)	pH	EC_e (dS m^{-1})
Upstream							
0.0-0.2	Clay loam	1.50	0.182	0.087	1.62	7.79	2.28
0.2-0.4	Clay loam	1.45	0.175	0.081	0.74	7.72	1.13
0.4-0.6	Sandy loam	1.47	0.142	0.060	0.36	7.98	1.37
Middle							
0.0-0.2	Loam	1.50	0.181	0.085	1.81	7.45	2.90
0.2-0.4	Sandy clay loam	1.45	0.172	0.080	0.83	7.68	2.30
0.4-0.6	Sandy clay loam	1.52	0.155	0.069	0.76	7.56	2.13
Downstream							
0.0-0.2	Clay loam	1.51	0.181	0.084	1.83	7.63	2.76
0.2-0.4	Loam	1.48	0.177	0.081	1.18	7.71	2.02
0.4-0.6	Sandy loam	1.49	0.150	0.066	0.68	7.71	1.98

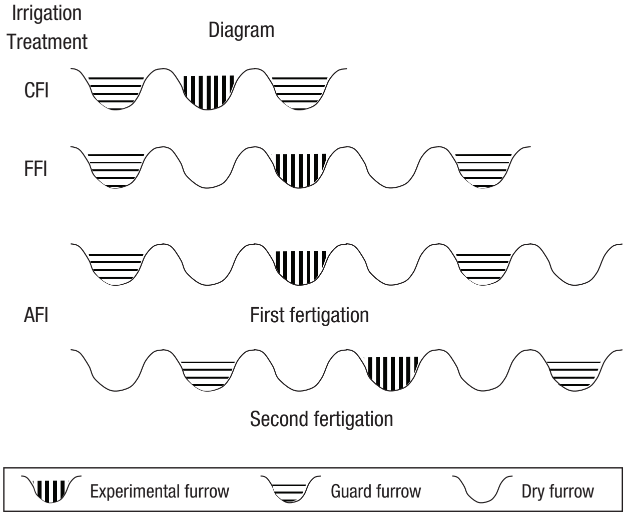

Figure 1. Experimental layout of the three furrow irrigation strategies, showing the number of furrows required for each strategy and the three types of furrows.

Irrigation water was pumped from a canal into a reservoir (Fig. 2). A weir was installed at a lateral reservoir outlet to provide constant head inside the reservoir and a constant discharge to each furrow. Water was delivered to each experimental furrow (main and guard furrows) using 25 mm polyethylene pipes. Furrow inflow and outflow (runoff) discharges were measured using Washington State College (WSC) flumes (Chamberlain, 1952). Stations were marked every 10 m along the furrows to determine irrigation advance and recession times.

The parameters of a Kostiakov-Lewis infiltration equation (Eq. [1]) were determined for each experimental furrow:

$$z = k\tau^a + f_0\tau \qquad [1]$$

where z is infiltrated water volume per unit furrow length (m^2), τ is infiltration opportunity time (min), and k (m^2 min^{-a}), a and f_0 (m^2 min^{-1}) are infiltration parameters. The average basic infiltration rate, f_o, was determined by the inflow-outflow method (Walker & Skogerboe, 1987). The two-point method (Elliott & Walker, 1982) was used to determine a and k.

Fertilizer solution was applied at the upstream end of each experimental furrow using 8 L containers equipped with regulation valves and floaters to maintain pre-set injection rates. The fertilizer solution was prepared in advance in a 220 L barrel. The containers were

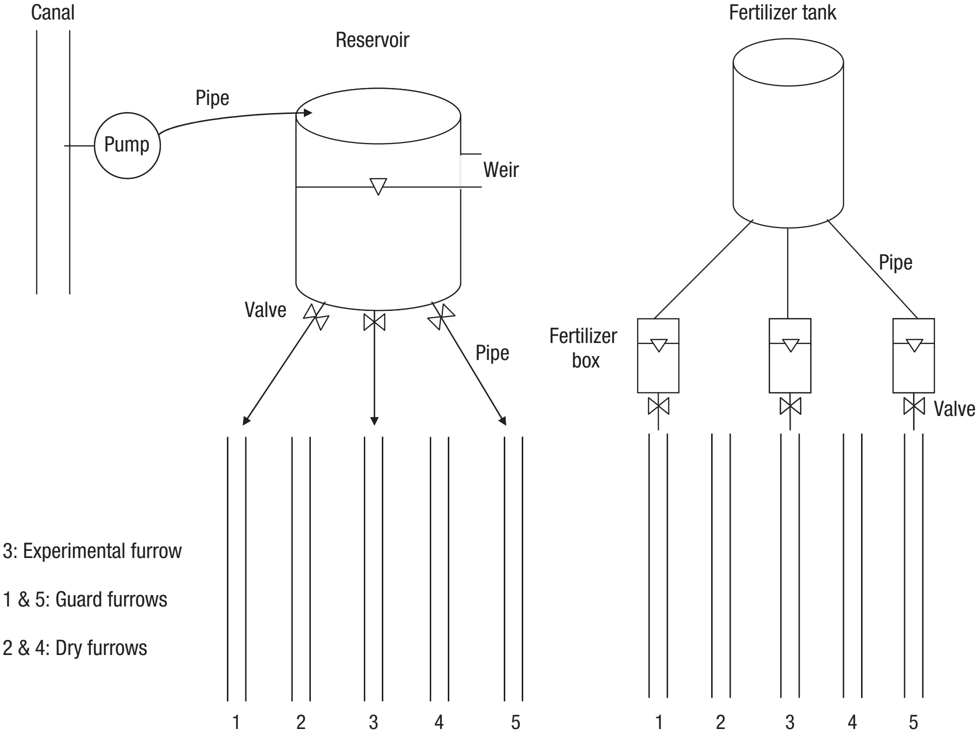

Figure 2. Scheme of water distribution and fertilizer solution injection systems. The case of the FFI treatment is presented as an example.

calibrated for the desired injection rate before each experiment. Each container was connected to the barrel using flexible pipe with a diameter of 12.5 mm (Fig. 2).

To monitor the evolution of soil water and nitrate concentration, soil samples were collected with an auger from dry (non-irrigated) and wet (irrigated) furrow beds and ridges. The diameter of the auger was about 5 cm. Samples were obtained at the upstream, middle and downstream parts of the field at three depths (0.0-0.2, 0.2-0.4 and 0.4-0.6 m). The soil samples were obtained on July 6, 8, and 13 for the first fertigation event (dated July 7) and on August 8, 11 and 15 for the second fertigation event (dated August 9). A total of 864 soil samples were collected. Soil water content was determined by oven drying at 105 °C. Soil nitrate was determined in 5:1 soil extracts (water:soil) using a spectrophotometer (6705 UV/Vis, Jenway). The nitrate content was determined from the fresh soil sample. Auger holes were immediately refilled with local soil to avoid preferential water and fertilizer flow leading to experimental errors.

Irrigation was applied on a 7 day interval throughout the irrigation season. During the first fertigation event, discharge was 0.262 L s^{-1}, and cutoff time was 240 min. In this event the fertilizer solution was injected after the time of advance (about 50 min, depending on the particular furrow). The injection time was 150 min in all furrows. During the second fertigation event, discharge was 0.388 L s^{-1}, and cutoff time was 360 min. In this event the fertilizer solution was injected during the first half of irrigation time (injection time of 180 min). The fertilizer concentration in the barrel was 200 kg m^{-3} in both events. Nitrate concentration of the irrigation water (before fertilizer injection) was 36.6 and 41.2 mg L^{-1} for the first and second fertigation events, respectively.

The volume of percolated water (V_{dp}) was determined using the following water balance equation (Walker & Skogerboe, 1987):

$$V_{dp} = V_{tot} - V_{ro} - V_{ET} - \Delta V_s \qquad [2]$$

in which;

$$V_{tot} = Q.T_{co} \qquad [3]$$

$$V_{ET} = ET_c.L.W \qquad [4]$$

$$\Delta V_s = (\Theta_2 - \Theta_1).\rho_b/\rho_w.D_{soil}.L.W \qquad [5]$$

where V_{tot} is total irrigation volume (m^3), V_{ro} is runoff volume (m^3), V_{ET} is crop evapotranspiration volume (m^3), ΔV_s is soil water storage volume (m^3), Q is inflow discharge (L min^{-1}), T_{co} is cutoff time (min), ET_c is crop evapotranspiration (m), L is furrow length (m), W is furrow spacing (0.75 m for CFI, 1.5 m for FFI and 1.5 m for AFI), Θ_1 and Θ_2 are gravimetric water contents before and after irrigation events, respectively, ρ_b/ρ_w is relative bulk density (dimensionless) and D_{soil} is soil depth (m). The uncertainty of the results of Eq. [2] depends on the uncertainty of the input variables.

The terms of these equations were obtained from field data, including the inflow and runoff hydrographs, soil water and crop evapotranspiration. Daily crop evapotranspiration during the first and second fertigation events was estimated as 4.8 and 6.6 mm day^{-1}, respectively (Allen *et al.,* 1998). Eq. [2] holds for an unstressed crop, in which evapotranspiration proceeds at the potential rate. Assuming soil water measurements are accurate, negative results from Eq. [2] imply crop water stress. In such cases, the analysis assumed $V_{dp} = 0$, and Eq. [2] was used to solve for V_{ET}, which will then be lower than potential. In this case, it can be foreseen that crop yield will also be lower than potential.

Deep percolation fraction (DP_w) is the percentage of the applied water percolating below the root zone:

$$DP_w = \frac{V_{dp}}{V_{tot}} \quad 100 \qquad [6]$$

Runoff fraction (RO_w) is the percentage of the applied water running off the field:

$$RO_w = \frac{V_{ro}}{V_{tot}} \quad 100 \qquad [7]$$

Application efficiency (E_a) is the percentage of the applied water stored in the crop root zone:

$$E_a = \frac{V_{tot} - V_{dp} - V_{ro}}{V_{tot}} \times 100 \qquad [8]$$

Nitrate mass in runoff (M_{ro}) was obtained multiplying the average runoff water nitrate concentration (C_{NO3}) by the runoff volume:

$$M_{ro} = C_{NO3} \quad V_{ro} \qquad [9]$$

Water nitrate concentration in runoff was determined using a spectrophotometer. Samples were collected at the furrow end at different times.

The nitrate runoff fraction (RO_N) is the percentage of the applied nitrate (M_{tot}) running off the field:

$$RO_N = \frac{M_{ro}}{M_{tot}} \quad 100 \qquad [10]$$

Soil water and nitrate measurements in the dry/wet furrows and the furrow ridge were averaged vertically (three soil depths) and horizontally (furrow bottom and ridge) to produce local averages (at the upstream, middle or downstream areas of the field). In the CFI treatment, values corresponding to the wet furrow and the furrow ridge were averaged. In the alternate furrow treatments, values corresponding to the dry and wet furrows and their respective furrow ridges were averaged. Averaging these values may result in estimation errors, since the number of available observations is always limited. It is therefore important to use these spatial averages with some caution.

Results and discussion

The data experimental set produced in this experiment can be downloaded from a public scientific repository (Ebrahimian *et al.*, 2012). The data set contains irrigation advance and recession, soil water and nitrate, inflow and outflow discharge and nitrate concentration, and meteorological data.

Water and nitrate losses

Measured inflow and runoff hydrographs for the three treatments are presented in Fig. 3. The runoff volume was larger for CFI than for AFI or FFI, while the differences between these two treatments were small. The estimated parameters of the Kostiakov-Lewis infiltration equation are presented in Table 2. Both alternate furrow irrigation methods (AFI and FFI) had higher cumulative infiltration than CFI. This was particularly true for the second fertigation event (Fig. 4). Higher infiltration due to more lateral flow in the alternate furrows resulted in lower runoff, as compared to the CFI management strategy (Fig. 3).

Maize water requirements were higher in August than in July. Therefore, a larger volume of irrigation water was applied in the second fertigation than in the first fertigation. This was accomplished through increased discharge and time of cutoff (Table 3). As a consequence, RO_w was higher for the second fertigation than for first fertigation: from 32% to 57% in the case of CFI, and from 23% to 39% in the case of AFI (Table 4). The runoff depth and nitrate mass per unit area for the two alternate furrow treatments were less than the half of the conventional treatment (Table 3). This represents

Table 2. Parameters of Kostiakov-Lewis infiltration equation for the three irrigation strategies in the first and second fertigation events

Fertigation	Irrigation	a	k ($m^2\,min^{-a}$)	f_0 ($m^2\,min^{-1}$)
First	CFI	0.174	0.0035	0.000088
	FFI	0.125	0.0038	0.000106
	AFI	0.137	0.0037	0.000112
Second	CFI	0.066	0.0090	0.000068
	FFI	0.137	0.0061	0.000132
	AFI	0.094	0.0073	0.000140

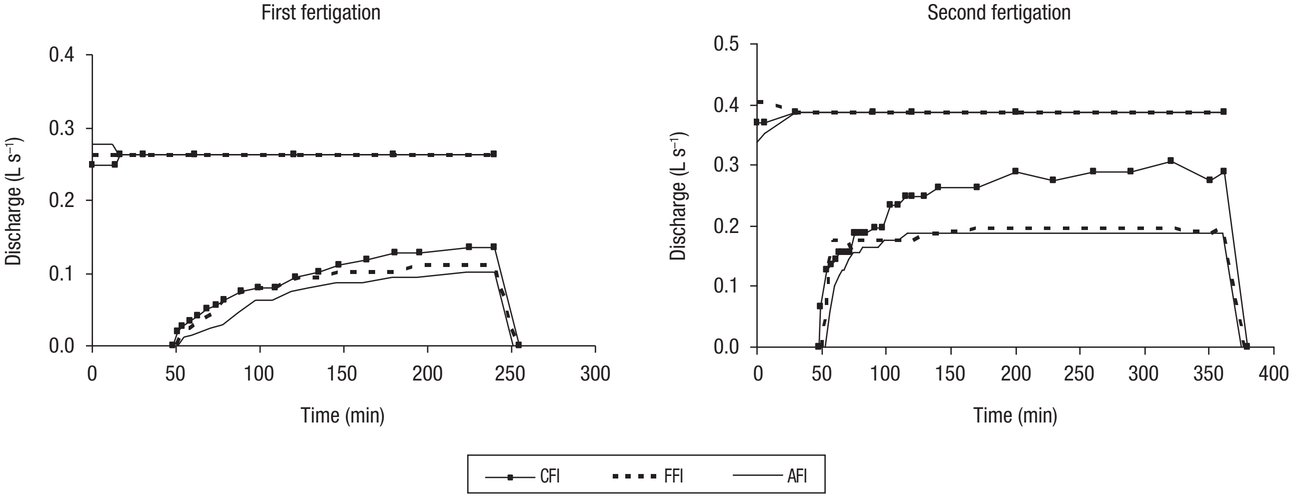

Figure 3. Inflow and runoff hydrographs for the first and second fertigation events.

Table 3. Water depth and nitrate mass of inflow, runoff and infiltration for the two fertigation events and the three irrigation strategies

Fertigation	Irrigation	Water depth (mm)			Nitrate mass (kg m^{-2})		
		Inflow	Runoff	Infiltration	Inflow	Runoff	Infiltration
First	CFI	58.3	18.9	39.4	0.0145	0.0047	0.0098
	FFI	29.2	8.2	21.0	0.0073	0.0023	0.0050
	AFI	29.4	6.8	22.6	0.0073	0.0019	0.0054
Second	CFI	129.6	74.3	55.3	0.0159	0.0070	0.0089
	FFI	65.3	26.9	38.4	0.0080	0.0028	0.0052
	AFI	64.5	25.3	39.2	0.0080	0.0026	0.0054

substantial water and nitrate savings resulting from the implementation of alternate furrow irrigation. E_a was satisfactory in the first fertigation event (between 61% and 77%), but poor in the second fertigation event (between 36% and 61%).

The same mass of fertilizer was applied in both fertigation events (0.857 kg of nitrate per irrigated furrow). Since nitrate concentration in the unfertilized irrigation water changed during the experimental season, the nitrate mass applied in the first and second fertigation events differed (Table 3). Similar to RO_w, RO_N was higher for the second fertigation than for the first fertigation (Table 4). However, differences in RO_N were lower than for RO_w (Table 4). In contrast with the first fertigation, in the second fertigation fertilizer was injected during the first half of the irrigation event, when runoff was low.

Higher water and nitrate losses in the second fertigation are due to higher inflow rate and cutoff time. In the CFI treatment, DP was estimated as 6.31% and 6.30% for the first and second fertigation events, respectively (Table 4). Since the solution of Eq. [2] for AFI and FFI yielded negative values, V_{dp} was set to zero and a lower value of V_{ET} was estimated from Eq. [2]. These results are in agreement with Kang *et al.* (2000b), who reported lower deep percolation in AFI and FFI than in CFI. In this study, deficit irrigation was observed in AFI and FFI when the same irrigation volume used for CFI was applied to two furrows instead of one (Table 4). Our results suggest that both runoff and deep percolation losses can be reduced by implementing alternate furrow irrigation. Slatni *et al.* (2011) obtained the highest and lowest average E_a for FFI (100%) and CFI (72%) for blocked-end furrows, respectively. Horst *et al.* (2007) also showed that alternate furrow irrigation resulted in improved water conservation and increased water productivity. Both alternate furrow strategies decreased water and nitrate runoff losses due to higher infiltration (Table 4, Fig. 4). AFI always resulted in less water and nitrate runoff than FFI, as well as in higher efficiency. Additional experimentation using a statistical experimental design would be required to firmly assess these differences.

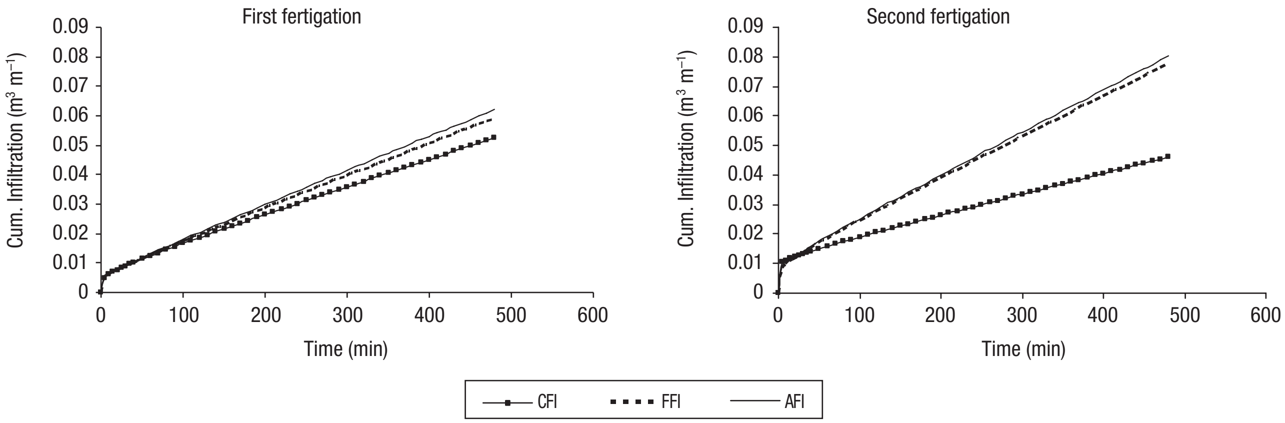

Figure 4. Cumulative infiltration *vs.* opportunity time for three irrigation strategies in the first and second fertigation events.

Table 4. Water balance elements (deep percolation and evapotranspiration), and water and nitrate losses for the two fertigation events and the three irrigation strategies

Fertigation	Irrigation	Water balance		Water			Nitrate
		DP (mm day⁻¹)	*ET* (mm day⁻¹)	RO_w (%)	*DP* (%)	E_a (%)	RO_N (%)
First	CFI	0.5	4.8	32.4	6.3	61.3	32.2
	FFI	0.0	4.1	28.1	0.0	71.8	31.5
	AFI	0.0	4.3	23.2	0.0	77.0	26.0
Second	CFI	1.2	6.6	57.3	6.3	36.4	44.0
	FFI	0.0	6.2	41.2	0.0	58.8	35.0
	AFI	0.0	6.2	39.2	0.0	60.7	32.5

Soil water

Figures 5 to 7 present soil water profiles at wet and dry furrows and at furrow ridges for the day before irrigation, two days after irrigation and six days after irrigation, for the second fertigation event. Similar data were obtained for the first fertigation event (Ebrahimian *et al.*, 2012).

These soil water profiles are relatively uniform, and show limited differences among locations along the field, location in the furrow cross section, wet/dry furrow and fertigation event. For instance, the average water content was 14.7, 14.0 and 13.7% for the upstream, middle and downstream parts of the experimental field of AFI two days after the second fertigation. This uniformity can be explained by crop water

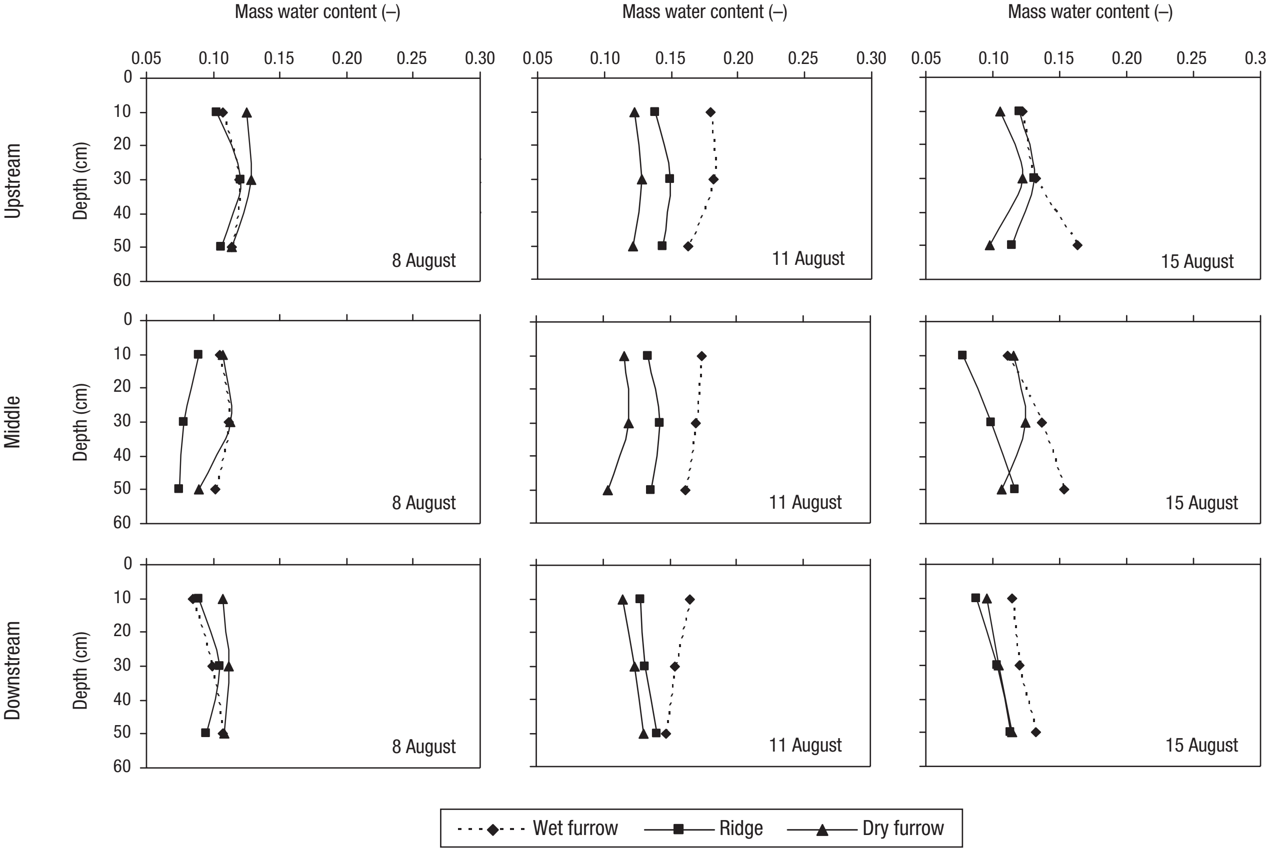

Figure 5. Temporal and spatial distribution of soil water for AFI in the second fertigation event.

extraction during the irrigation interval. Limited drainage (Table 4) also contributes to explain the vertical soil water profile and the reduced spatial variability. The main difference between the two fertigation events was due to progressive depletion of soil water, connected to the reported water stress (Table 4). In the month separating both events, the average soil water (all soil profiles and locations within the field) was reduced from 12.4% to 10.6%. This represents a reduction in soil water from 109 mm to 94 mm, with an average extraction of 15 mm in this 33 day period.

Figure 5 permits to appreciate soil water recharge following the second fertigation event for the AFI treatment. The time lag between soil water measurements was three days (one day before irrigation and two days after irrigation). The dry furrow was slightly affected by irrigation (Figs. 5 and 6). Kang *et al.* (2000b) reported a large difference in matric potential between the wet and dry furrows in an FFI strategy. In this study, similar results were found for AFI and FFI, although the difference in water content between irrigated and non-irrigated furrows was more important in FFI than in AFI.

The reduction in soil water along the field can be related to the differences in opportunity time. For instance, for the first fertigation event, AFI treatment, soil water content following irrigation decreased from 127.0 mm at the upstream end to 120.9 mm at the downstream end. For the same event and locations, the opportunity time was 242 and 206 min, respectively.

Following both fertigation events, the CFI treatment resulted in higher water content along the field than AFI and FFI. Slightly higher water recharge was observed in AFI than in FFI (15.9 *vs.* 15.4 mm for the first fertigation; 24.7 *vs.* 23.7 mm for the second fertigation, respectively). The difference in recharge was attributed to the difference in infiltration evidenced in Fig. 4, and ultimately to the change in irrigated furrow that characterizes the AFI treatment. In fact, before the irrigation event the irrigated furrow of the AFI treatment always showed lower water content than the irrigated

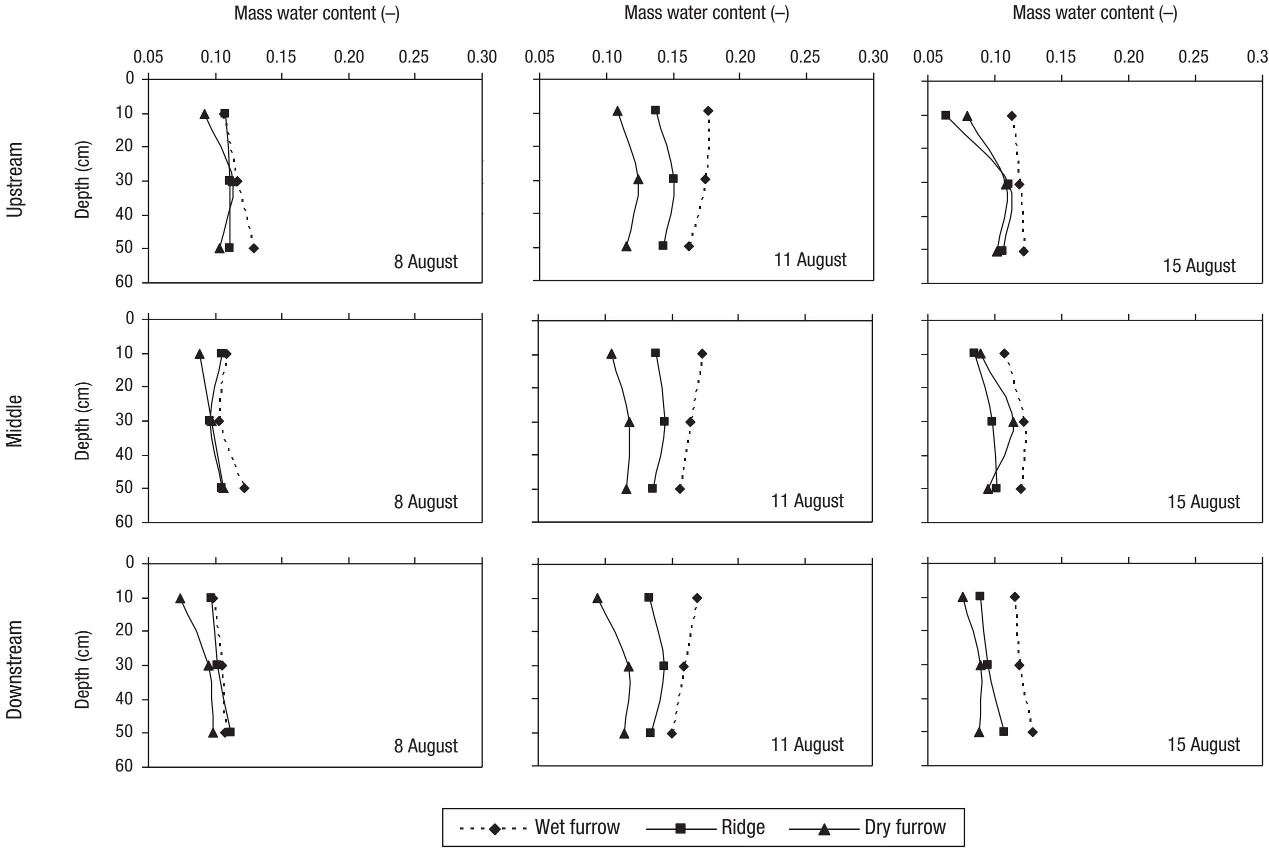

Figure 6. Temporal and spatial distribution of soil water for FFI in the second fertigation event.

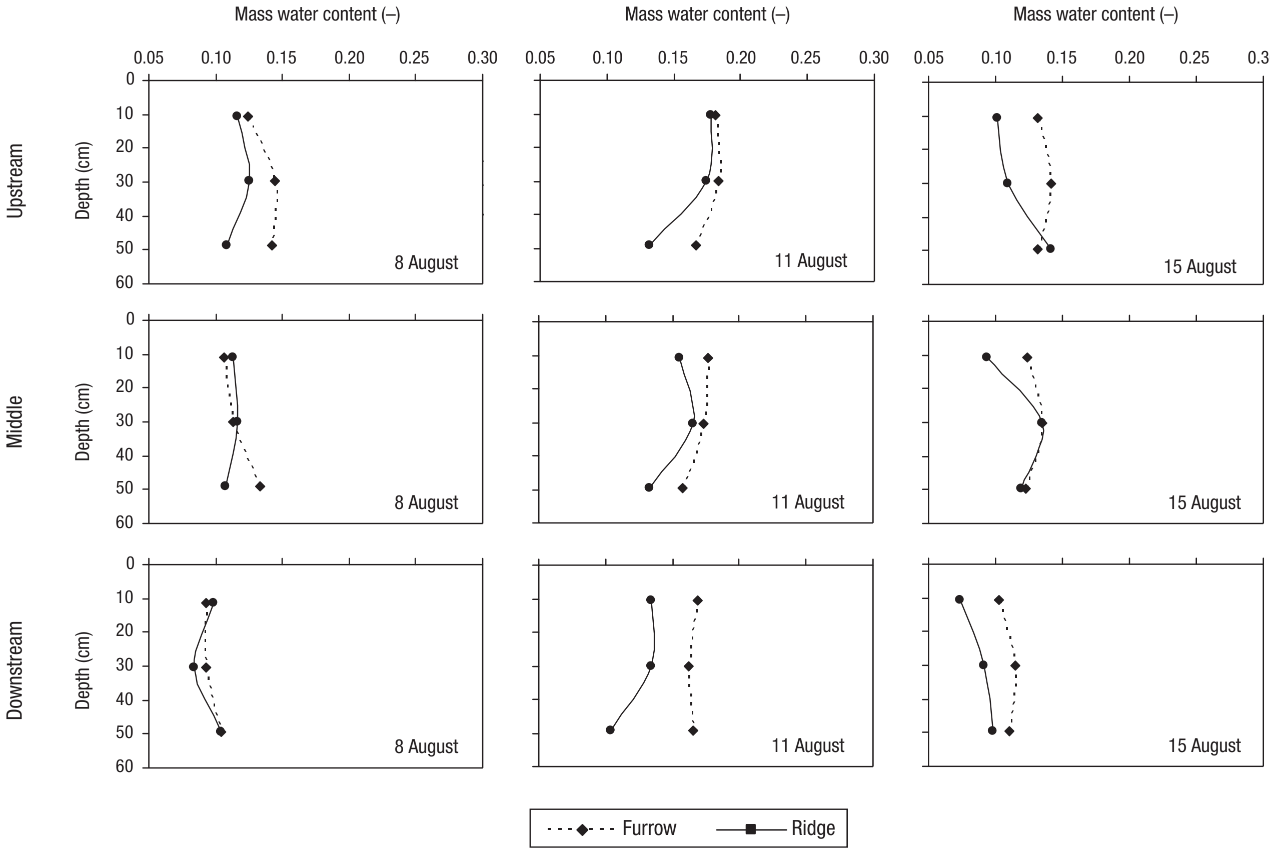

Figure 7. Temporal and spatial distributions of soil water for CFI in the second fertigation event.

FFI furrow. This resulted in increased infiltration for the same opportunity time.

Nitrate concentration

Figures 8 to 11 present soil nitrate profiles for FFI and CFI corresponding to the first and second fertigation events. In the first fertigation event, measurements were taken at three times: one the day before irrigation, one day after irrigation and six days after irrigation. In the second fertigation event, the second measurement time was two days after the irrigation event. Similar results were obtained for AFI (Ebrahimian *et al.*, 2012).

Differences in the soil nitrate profile were expected between fertigation events because of differences in the timing of fertilizer application. In the first fertigation, fertilizer was applied after completion of the advance phase. This situation is expected to result in uniform fertilizer applications, particularly in the presence of runoff (Playán & Faci, 1997). Confirming these expectations, Figures 8 and 9 show a relatively uniform nitrate accumulation in the soil profile along the length of the field. For instance, the average nitrate concentration was 6.1, 5.8 and 5.4 mg L^{-1} for the upstream, middle and downstream parts of the experimental field of AFI two days after the second fertigation. Since fertilizer application ceased late in the irrigation, maxima values of nitrate concentration can be observed at the soil surface one day after the fertigation event. In the second fertigation event, fertilizer application started with irrigation, and lasted for the first half of the irrigation period. Fertilizer infiltration can be much higher at the upstream end than at the downstream end, resulting in uneven fertilizer application. In addition, some unfertilized water infiltrated into the soil following fertilizer infiltration. Comparing both fertigation events, different fertilizer application schemes resulted in quite different horizontal and vertical distributions of nitrate. Differences in nitrate concentration along the field two days after the irrigation event are relevant. In particular, in the second fertigation the peak in nitrate concentration does not happen at the soil surface, but at the intermediate soil layer (0.2-0.4 m).

The figures show a common trait in relations between fertilizer concentration one or two days after the event and six days after the event: nitrate concentration generally increased with time, particularly at the wet furrow and at the soil depth where most fertilizer was received (as compared to the nitrate content the day before fertigation). This finding can be explained by ammonium nitrification in the soil (the biological conversion of NH_4^+ to NO_3^-). Nitrification only occurs under aerobic conditions. As a consequence, its rate increases with decreasing water content and/or increasing soil oxygen (Rodriguez *et al.*, 2005). Therefore, nitrification is particularly important near the soil surface. Hanson *et al.* (2006), analyzing drip fertigation, showed that nitrate concentration throughout the soil profile increased with time —particularly near the drip line— because of the hydrolysis and nitrification of the applied fertilizer. A number of researchers have proved that intense nitrification is more common during warm months. In fact, nitrification has been reported to reach maximum rate at temperatures close to 30°C (U.S. Environmental Protection Agency, 2002). The daily average air temperatures during the weeks of the first and second fertigation events were 31.8°C and 27.8°C, respectively. Time differences in nitrate concentration result from the balance between nitrate leaching, plant uptake and nitrification. More nitrification occurred after the first fertigation event, since fertilizer accumulated at the upper layer (warmer and better oxygenated), and that air temperature was quite high. As a consequence, the differences in nitrate concentration one and six days after the event are clear, particularly at the upper layer (5.5 mg L^{-1} *vs.* 8.3 mg L^{-1} , respectively, for the average of all depths and irrigation strategies. In the second fertigation event, nitrification did not result nearly as relevant, and nitrate concentrations were quite similar two and six days after the fertigation event (6.2 mg L^{-1} *vs.* 6.6 mg L^{-1}, respectively for the average of all depths and irrigation strategies.

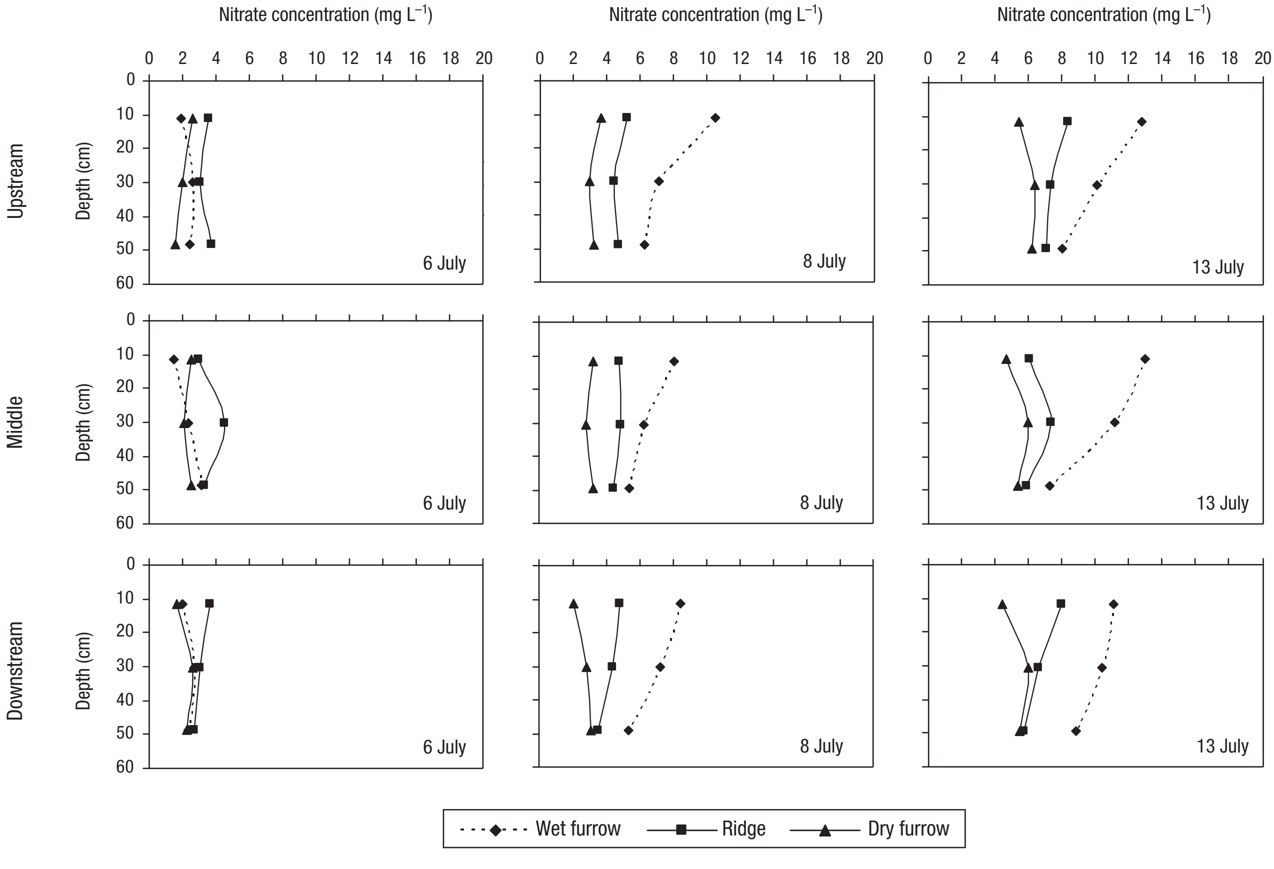

Figure 8. Temporal and spatial distribution of nitrate concentration for FFI in the first fertigation event.

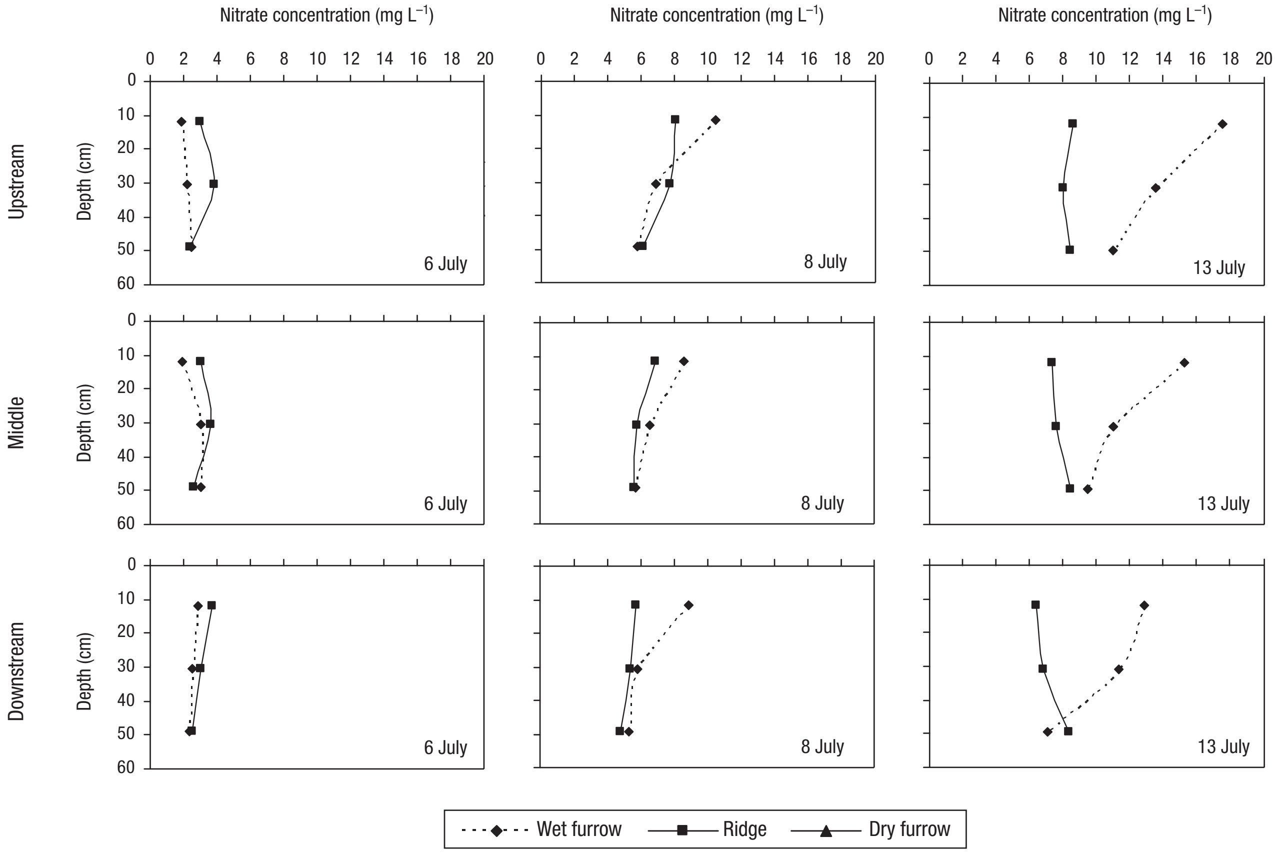

Figure 9. Temporal and spatial distribution of nitrate concentration for CFI in the first fertigation event.

Soil nitrate profiles were relatively similar to those of soil water. Wet furrows stored more water and also more nitrate. Nitrate has high mobility and is transported with water. Since nitrate is negatively charged, it can not be adsorbed to the soil particles (unlike ammonium). Consequently, nitrate followed water inside the soil profile. Nitrate concentration decreased from the wet furrows to ridges and then to the dry furrows.

Soil nitrate concentrations were higher in CFI than in AFI or FFI for both fertigation events. Fertilizer application was equal in all irrigated furrows, and AFI and FFI only irrigated half of the furrows. AFI resulted in somewhat higher nitrate concentrations than FFI. These differences could be related to increased soil water recharge (with fertilized water) in AFI, with respect to FFI. Both soil water and nitrate concentration decreased with distance to the furrow upstream end. Twice as much fertilizer per unit area was applied in CFI than in AFI or FFI. However, in the alternate furrow treatments soil nitrate concentration amounted to much more than half of the concentrations obtained for CFI.

As conclusions, the AFI and FFI strategies were characterized by higher infiltration than CFI. This resulted in decreased water and nitrate runoff losses. On the average of the experimental results, alternate furrow fertigation reduced water runoff from 44% to 33% and nitrate runoff from 38% to 31%. Average nitrate runoff was 33% for FFI and 29% for AFI. Deep percolation losses were estimated at both fertigation events in the CFI treatment (6%), while a certain water stress was determined in AFI and FFI. Alternate furrow irrigation increased application efficiency from 49 to 67%. Average application efficiency was 65% for FFI and 69% for AFI. Even though the amount of applied water and fertilizer per unit of area was doubled in the CFI treatment relative to alternate furrow treatments, soil water and nitrate concentrations in AFI and FFI were much higher than half of the corresponding values in the CFI

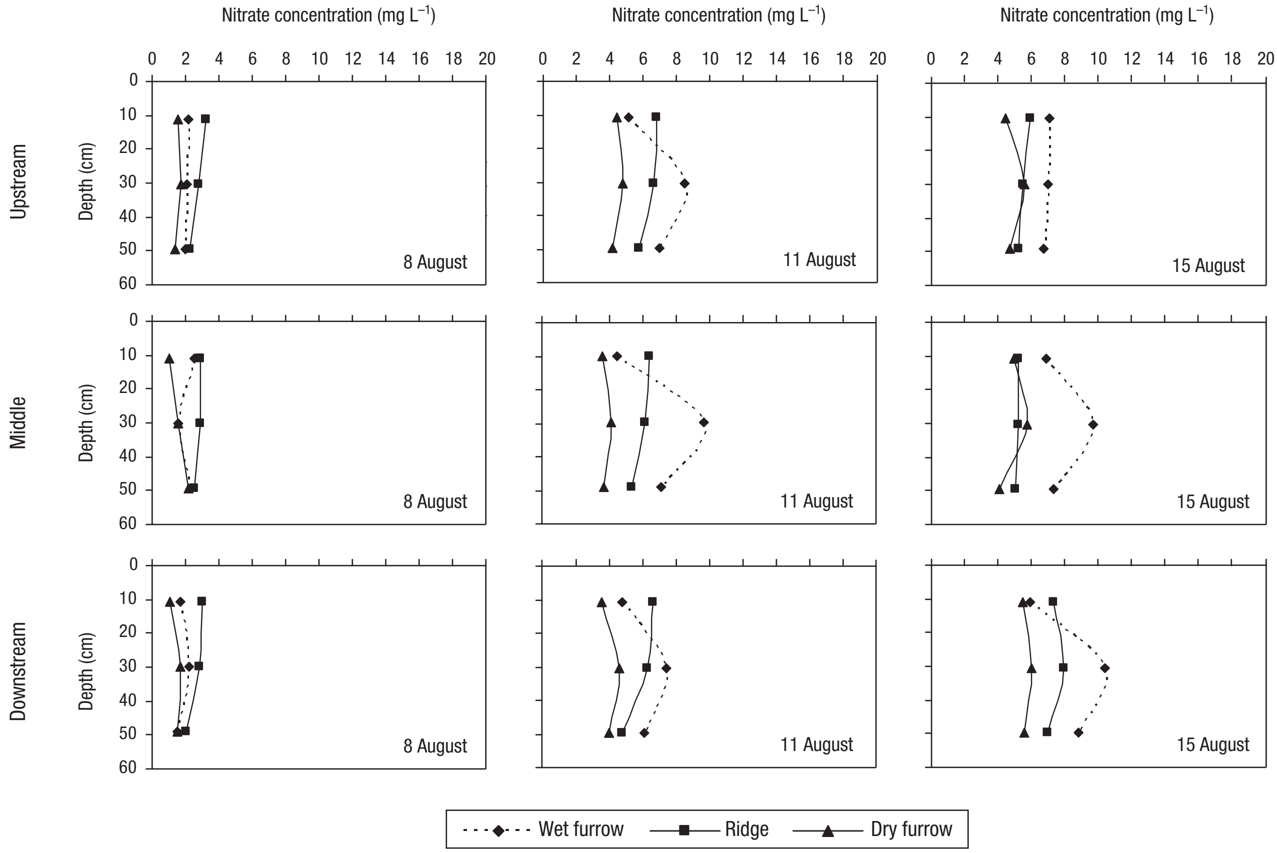

Figure 10. Temporal and spatial distribution of nitrate concentration for FFI in the second fertigation event.

strategy. These results indicate that alternate furrow irrigation has potential to keep more water and nitrate in the root zone due to its increased potential for horizontal movement of water and nitrate. The AFI strategy showed slightly better performance than FFI, regarding water and nitrate losses.

Responding to the reported complexity of furrow fertigation experimentation, a comprehensive data set is disseminated with this paper. The data set is intended to support model development and the identification of best fertigation management practices. Due to the reported differences in furrow infiltration, optimum fertigation parameters for AFI, FFI and particularly CFI will be different, even for the same soil parameters.

Simple irrigation system modifications (irrigating every other furrow), can result in a considerable decrease of water and nitrate runoff losses in agricultural lands. This is particularly relevant in arid and semi-arid regions, where alternate furrow irrigation stands as a practical choice to alleviate water shortages and pollution threats. Since this research is not based on a statistical design and analysis, conclusions regarding the differences between CFI, AFI and FFI can not be considered firm. However, the accumulation of water and nitrate in different amounts and in different areas of the furrow results indicative of differences which can lead to efficient and environmental friendly furrow irrigation systems based on alternate furrow irrigation. Further experimentation will add evidences about these issues, while simulation models will permit to analyze untested parameter combinations.

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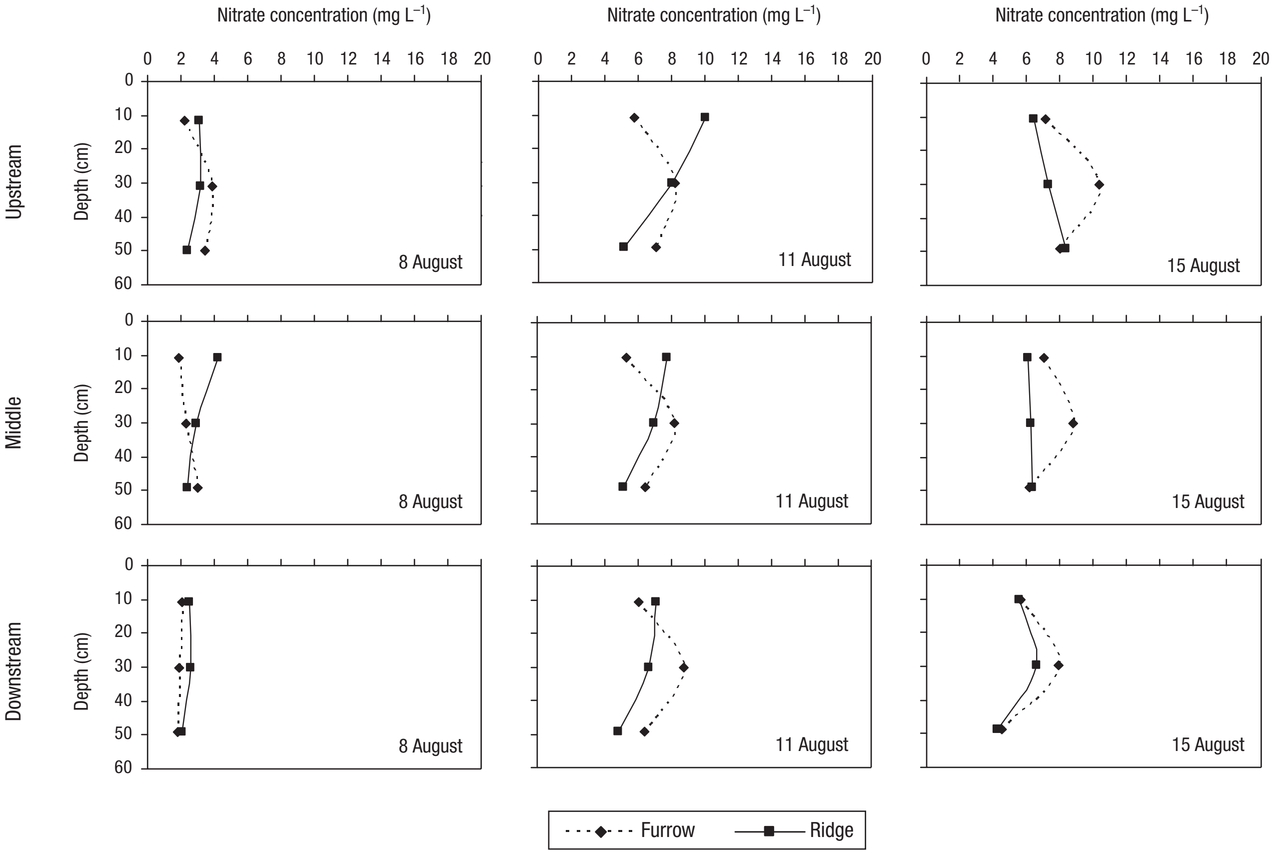

Figure 11. Temporal and spatial distribution of nitrate concentration for CFI in the second fertigation event.

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