Optimum management of furrow fertigation to maximize water and fertilizer application efficiency and uniformity

Abstract

High efficiency and uniformity of water and fertilizer application are usually the ultimate goal of an appropriate design and management of irrigation and fertigation systems. The objective of this paper was to present a simulation-optimization model for alternate and conventional furrow fertigation. This model used two simulation models (surface fertigation and SWMS-2D models) and an optimization approach (genetic algorithm). Inflow discharge, irrigation cutoff time and start time and duration of fertilizer injection were chosen as decision variables to be optimized for maximizing two objective (fitness) functions based on water and nitrate application efficiency and uniformity. Experiments were conducted to collect field data (e.g. soil water content, soil nitrate concentration, discharge and nitrate concentration of runoff and advance and recession times) in order to calibrate the simulation models. The simulation-optimization model indicated that variable and fixed alternate furrow fertigation had higher water and nitrate efficiency than conventional furrow fertigation. However, minor differences were found between these types of furrow irrigation regarding water and nitrate uniformity. This approach substantially improved water and nitrate application efficiency and uniformity compared to experimental conditions. Water and nitrate application efficiency ranged from 72 to 88 % and from 70 to 89 %, respectively. Christiansen uniformity coefficients for water and nitrate varied between 80 and 90 % and between 86 and 96 %, respectively. Higher improvement was observed in conventional furrow fertigation than in both alternate furrow fertigation treatments. The potential of the simulation-optimization model to improve design and management of furrow fertigation is highlighted.

Key words: Furrow fertigation, Optimization, Efficiency, Uniformity, Nitrate

1. Introduction

Agricultural activities have been reported to pollute water resources because of abusing agrochemicals such as fertilizers and pesticides (Ongley, 1996). Over 90 % of the total available water resources in Iran are consumed to irrigate agricultural lands (AQUASTAT, 2008). In this region, surface irrigation is the main irrigation system totalizing more than 90 % of the total irrigated area. Therefore, the correct management of water and fertilizer application is a key factor to control water losses and environmental hazards resulting from pollutants like nitrate and phosphorus. Increasing water and fertilizer efficiency and uniformity is one of the best solutions to reach sustainable agriculture from economical, environmental and social points of view. Surface fertigation has been identified as an interesting technique to achieve this purpose (Playán and Faci, 1997; Abbasi *et al.*, 2003; Burguete *et al.*, 2009; Perea *et al.*, 2011). Fertigation has frequently and effectively been applied in pressurized irrigation systems. However, this practice should be cautiously applied in surface irrigation systems due to the additional requirement of management skills. If surface irrigation design and management are not optimized, large fertilizer losses can be expected.

The governing equations for water flow and solute transport in surface fertigation are not explicit functions of the design variables (such as inflow discharge or fertilizer injection duration). Complex numerical and mathematical models are required to simulate water and fertilizer transfer and to establish the impact of design parameters on performance indexes such as efficiency and uniformity. These models can be built to assist the user in identifying the best set of decision variables. Playán and Faci (1997) presented a mathematical model for border fertigation. They stated that a short duration of fertilizer injection often resulted in low fertilizer distribution uniformity in border fertigation. While developing and validating a mathematical model of furrow fertigation, Sabillon and Merkley (2004) indicated that the fertilizer solution injection start and end times can dramatically affect the efficiency and uniformity of fertilizer application. They ran the proposed model 50,000 times and suggested that the best injection duration ranged from 5 to 15 % of cutoff time in their experimental conditions. Burguete *et al.* (2009) developed a numerical fertigation model for level furrow systems. Simulations proved useful to predict the concentration distribution in time and space for all the fertilizer application possibilities. Perea *et al.* (2011) presented a cross-section averaged advection-dispersion equation model to simulate the transport of fertilizer in furrow irrigation. An evaluation of several fertigation strategies for furrow systems indicated that fertigation by pulses could reduce leaching and runoff losses in surface irrigation systems. Ebrahimian *et al.* (2013) simulated alternate furrow fertigation using the HYDRUS-2D model (Šimůnek *et al.*, 1999) and a surface fertigation model (Abbasi *et al.*, 2003). Combination of these models could adequately predict water flow and nitrate transport on the soil surface and in the soil.

Genetic algorithm (Goldberg, 1989), one of the most popular optimization methods, has been recently applied to optimize design and management of irrigation systems. Nixon *et al.* (2001) used genetic algorithms (GA) to identify water delivery schedules for an open-channel irrigation system. The GA technique efficiently identified the optimal schedule, maximizing the number of orders and minimizing variations in the channel flow rate. Montesinos *et al.* (2001) developed a seasonal furrow irrigation model to maximize net profit. The model used a soil moisture model, an irrigation hydraulic model, a crop yield model and an economic optimization module (using GA). GA could overcome the difficulties in establishing an explicit function relating profit, water depth and flow rate. Soundharajan and Sudheer (2009) proposed a simulation–optimization framework for developing optimal irrigation schedules for a rice crop (*Oryza sativa*) under water deficit conditions. These authors found significant improvements in predicting total yield and water use efficiency. Parviz *et al.* (2010) used different estimation methods to forecast stream flow of Ouromieh River basin in Iran. This research indicated that the genetic algorithm and unconditional likelihood methods are, respectively, more appropriate in comparison with other methods. Jimenez-Bello *et al.* (2011) used hydraulic simulation models with genetic algorithms to improve fertilizer distribution in pressurized irrigation systems. They stated that this approach is a valuable tool to improve central fertigation management and design.

Several researchers have reported that alternate furrow irrigation has a great potential to improve water productivity and reduce water and fertilizer losses as compared to conventional furrow irrigation (Sepaskhah and Afshar-Chamanabad, 2002; Horst *et al.*, 2007; Thind *et al.*, 2010; Ebrahimian *et al.*, 2012). Application of fertigation in alternate furrows can double fertilizer conservation as well as water savings. As stated above, simulation and optimization are elaborated tools to achieve superior design and management of irrigation systems. The objective of this study was to present a simulation-optimization model of furrow fertigation maximizing the product of water and fertilizer efficiency and uniformity. The model was applied to two types of alternate furrow irrigation (variable alternate furrow irrigation, AFI, and fixed alternate furrow irrigation, FFI), as well as to conventional furrow irrigation (CFI) under fertigation practice. Optimization results were compared with experimental results.

2. Materials and methods

2.1. Field experiment

A field experiment was carried out at the Experimental Station of the College of Agriculture and Natural Resources, University of Tehran, Karaj in 2010. The purpose of this experiment was to collect field data on alternate and conventional furrow fertigation, which were used to calibrate the simulation models used in this research. Ebrahimian *et al.*, (2012) presented this experiment in detail, and disseminated the experimental database. A brief description of the experimental conditions follows.

The field study involved two types of alternate furrow irrigation (AFI and FFI), as well as conventional furrow irrigation (CFI). Fertigation practices were performed to satisfy the water and nutrient needs of maize production. Pre-sowing fertilizer application was limited to 10 % of the crop's nitrogen fertilizer requirements (200 kg N ha^{-1}), and was applied a day before sowing (June 9) using a mechanical broadcaster. Three nitrogen dressings (each one amounting to 30% of the fertilizer requirements) were applied at the vegetative (seven leaves, in July 7), flowering (August 9) and grain filling (August 30) stages using surface fertigation. Nitrogen fertilizer was applied in the form of granulated ammonium nitrate. The same amount of water and fertilizer was applied to all irrigated furrows. Thus, the water and fertilizer application rate per unit area were twice as much for conventional irrigation than for the two alternate irrigation treatments.

Soil depth was limited to 0.60 m due to the presence of a gravel layer. The average physical properties of the soil are presented in Table 1. A total of 14 furrows were used in this experimental study (3, 5, and 6 furrows for the CFI, FFI, and AFI treatments, respectively). The properties of the experimental furrows are presented in Table 2. Irrigation was applied on a seven day interval throughout the irrigation season. Water samples at the furrows' inflow and outflow were used to measure nitrate concentration using a spectrophotometer (6705 UV/Vis, Jenway). Auger soil samples were collected at the dry (non-irrigated) and wet (irrigated) furrow beds and ridges in three soil layers (0.0-0.2, 0.2-0.4 and 0.4-0.6 m). Soil water content and nitrate concentration were determined in the soil samples by oven drying at 105ºC and spectrophotometer analysis, respectively, before and after the fertigation events. The parameters of a Kostiakov-Lewis infiltration equation were separately estimated for all irrigation treatments in each fertigation event using the two-point method (Elliott and Walker, 1982). Fertilizer solutions were applied at a constant rate during each fertigation. Irrigation, fertigation and infiltration parameters for each irrigation treatment and for both fertigation events are presented in Table 3. In the first fertigation event, fertilizer injection started at the completion of the advance phase. In the second fertigation event, the fertilizer solution was injected during the first half of the irrigation time.

2.2. Objective function

When designing and managing irrigation/fertigation systems, efficient use of water/fertilizer and optimum crop production are common objectives. Efficiency and uniformity are the most common irrigation/fertigation performance indicators. Considering this, two objective functions were designed to optimize water and fertilizer (nitrate) efficiency and uniformity in alternate and conventional furrow fertigation. The first one was designed to maximize the product of water and nitrate efficiency and uniformity (OF_1). The second one was designed to maximize only the product of nitrate efficiency and uniformity (OF_2).

$$OF_1 = \frac{E_w \times CU_w + E_n \times CU_n}{200} \qquad (1)$$

$$OF_2 = \frac{E_n \times CU_n}{100} \qquad (2)$$

where E_w (%) and E_n (%) are water and nitrate application efficiency, respectively, and CU_w (%) and CU_n (%) are Christiansen uniformity coefficients for water and nitrate, respectively. The maximum value of both objective functions is 100%, implying that perfect efficiency and uniformity of water and fertilizer application was attained.

Water and nitrate runoff (RO_w and RO_n) and deep percolation (DP_w and DP_n) can be estimated as the ratio between the lost and applied nitrate and water. This permits to obtain an estimate of the efficiency associated to water and nitrate application (E_w and E_n, respectively):

$$E_w = 1 - (DP_w + RO_w) \qquad (3)$$

$$E_n = 1 - (DP_n + RO_n) \qquad (4)$$

Deep percolation and runoff were used to determine water and nitrate efficiency. These parameters were estimated using SWMS-2D (Šimůnek *et al.*, 1994) and the surface fertigation model (Abbasi *et al.*, 2003), respectively.

The Christiansen uniformity coefficient was calculated using the following equation (Christiansen, 1941):

$$CU = (1 - \frac{\sum_{i=1}^{n} |x_i - x_{ave}|}{n x_{ave}}) \times 100 \qquad (5)$$

where x_i is ith water/nitrate infiltrated depth and x_{ave} is the mean of the water/nitrate infiltrated depth at n locations along the furrow. The values of CU_w and CU_n were estimated *via* the surface fertigation model.

2.3. Decision variables and constraints

Four important parameters of furrow fertigation (inflow discharge, irrigation cutoff time and start time and the duration of fertigation) were chosen as decision variables to be optimized, due to their significant effects on irrigation and fertigation efficiency and uniformity (Zerihun *et al.*, 1996; Sanchez and Zerihun 2002; Smith *et al.*, 2007). These decision variables are management parameters, and can be easily modified by farmers.

The following constraints involving the decision variables were considered in order to obtain sensible and practical results:

$$q_{\min} \leq q \leq q_{\max} \tag{6}$$

$$t_{\min} \leq t_{co} \leq t_{\max} \tag{7}$$

$$t_s + t_d \leq t_{co} \tag{8}$$

$$E_w \geq 0.4 \tag{9}$$

$$CU_w \geq 0.6 \tag{10}$$

where q, t_{co}, t_s and t_d are inflow discharge (L/s), cutoff time (min) and start time (min), and duration (min) of fertilizer solution injection, respectively. q_{min} and q_{max} are minimum and maximum inflow discharge (L/s), respectively. t_{min} and t_{max} are minimum and maximum cutoff time (min), respectively.

The maximum inflow discharge (q_{max}) was calculated by the following simple empirical function (Booher, 1976):

$$q_{\max} = \frac{0.6}{S} \tag{11}$$

where S is furrow slope (%). The minimum inflow discharge (q_{min}) was assumed to be 10% of q_{max}.

The minimum cutoff time was based on full irrigation at the end of the furrow, and was calculated as the sum of net opportunity time for target application depth (t_{req}) and total advance time (t_l).

$$t_{\min} = t_{req} + t_l \tag{12}$$

Maximum cutoff time was approximated as follows:

$$t_{\max} = t_{\min} + 2t_{req} \tag{13}$$

Restrictions above are flexible and can be modified at the discretion of the user of the optimization software produced in this research, responding to actual field conditions.

2.4. Model development

The simulation-optimization model includes six subprograms: 1. Determination of cutoff time, 2. Surface fertigation simulation, 3. SWMS-2D simulation, 4. Preparation of input files for SWMS-2D, 5. Determination of water and nitrate losses in deep percolation, and 6. Genetic algorithm. All these subprograms were written in the Fortran programming language. Brief descriptions of the different subprograms are presented in the following sections.

2.4.1. Cutoff time

This subprogram was developed to determine the minimum and maximum values of the cutoff time (Eqs. 12 and 13). The cutoff time was calculated based on the approach of the SIRMOD model (Walker, 2003):

2.4.2. Surface fertigation

A combined overland water flow and solute transport model was used for simulation of surface fertigation (Abbasi *et al.*, 2003). The governing equations for water flow were solved in the form of a zero-inertia model of the Saint-Venant's equations. Solute transport was modeled using an advection-dispersion equation. Description of the governing equations of water flow, solute transport, related initial and boundary conditions and numerical solutions can be obtained from Abbasi *et al.* (2003).

The model can simulate different fertigation practices, including free-draining and blocked-end furrows. Input data include furrow geometry, infiltration, roughness, flow, and solute properties. Model outputs include water runoff ratio, nitrate concentration and mass in runoff and the uniformity coefficients of water and nitrate. These variables are used in the present software application to determine the objective function and the constraints to be satisfied. Ebrahimian *et al.* (2013) indicated that this model successfully predicted surface water and nitrate transfer for alternate and conventional furrow fertigation.

2.4.3. SWMS-2D

The 2D water and solute transport model SWMS-2D (Šimůnek *et al.*, 1994) was applied for simulating water and nitrate transfer in the soil. The governing water flow equation is given by the modified form of the Richards' equation. In this study, nitrate transfer was simulated by solving the advection–dispersion equation. The Galerkin finite element method was used to solve this equation, subjected to appropriate initial and boundary conditions

The SWMS-2D model is a previous version of HYDRUS-2D. The governing equations of water flow and solute transport of these models are essentially the same (Šimůnek *et al.*, 1999). During model calibration, the water flow and nitrate transport parameters were estimated by inverse solution, using the Levenberg–Marquardt optimization module in the HYDRUS-2D software (Šimůnek *et al.*, 1999) because SWMS-2D does not have this module for inverse solution. The SWMS-2D model was separately calibrated at the upstream, middle and downstream furrow sections for each irrigation treatment using the calibrated parameters estimated by the inverse solution of HYDRUS-2D. The method for calibrating, validating and defining initial/boundary conditions of HYDRUS-2D in the specific conditions of this problem was presented by Ebrahimian *et al.* (2013). The method for defining initial/boundary conditions used in SWMS-2D and HYDRUS-2D was the same.

2.4.4. Generating input files for SWMS-2D

The SWMS-2D model needs three input files containing the soil water retention curve, the number of soil layers, plant uptake, the solute transport parameters, the flow domain geometry, the initial values of soil water and nitrate content, the boundary conditions, evaporation, transpiration, rainfall, nitrate concentration of irrigation water, start time and duration of fertilizer solution injection, cutoff time, irrigation interval and water depth/infiltration rate in furrow. The input files are updated during the optimization process. Therefore, this subprogram modified input data such as start time and duration of fertilizer solution injection, cutoff time and water depth in furrow each time the decision variables were updated by the genetic algorithm. The subprogram generates the input files for the upstream, middle and downstream furrow sections, in accordance with the advance and recession times. Soil water and solute flow in each furrow were simulated at these three sections, in an effort to characterize the effect of irrigation variability on the soil.

2.4.5. Water and nitrate losses in deep percolation

The average value of water and nitrate losses to deep percolation along the furrow was used for calculating water and nitrate efficiency. This subprogram used SWMS-2D output. The mean of water/nitrate deep percolation was calculated by averaging it at the upstream, middle and downstream of the field. The spatial domain was defined as the depth of the root zone (0.60 m). The temporal domain was defined as the irrigation interval (7 days) in the SWMS-2D model.

2.4.6. Genetic algorithm

A genetic algorithm (GA) is a search/optimization technique based on reproducing the mechanisms of natural selection. Successive generations evolve and generate more fit individuals based on Darwinian survival of the fittest. The Carroll FORTRAN GA (Carroll, 1996) is a computer simulation of such evolution where the user provides the environment (function) in which the population must evolve. This software release includes conventional GA concepts in addition to jump/creep mutations, uniform crossover, niching and elitism. The scheme used in this research was "tournament selection", with a shuffling technique for choosing random pairs for mating. This program initializes a random sample of individuals with different parameters to be optimized using the genetic algorithm approach. In order to obtain fast convergence and a global optimum value, it is important to choose adequate values of the population size, the number of generations and the crossover and mutation probabilities. The respective values of these parameters were set to 200, 200, 0.5 and 0.01, respectively, following Carrol (1996) and Praveen *et al.* (2006).

2.5. Optimization process

The different simulation models were linked to the genetic algorithm in order to optimize the decision variables (q, t_{co}, t_s and t_d), by maximizing the objective functions. The optimum set of decision variables must satisfy all constraints.

The flowchart of the simulation-optimization model is presented for the first objective function in Figure 1. First, the initial population (containing values of the decision variables for each individual) is generated. Then, the simulation models are executed for each individual and the values of the objective function are determined regarding calculated water and nitrate application efficiency and uniformity. The convergence criterion (the number of generations) is checked. If this criterion is satisfied, the model stops. Otherwise, three genetic algorithm operators (selection, crossover and mutation) are executed to produce a new generation (characterized by new individual values of the decision variables).

The model was run in a cluster of 28 high-performance processors using the Linux operative system located at the Fluid Mechanics Area of the University of Zaragoza. The processing speed of each processor is 2.80 GHz. Consequently, the compound processing speed of the cluster is 78.4 GHz. The code was parallelized to exploit the computing power of the cluster and to reduce the computational time.

The model was run for six times (three irrigation treatments times two fertigation events) for each objective function. Each run explored 40,000 different sets of values of the decision variables (the population size multiplied by the number of generations). If the set of decision variables satisfied the constraints, the SWMS-2D and surface fertigation models were run three times (once at each of the three locations: upstream, middle and downstream furrow sections) and one time, respectively. In one of the cluster processors, the SWMS and surface fertigation models required execution times of 10-20 and 10-120 s, respectively, depending on the values of the decision variables and on the irrigation treatment. Computational time was larger for alternate furrow irrigation than for conventional furrow irrigation, owing to the flow domain requirements in SWMS-2D.

2.6. Calibration of simulation models

The values of the estimated parameters for calibrating SWMS-2D resulted in a minimum error between observed and simulated values of soil water content and nitrate concentration (Ebrahimian *et al.*, 2013). Given the measurements of the advance data and basic infiltration rate (steady-infiltration rate) in the experimental field, the infiltration parameters were estimated to calibrate the surface fertigation model. Relative Error (*RE*) was calculated for assessing the estimated infiltration parameters:

$$RE = \frac{(P_i - M_i)}{M_i} * 100 \quad (14)$$

where P_i and M_i are the predicted and measured values of total infiltrated volume, respectively. The average relative error for estimating the total infiltrated volume was lower than 4% for all irrigation treatments and fertigation events. The surface fertigation and SWMS-2D models are run separately. The assumption behind this study was that the infiltration calculated with the extended Kostiakov equation was very similar to SWMS-2D results. For instance, the total estimated infiltrated volume of variable alternate furrow irrigation was 2.875 and 2.878 m^3 for the surface fertigation and SWMS models, respectively. Both figures are very close to the measured value in the first fertigation (2.905 m^3).

Calibration and validation of the simulation models showed that these models could successfully simulate water and nitrate transport (Ebrahimian *et al.*, 2013). Using these calibrated models to develop the optimization model, an optimal fertigation strategy would be determined. Thus, the optimization model could conceptually support fertigation management.

3. Results and discussions

3.1. Field results

Table 4 presents the values of both objective functions for the three irrigation treatments. Objective functions were calculated using the output of the simulation models under field conditions (without the optimization process). AFI showed greater values of OF_1 and OF_2 than FFI and CFI in the first and second fertigation events. CFI had the lowest values of OF_1 and OF_2 as compared to others, particularly in the second fertigation. All irrigation treatments had high values of CU_w and CU_n (> 93 %) in the first and second fertigation events. Full irrigation at the downstream end of the field to obtain complete irrigation adequacy (Walker and Skogerboe, 1987), short experimental furrows and relatively fine soil texture resulted in high distribution uniformity of water and fertilizer. E_w was larger than E_n in all cases. CFI caused larger nitrate and water losses relative to the alternate furrow irrigation treatments, particularly in the second fertigation due to higher infiltration rate in alternate furrows than in conventional furrows. In this respect, AFI showed better performance than FFI. The values of E_w and E_n in the second fertigation were lower than in the first event. This phenomenon indicated that in the first fertigation event the irrigation and fertigation parameters were adequately chosen. This resulted in lower water and nitrate runoff losses than in the second fertigation (Ebrahimian *et al.*, 2012). However, only small differences were found between both fertigation events from the viewpoint of CU_w and CU_n. For this reason, higher values of the objective functions were obtained in the first fertigation than in the second.

3.2. Optimization results

The maximum values of the first and second objective functions were substantially higher than the values obtained under field conditions (Tables 5 and 6). Optimization increased OF_1 by

27.2, 30.2 and 46.1 % in the first fertigation and by 48.3, 50.5 and 138.6 % in the second fertigation, in comparison with the experimental values, and for the AFI, FFI and CFI treatments, respectively. Optimization also increased OF_2 by 48.2, 65.9 and 68.2 % in the first fertigation and by 73.6, 90.2 and 202.0 % in the second fertigation, in comparison with the experimental values, and for the AFI, FFI and CFI treatments, respectively. The simulation-optimization model showed a great potential to improve furrow fertigation management, particularly for the CFI treatment.

AFI showed the highest values of the objective functions, as compared to FFI and CFI. Similar to field conditions, optimum CFI resulted in the lowest values of OF_1 and OF_2. AFI and FFI showed small differences in the second fertigation. The same result was found between FFI and CFI in the first fertigation. Similar to field results, the alternate furrow irrigation treatments resulted in higher values of E_w and E_n, as compared to the CFI treatment.

The model chose low values of inflow discharge and large values of cutoff time to considerably reduce runoff losses and consequently increase water and nitrate efficiency. This was more obvious for the CFI treatment, since it showed low water and nitrate efficiency under field conditions. Different sets of optimum decision variables were obtained for each irrigation treatment. This could be related to different infiltration characteristics in alternate furrows relative to conventional furrows. A higher infiltration rate in alternate furrows resulted in higher optimum inflow discharge in AFI and FFI than in CFI (Tables 5 and 6). Therefore, the cutoff time was higher in CFI than in AFI and FFI for both fertigation events. The optimum values of t_s and t_d obtained in both objective functions were generally higher than the field values for all irrigation treatments and fertigation events. In fact, increasing the duration of fertilizer solution injection could reduce nitrate losses. Playán and Faci (1997) stated that maximum uniformity could be often obtained under the application of fertilizer during the entire irrigation event in blocked-end borders and level basins. Abbasi *et al.* (2003) reported that fertilizer application in the first and second halves of irrigation increased fertilizer application efficiency and fertilizer uniformity, respectively, for blocked-end and free draining furrows.

E_w and E_n ranged from 72 to 88 % and from 70 to 89 %, respectively. The values of CU_w varied between 80 and 90 %, while CU_n ranged between 86 and 96 %. CU_n was larger than CU_w in all irrigation treatments and fertigation events, while the values of E_w were similar to E_n in all cases. Optimization resulted in a small reduction in *CU* and a considerable increase in efficiency for both water and nitrate, as compared to experimental conditions. Therefore, the combination of uniformity coefficient and efficiency produced higher values of both the objective functions.

The variations of the first and second objective functions for each generation are presented for all irrigation treatments in Figures 2 and 3, respectively. This graphical comparison also showed that the AFI and CFI treatments had the highest and lowest values of both the objective functions, respectively. As seen in these figures, the values of OF_1 and OF_2 strongly changed during the first generations. Gradual and small variations could be observed in the next generations, until the optimization solution converged to constant and final value. Differences between the values of the objective functions decreased with increasing generations. Adequate convergence of the simulation-optimization model was observed in all cases.

In all cases, water and nitrate efficiency generally increased and uniformity coefficient of water decreased with increasing generations (Figures 4 and 5). The uniformity coefficient of nitrate did not show a clear trend: it increased in some cases and decreased in other cases. Similar trends were observed for E_w and E_n, indicating that nitrate was transferred by flowing water, due to high solubility of nitrate in water.

The most important performance problem under field conditions was low water and nitrate efficiency. Thus, the simulation-optimization model selected values of the decision variables that strongly increased water and nitrate efficiency and moderately reduced water and nitrate uniformity. As a consequence, both the objective functions were maximized. It was impossible to simultaneously maximize efficiency and uniformity due to the interaction between these two performance indices. Feyen and Zerihun (1999), and Jurriens *et al.* (2001) indicated that irrigation efficiency and uniformity decreased and increased with increasing inflow discharge (or decreasing cutoff time), respectively. This study confirmed these findings for fertigation as well. In fact there, a trade-off was found between efficiency and uniformity for both irrigation and fertigation practices, which nevertheless permitted to maximize the objective functions.

Conclusions

A simulation-optimization model was presented for the optimum management of alternate and conventional furrow fertigation. Two objective functions were considered for maximization, based on water and nitrate application efficiency and uniformity. The optimum values of the decision variables could substantially improve water and nitrate efficiency as compared to the experimental results. Ranges of water and nitrate application efficiency were 72-88 % and 70-89 %, respectively. While these values varied between 33.6 and 70.5 % and 21.1 and 60.3 %, respectively, under field conditions. Small reductions in the values of water and nitrate uniformity were found due to the increase in water and nitrate efficiency. A trade off was observed between these two performance indices. The model opted to decrease inflow discharge due to a high potential of the experimental furrows in producing runoff losses. Higher values of irrigation cutoff time and fertilizer injection duration were chosen in all irrigation treatments and fertigation events.

Simulation-optimization results proved that variable and fixed alternate furrow fertigation treatments had lower water and nitrate losses than conventional furrow fertigation. However, minor differences were found between irrigation treatments in water and nitrate uniformity. Results also indicated that optimum decision variables in alternate furrow fertigation are different from conventional furrow fertigation.

The model strongly increased both objective functions as compared to experimental conditions, particularly for the CFI treatment. The simulation-optimization model stands as a robust approach to identify optimum furrow fertigation strategies in order to control environmental hazards from agricultural pollutants and increase water and fertilizer productivity.

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Table 1. Soil physical properties of the experimental field

Depth (m)	Soil texture classification	Soil particles (%)			Bulk density (Mg m^{-3})	Organic matter (%)
		Clay <0.002 mm	Silt 0.002-0.05 mm	Sand 0.05-2 mm		
0.0-0.2	Clay loam	31.0	31.7	37.3	1.51	1.83
0.2-0.4	Loam	26.8	30.4	42.8	1.48	1.18
0.4-0.6	Sandy loam	20.2	24.6	55.3	1.49	0.68

Table 2. Properties of the experimental furrows

Length (m)	Spacing (m)	Slope (%)	Top width (m)	Middle width (m)	Bottom width (m)	Maximum height (m)
86.0	0.75	0.0093	0.456	0.278	0.094	0.103

Table 3. Irrigation, fertigation and infiltration parameters for the three irrigation treatments in the first and second fertigation events.

Fertigation	Irrigation treatment	*Inflow discharge, Q* (Ls^{-1})	*Cutoff time,* t_{co} (min)	*Injection start time,* t_s (min)	*Injection duration,* t_d (min)	*Kostiakov-Lewis infiltration parameters*		
						a (-)	*k* (m^2/min^a)	f_0 (m^2/min)
First	CFI	0.262	240.0	48.2	150.0	0.174	0.0035	0.000088
	FFI	0.262	240.0	49.7	150.0	0.125	0.0038	0.000106
	AFI	0.262	240.0	51.3	150.0	0.137	0.0037	0.000112
Second	CFI	0.388	360.0	0.0	180.0	0.066	0.0090	0.000068
	FFI	0.388	360.0	0.0	180.0	0.137	0.0061	0.000132
	AFI	0.388	360.0	0.0	180.0	0.094	0.0073	0.000140

Table 4. The values of the objective functions and the outputs of the simulation models for field condition.

	First fertigation			Second fertigation		
	AFI	FFI	CFI	AFI	FFI	CFI
Objective function						
OF_1* (%)	61.7	52.0	46.0	52.0	49.3	26.4
OF_2 (%)	57.5	45.1	42.2	46.9	42.9	20.3
Simulation outputs						
CU_w (%)	93.6	94.0	94.1	95.5	96.1	96.7
CU_n (%)	95.3	96.8	93.9	94.2	94.6	96.0
E_w (%)	70.5	62.6	53.0	59.8	57.9	33.6
E_n (%)	60.3	46.6	44.9	49.8	45.4	21.1

* OF_1 and OF_2 are the first and second objective functions; CU_w and CU_n are water and nitrate Christiansen uniformity coefficients, respectively; E_w and E_n are water and nitrate application efficiency, respectively.

Table 5. Maximum first objective function, optimum decision variables and the outputs of the simulation models.

	First fertigation			Second fertigation		
	AFI	FFI	CFI	AFI	FFI	CFI
Objective function						
OF_1^* (%)	78.5	67.7	67.2	77.1	74.2	63.0
Decision variables						
q (L s^{-1})	0.184	0.174	0.158	0.222	0.228	0.127
t_{co} (min)	304.4	319.0	381.6	396.4	412.8	723.7
t_s (min)	68.8	79.8	63.3	125.6	119.7	63.0
t_d (min)	217.9	136.7	159.9	244.6	159.5	298.0
Simulation outputs						
CU_w (%)	84.3	85.1	87.6	82.7	87.6	90.0
CU_n (%)	94.0	91.6	89.6	93.5	90.5	86.4
E_w (%)	87.6	73.5	73.2	88.4	84.7	71.8
E_n (%)	88.5	79.4	78.5	87.0	82.0	71.2

* OF_1 is the first objective function; q, t_{co}, t_s and t_d are inflow discharge, irrigation cutoff time and start time and duration of fertilizer injection, respectively; CU_w and CU_n are water and nitrate Christiansen uniformity coefficients, respectively; E_w and E_n are water and nitrate application efficiency, respectively.

Table 6. Maximum second objective function, optimum decision variables and the outputs of the simulation models.

	First fertigation			Second fertigation		
	AFI	FFI	CFI	AFI	FFI	CFI
Objective function						
OF_2^* (%)	85.2	74.8	71.0	81.4	81.6	61.3
Decision variables						
q (L s^{-1})	0.175	0.167	0.147	0.216	0.214	0.120
t_{co} (min)	347.7	343.7	425.1	425.7	413.7	775.1
t_s (min)	126.0	123.1	125.7	166.8	137.7	105.5
t_d (min)	221.3	212.9	220.6	227.7	274.0	312.2
Simulation outputs						
CU_w (%)	80.8	81.6	83.5	80.1	82.1	88.8
CU_n (%)	95.5	95.2	92.7	93.6	94.3	87.2
E_w (%)	87.7	74.3	74.1	88.0	88.1	73.0
E_n (%)	89.2	78.5	76.6	86.9	86.6	70.3

* OF_2 is the second objective function; q, t_{co}, t_s and t_d are inflow discharge, irrigation cutoff time and start time and duration of fertilizer injection, respectively; CU_w and CU_n are water and nitrate Christiansen uniformity coefficients, respectively; E_w and E_n are water and nitrate application efficiency, respectively.

Figure 1. Flowchart of the simulation-optimization model for the first objective function.

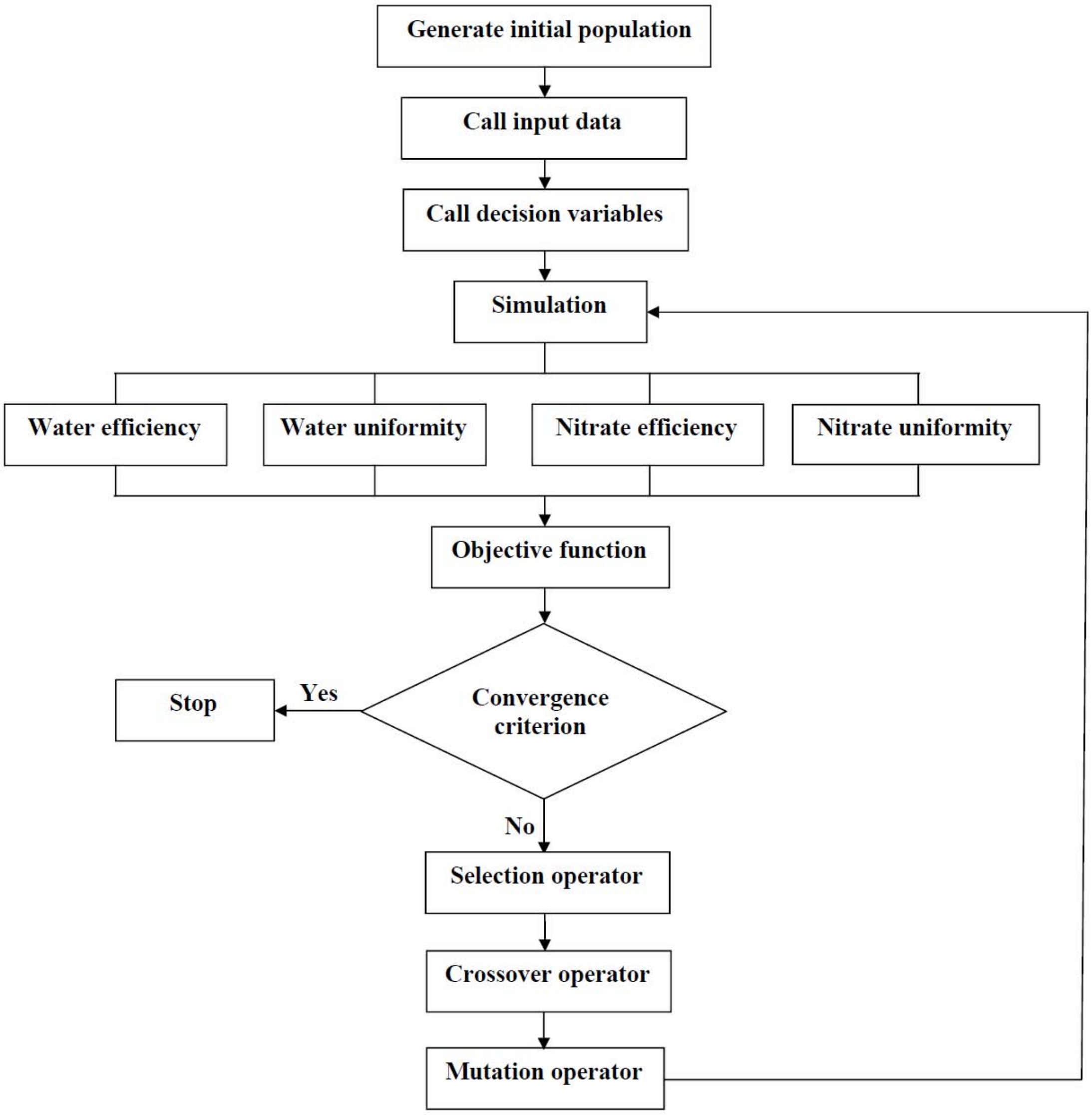

Figure 2. Evolution of the first objective function (OF_1) for each generation in the first and second fertigation.

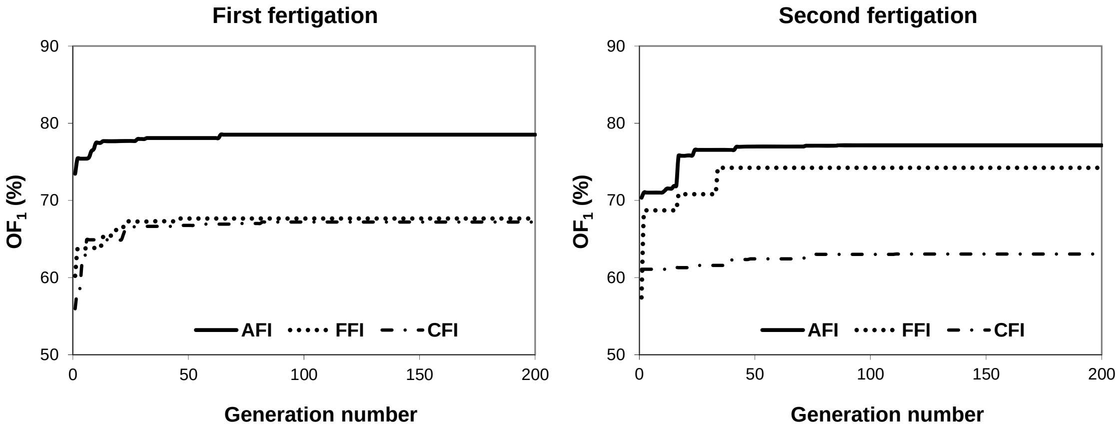

Figure 3. Evolution of the second objective function (OF_2) for each generation in the first and second fertigation.

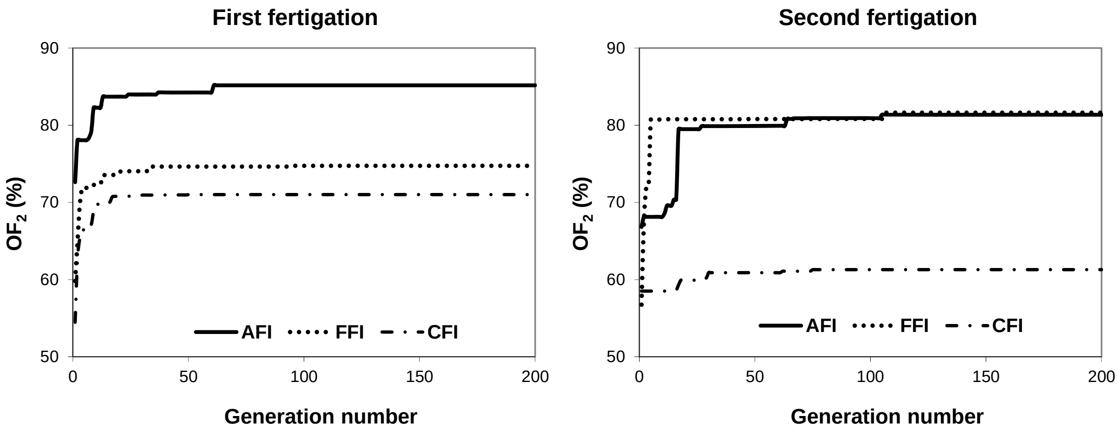

Figure 4. Water and nitrate efficiency and uniformity for each generation of the first objective function (OF_1) in the first and second fertigation**.**

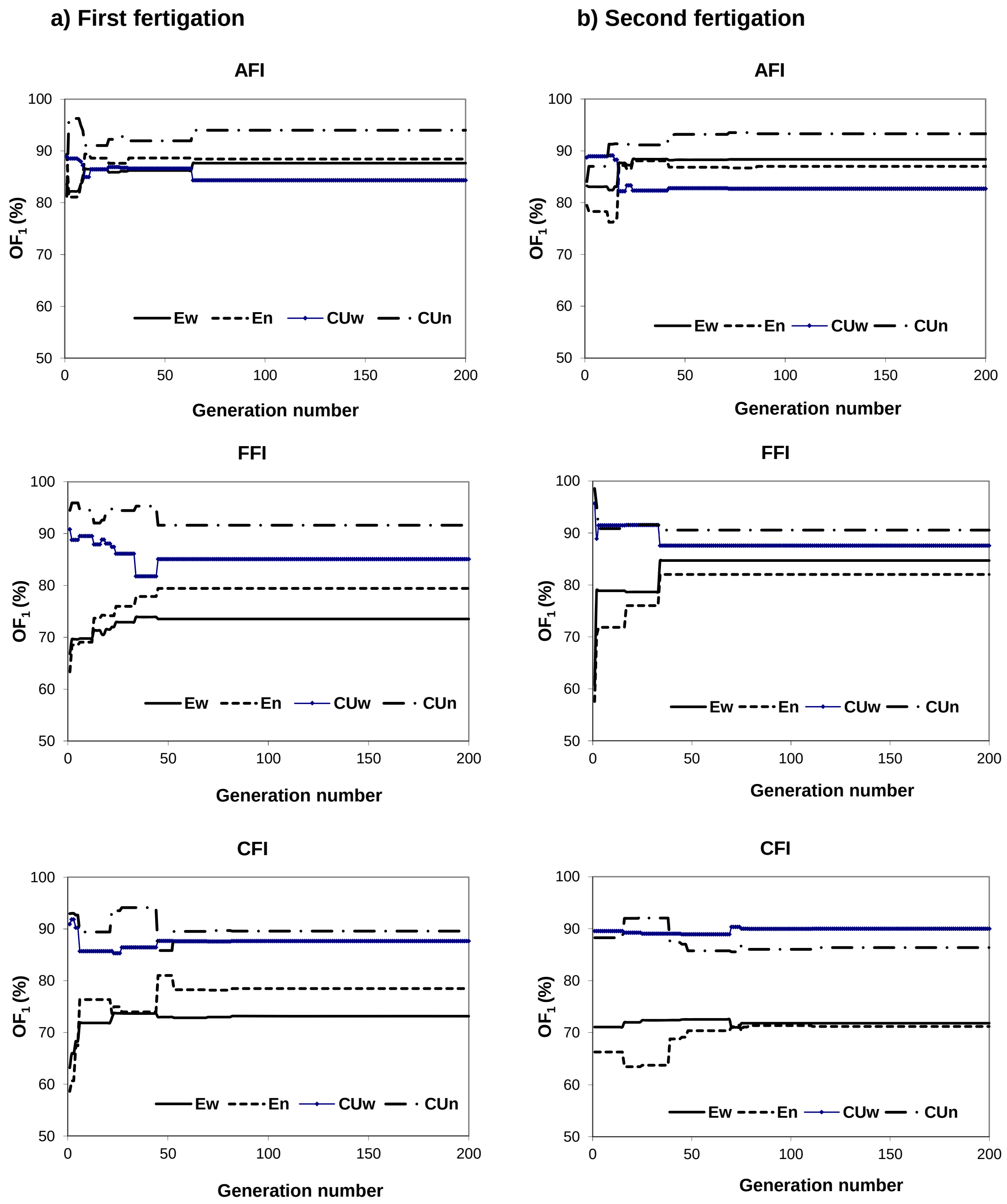

Figure 5. Water and nitrate efficiency and uniformity for each generation of the second objective function (OF_2) in the first and second fertigation.