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Optimum Management of Furrow Fertigation to Maximize Water and Fertilizer Application Efficiency and Uniformity

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ABSTRACT

High efficiency and uniformity of water and fertilizer application are usually, considered as the ultimate goals of an appropriate design and management of irrigation and fertigation systems. The objective followed in this paper was to present a simulation-optimization model for alternate *vs.* conventional furrow fertigation. Two simulation models (surface fertigation and SWMS-2D models) along with an optimization approach (genetic algorithm) were employed. Inflow discharge, irrigation cutoff and start times as well as 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 plus uniformity. Experiments were conducted to collect field data (soil water content, soil nitrate concentration, discharge and nitrate concentration in runoff, as well as advance and recession times) in order to calibrate the simulation models. The simulation-optimization model indicated that variable and fixed alternate furrow fertigations benefited from higher water and nitrate efficiencies than the conventional furrow fertigation. However, minor differences were observed between these types of furrow irrigation regarding water and nitrate uniformity. This approach substantially improved water and nitrate application efficiency as well as uniformity, taking into account the field experimental conditions. Water and nitrate application efficiencies ranged from 72 to 88% and from 70 to 89%, respectively. Christiansen uniformity coefficients for water and nitrate varied between 80 and 90% and from 86 to 96%, respectively. A higher improvement was observed in conventional furrow fertigation than those in both alternate furrow fertigation treatments. The potential of the simulation-optimization model to improve design and management of furrow fertigation is highlighted.

Keywords: Efficiency, Furrow fertigation, Nitrate, Optimization, Uniformity.

INTRODUCTION

Agricultural activities have been reported to pollute water resources because of misusage of such agrochemicals as fertilizers and pesticides (Ongley, 1996). Over 90 % of the total available water resources in Iran goes to irrigate agricultural lands (Aquastat, 2008). In here, surface irrigation is the main irrigation system covering more than 90% of the total irrigated land. Therefore, a correct management of water and fertilizer application is the key to control water losses and prevent environmental hazards resulting from pollutants introduction of such as nitrate and phosphorus. Increasing water and fertilizer efficiency along with uniformity of application are some of the proper solutions to reach sustainable agriculture from economical, environmental and social points of view. Surface fertigation has been

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identified as an interesting practical 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 such performance indexes as efficiency and uniformity. These models can be built to assist the user in identifying the most appropriate 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 as 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 within the frameworks of time and space for all the fertilizer application possibilities. Perea *et al.* (2011) presented a cross-sectional 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). A combination of these models could adequately predict water flow and nitrate transport on the soil surface and as well 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 benefits from a great potential to improve water productivity, reducing water and fertilizer losses as compared with 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 followed in the present study was to present a simulation-optimization model of furrow fertigation that maximizes the product of water and fertilizer efficiency and uniformity. The model was applied to two types of alternate furrow irrigations [variable Alternate Furrow Irrigation (AFI), and Fixed alternate Furrow Irrigation (FFI)], and as well to Conventional Furrow Irrigation (CFI) under fertigation practice. Optimization results were compared with the experimental results.

MATERIALS AND METHODS

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 was to collect field data on alternate and conventional furrow fertigation, employed to calibrate the simulation models used in the present 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 a maize crop 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 requirement) 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 quantities of water and fertilizer were applied to all the irrigated furrows. Thus, the water and fertilizer application rates per unit area were twice as much for conventional irrigation as for either of the two alternate irrigation treatments.

Soil depth was limited to 0.60 m due to the presence of a gravel layer. The average figures for the physical properties of the soil are presented in Table 1. A total of 14 furrows were employed in the study (3, 5, and 6 furrows for the CFI, FFI, and AFI treatments, respectively). The data related to 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 taken to measure the nitrate concentration using a spectrophotometer (6705 UV/Vis, Jenway). Auger soil samples were collected at the dry

Table 1. Physical properties of the experimental field soil.

Depth (m)	Soil texture	Soil particles (%) Clay < 0.002 mm	Silt 0.002-0.05 mm	Sand 0.05-2 mm	Bulk density (Mg m^{-3})	Organic matter (%)
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

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Table 2. Numerical 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

(non-irrigated) and wet (irrigated) furrow beds and ridges within three soil layers (0.0-0.2, 0.2-0.4 and 0.4-0.6 m). Soil water content and nitrate concentrations were determined for the soil samples by oven drying at 105ºC and through spectrophotometric analysis, respectively, prior to, and following the fertigation events. The parameters of a Kostiakov-Lewis infiltration equation were separately estimated for all the 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.

Objective Function

In the design and planning for the proper management of the irrigation/fertigation systems, efficient use of water/fertilizer along with optimum crop production are the common objectives. Efficiency and uniformity are among the most common irrigation/fertigation performance indicators. Having this in mind, two objective functions were designed to optimize water and fertilizer (nitrate) efficiencies, as well as uniformity in alternate *vs.* conventional furrow fertigation. The first one was designed to maximize the interaction of water and nitrate efficiencies, and uniformity (OF_1), while the second one designed to maximize the interaction of nitrate efficiency and uniformity only (OF_2).

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

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

Where, E_w (%) and E_n (%) are water and nitrate application efficiencies, respectively, and CU_w (%) and CU_n (%) 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)

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

Fertigation	Irrigation treatment	Inflow discharge (Q) ($L\ s^{-1}$)	Cutoff time (t_{co}) (Min)	Injection start time, (t_s) (Min)	Injection duration (t_d) (Min)	Kostiakov-Lewis infiltration parameters		
						a (-)	k ($m^2\ min^{-1a}$)	f_0 ($m^2\ min^{-1}$)
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

CFI: Conventional Furrow Irrigation; FFI: Fixed alternate Furrow Irrigation; AFI: variable Alternate Furrow Irrigation.

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

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

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

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

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

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

Where, x_i is the *i*th water/nitrate infiltrated depth and x_{ave} the mean 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.

Decision Variables and Constraints

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

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

$$q_{\min} \le q \le q_{\max} \quad (6)$$

$$t_{\min} \le t_{co} \le t_{\max} \quad (7)$$

$$t_s + t_d \le t_{co} \quad (8)$$

$$E_w \ge 0.4 \quad (9)$$

$$CU_w \ge 0.6 \quad (10)$$

Where, q, t_{co}, t_s and t_d are inflow discharge (L s^{-1}), cutoff, start, and duration times (min) of fertilizer solution injection, respectively. The terms q_{min} and q_{max} are minimum and maximum inflow discharges (L s^{-1}), respectively, while t_{min} and t_{max} representing minimum and maximum cutoff times (min)..

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

$$q_{\max} = \frac{0.6}{S} \quad (11)$$

Where, *S* stands for 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).

$$t_{min} = t_{req} + t_{min} \quad (12)$$

Maximum cutoff time was approximated as follows:

$$t_{\max} = t_{\min} + 2t_{req} \quad (13)$$

The above restrictions are flexible and can be modified as discretion by the user of the optimization software produced in the research, responding to the actual field conditions.

Model Development

The simulation-optimization model includes six subprograms namely: (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. These subprograms were written in the Fortran programming language. Brief descriptions of the different subprograms are presented in the following sections.

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Cutoff Time

This subprogram was developed to determine the minimum and maximum values of the cutoff time [Equations (12) and (13)]. The cutoff time was assessed as based upon the approach of SIRMOD model (Walker, 2003):

Surface Fertigation

A combined overland water flow and solute transport model was employed 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 as well as numerical solutions can be obtained from Abbasi *et al.* (2003).

The model can be used to simulate different fertigation practices, including free-drainage 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 as well the uniformity coefficients of water and nitrate. These variables are employed 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 for nitrate transfer for alternate and conventional furrow fertigation.

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 utilized 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.

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 such input data 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.

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 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.

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 fitting individuals based upon 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. 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 as well as mutation probabilities. The respective values of these parameters were set at 200, 200, 0.5 and 0.01, respectively, following Carrol (1996) and Praveen *et al.* (2006).

Optimization Process

The different simulation models were linked to the genetic algorithm 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 the 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 (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 treatment 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

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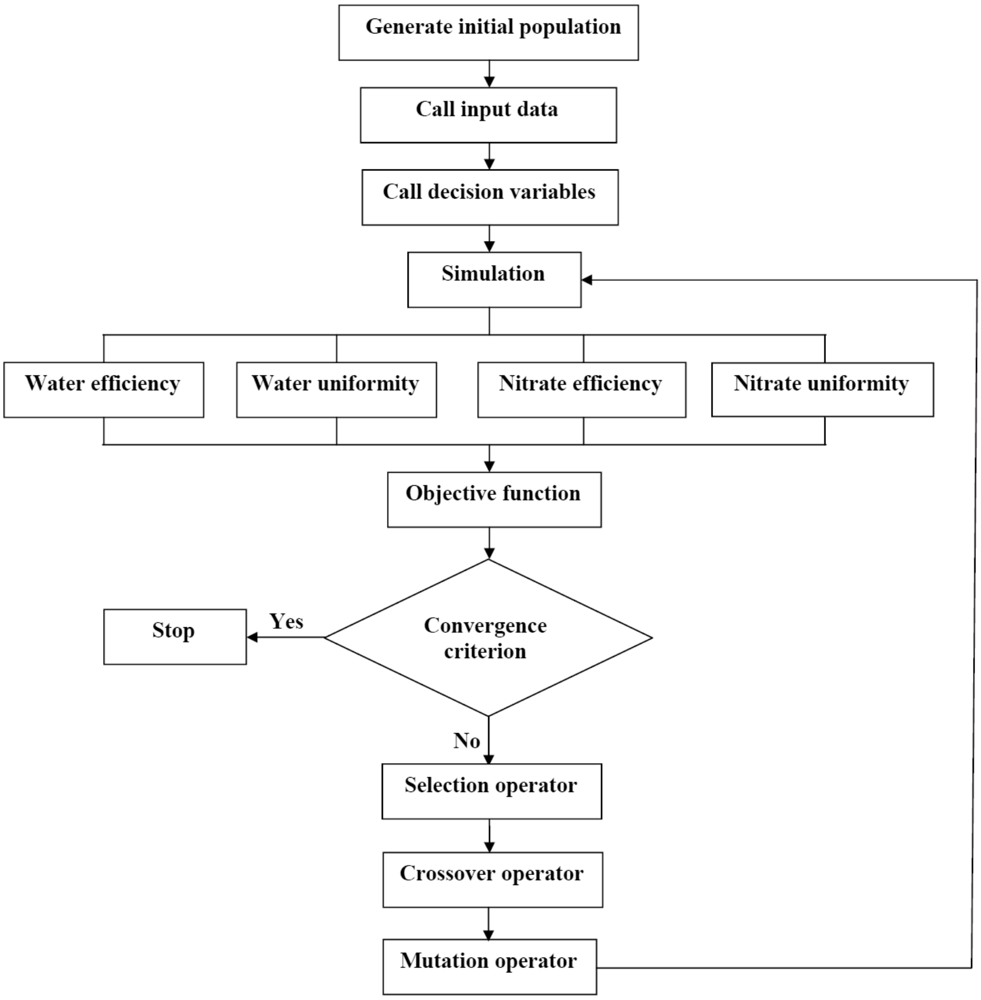

Figure 1. Flowchart of the simulation-optimization model for the first objective function.

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 seconds, respectively, depending on the values of the decision variables and on the irrigation treatment. Computational time was more for alternate furrow irrigation than for conventional furrow irrigation, owing to the flow domain requirements in SWMS-2D.

Calibration of Simulation Models

The values of the estimated parameters for calibrating SWMS-2D resulted in a minimum error between the 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.

RESULTS AND DISCUSSION

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 with 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.

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

	First fertigation			Second fertigation		
	AFI	FFI	CFI	AFI	FFI	CFI
Objective function[a]						
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[b]						
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

[a] OF_1 and OF_2 are the first and second objective functions, [b] CU_w and CU_n are water and nitrate Christiansen Uniformity coefficients, respectively; E_w and E_n are water and nitrate application efficiencies, respectively.

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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.

Optimization Results

The maximum values of the first and second objective functions were substantially higher than the values obtained under field conditions (Table 5). 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 presented the highest values of the objective functions, as compared with FFI and CFI. Similar to field conditions, optimum CFI resulted in the lowest values of OF_1 and OF_2. AFI and FFI revealed 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 with the CFI treatment.

The model chose low values of inflow discharge vs. large values of cutoff time to considerably reduce runoff losses and

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

Variable	First fertigation			Second fertigation			Variable	First fertigation			Second fertigation		
	AFI	FFI	CFI	AFI	FFI	CFI		AFI	FFI	CFI	AFI	FFI	CFI
Objective function [a]							Objective function						
OF_1^* (%)	78.5	67.7	67.2	77.1	74.2	63.0	OF_2^* (%)	85.2	74.8	71.0	81.4	81.6	61.3
Decision variables [b]							Decision variables						
q (L s^{-1})	0.184	0.174	0.158	0.222	0.228	0.127	q (L s^{-1})	0.175	0.167	0.147	0.216	0.214	0.120
t_{co} (min)	304.4	319.0	381.6	396.4	412.8	723.7	t_{co} (min)	347.7	343.7	425.1	425.7	413.7	775.1
t_s (min)	68.8	79.8	63.3	125.6	119.7	63.0	t_s (min)	126.0	123.1	125.7	166.8	137.7	105.5
t_d (min)	217.9	136.7	159.9	244.6	159.5	298.0	t_d (min)	221.3	212.9	220.6	227.7	274.0	312.2
Simulation outputs [c]							Simulation outputs						
CU_w (%)	84.3	85.1	87.6	82.7	87.6	90.0	CU_w (%)	80.8	81.6	83.5	80.1	82.1	88.8
CU_n (%)	94.0	91.6	89.6	93.5	90.5	86.4	CU_n (%)	95.5	95.2	92.7	93.6	94.3	87.2
E_w (%)	87.6	73.5	73.2	88.4	84.7	71.8	E_w (%)	87.7	74.3	74.1	88.0	88.1	73.0
E_n (%)	88.5	79.4	78.5	87.0	82.0	71.2	E_n (%)	89.2	78.5	76.6	86.9	86.6	70.3

[a] OF_1 and OF_2 are the first and second objective functions, respectively; [b] q, t_{co}, t_s and t_d are inflow discharge, irrigation cutoff time and start time and duration of fertilizer injection, respectively; [c] 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.

consequently increase water and nitrate efficiencies. 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 (Table 5). 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 in general higher than the field values for all the 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 often be 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 the all irrigation treatments and fertigation events, while the values of E_w were similar to E_n in all the cases. Optimization resulted in a small reduction in *CU* and a considerable increase in efficiency for both water and nitrate, taking into account the experimental conditions. Therefore, the combination of uniformity coefficient and efficiency led to higher values for both of the objective functions.

The variations of the first and second objective functions for each generation are presented for all the 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 its 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 the cases.

In all cases, water and nitrate efficiency in

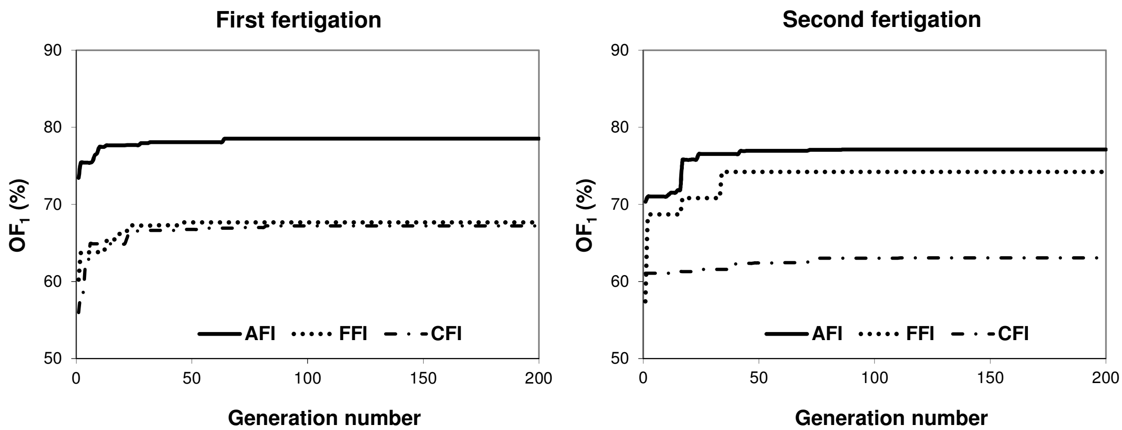

Figure 2. Evolution of the first Objective Function (OF_1) for each generation in the first and second fertigations.

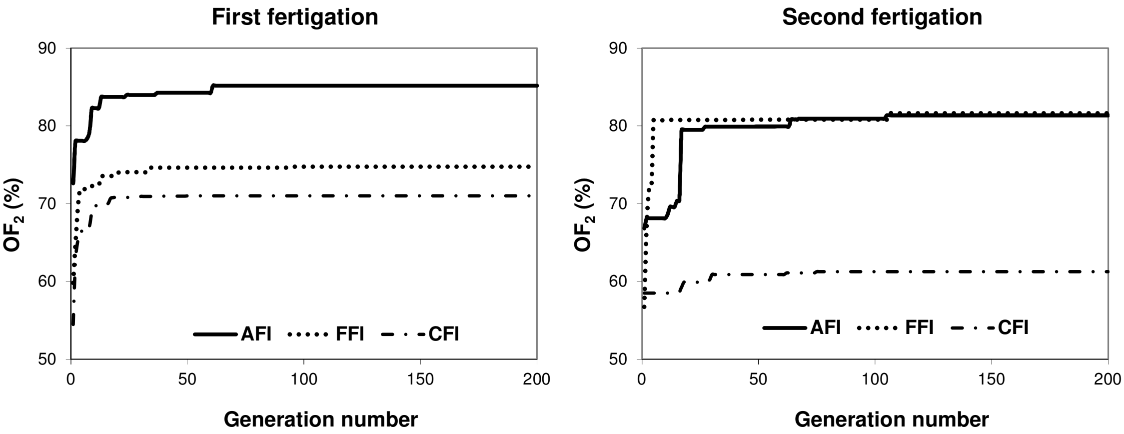

Figure 3. Evolution of the second Objective Function (OF_2) for each generation in the first and second fertigations.

general increased while uniformity coefficient of water decreased with increasing generations (Figures 4 and 5). The uniformity coefficient of nitrate did not show a clear trend, i.e. it increased in some cases while decreasing in other ones. Similar trends were observed for E_w and E_n, indicating that nitrate was transferred by flowing water, due to its high solubility in water.

The most important performance problem under field conditions was low water and nitrate efficiencies. Thus, the simulation-optimization model tended to select those values of the decision variables that strongly increased water and nitrate efficiencies while moderately reducing water and nitrate uniformity. As a consequence, both of 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), as well as Jurriens *et al.* (2001) indicated that irrigation efficiency *vs*. 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 was a trade-off found between efficiency and uniformity for irrigation and fertigation practices, which nevertheless permitted a maximization of the objective functions.

CONCLUSIONS

A simulation-optimization model was presented for the optimum management of alternate *vs.* conventional furrow fertigation. Two objective functions were considered for maximization, based on water and nitrate application efficiencies and as well uniformity. The optimum values of the decision variables could substantially improve water and nitrate efficiencies as compared with the experimental results. Ranges of water and nitrate application efficiencies were found as 72-88 and 70-89%, respectively, while these values varied in the ranges of 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 efficiencies. A trade off was observed between these two performance indices. The model opted for a decrease of 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 the irrigation treatments and fertigation events.

Simulation-optimization results proved that variable and fixed alternate furrow fertigation treatments led to lower water and nitrate losses than the conventional furrow fertigation. However, minor differences

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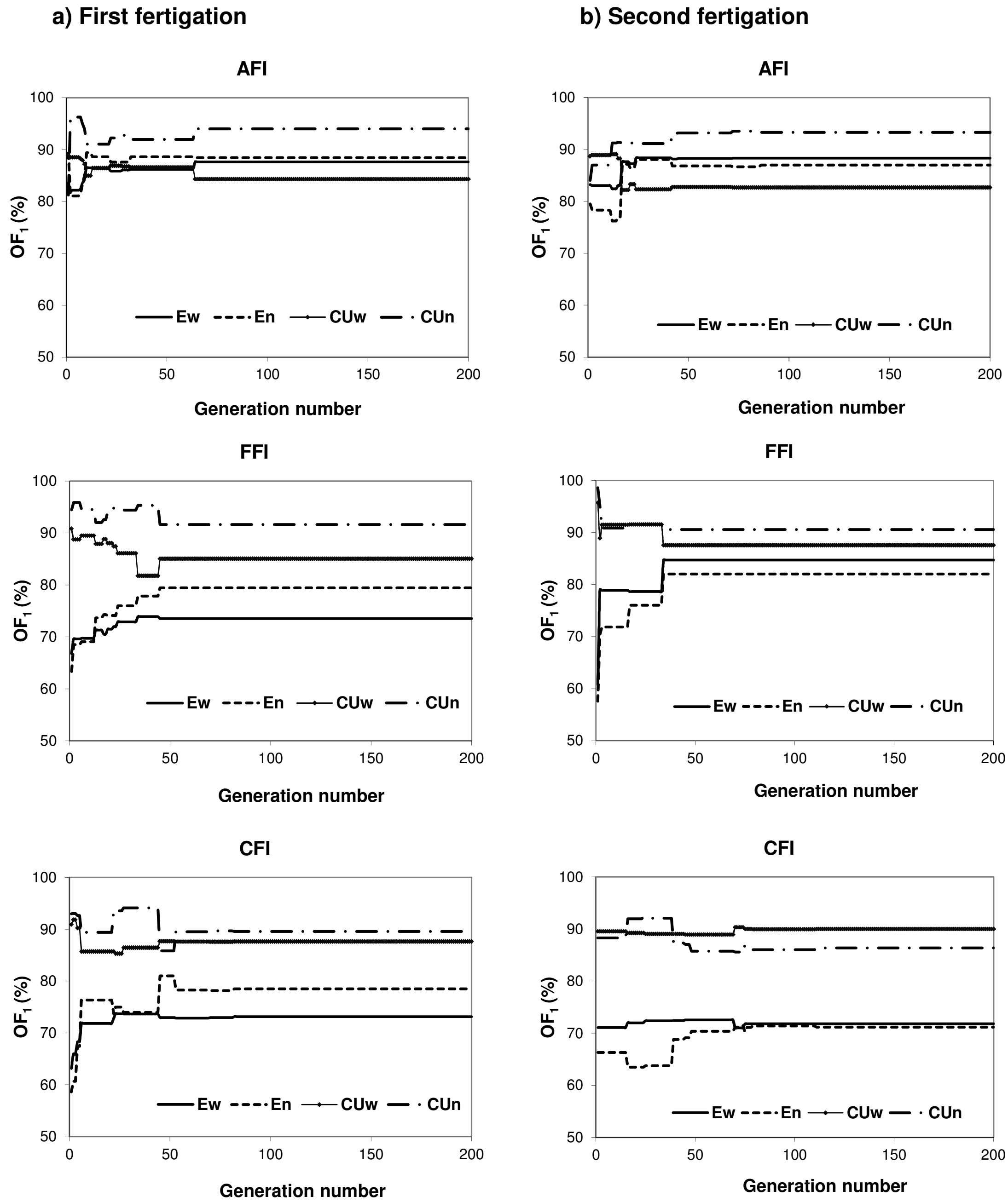

Figure 4. Water and nitrate efficiency and uniformity for each generation of the first Objective Function (OF_1) in the first and second fertigations.

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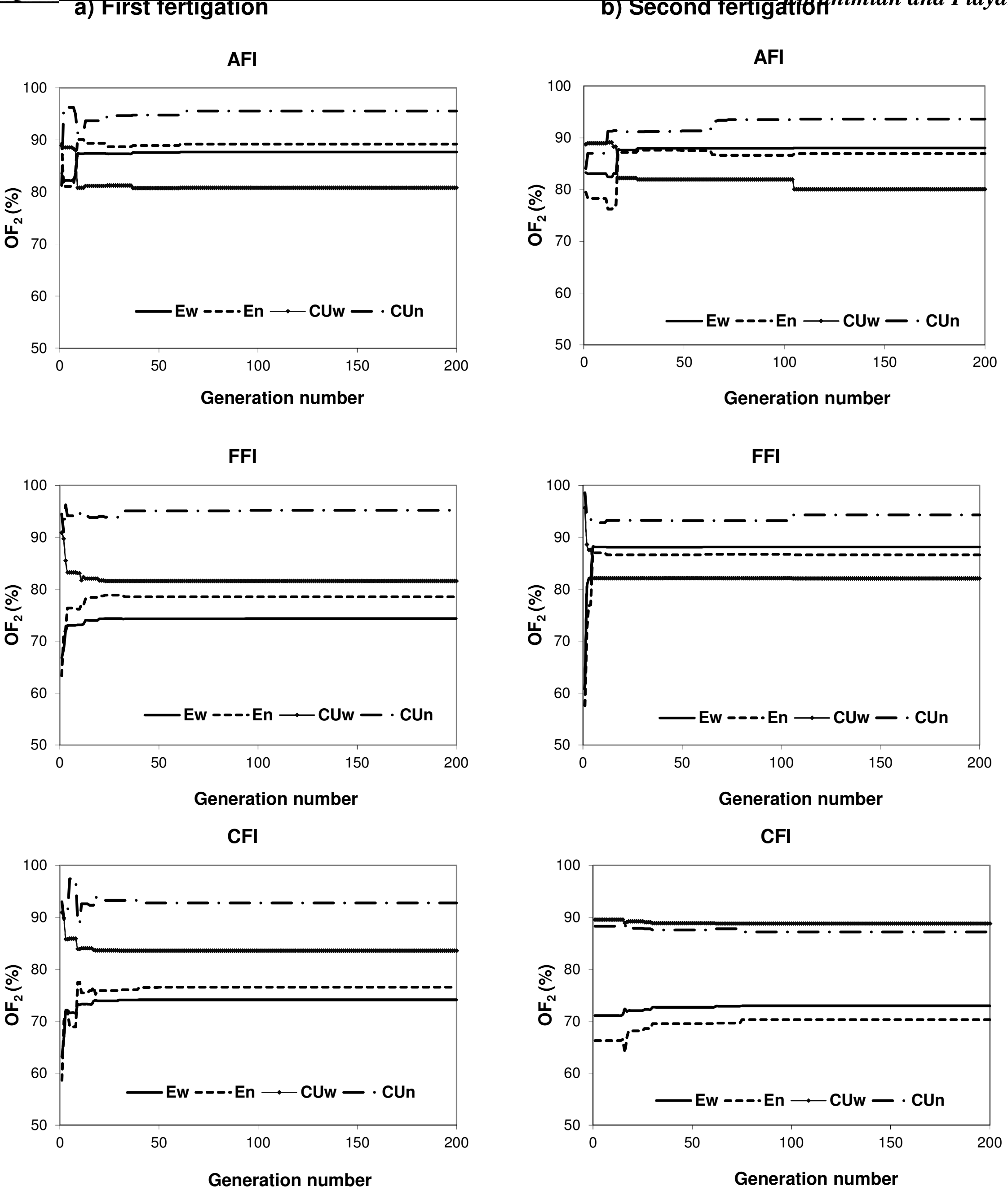

Figure 5. Water and nitrate efficiency and uniformity for each generation of the second Objective Function (OF_2) in the first and second fertigations.

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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 taking into account the field experimental conditions, particularly for the CFI treatment. The simulation-optimization model stands as a robust approach to identify optimum furrow fertigation strategies to diminish the environmental hazards from agricultural pollutants and whilst increasing water and fertilizer productivities.

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مدیریت بهینه کودآبیاری جویچه‌ای به منظور بیشینه‌سازی راندمان و یکنواختی توزیع آب و کود

ح. ابراهیمیان و ا. پلایان

چکیده

معمولاً هدف نهایی یک طراحی و مدیریت مناسب سامانه‌های آبیاری و کودآبیاری رسیدن به راندمان و یکنواختی بالای توزیع آب و کود است. هدف این مقاله ارائه یک مدل شبیه‌سازی–بهینه‌سازی برای کودآبیاری جویچه‌ای یک در میان و معمولی بود. این مدل از دو مدل شبیه‌سازی (کودآبیاری سطحی و SWMS-2D) و یک روش بهینه‌سازی (الگوریتم ژنتیک) استفاده می‌کند. دبی ورودی، زمان قطع آبیاری و زمان شروع و مدت زمان تزریق کود به عنوان متغیرهای تصمیم انتخاب شدند. این متغیرها به منظور بیشینه‌سازی دو تابع هدف که بر مبنای راندمان و یکنواختی کاربرد آب و نیترات بودند بهینه شدند. آزمایشات برای جمع‌آوری داده‌های مزرعه‌ای (مانند رطوبت و غلظت نیترات خاک، دبی و غلظت نیترات رواناب و زمان های پیشروی و پسروی) به منظور واسنجی مدل‌های شبیه‌سازی انجام گردید. مدل شبیه‌سازی–بهینه‌سازی نشان داد که کودآبیاری جویچه‌ای یک در میان متغیر و ثابت دارای مقادیر بیشتر راندمان آب و نیترات نسبت به کودآبیاری جویچه‌ای معمولی بود. اما اختلاف ناچیزی بین این نوع روش‌های آبیاری از نظر یکنواختی پخش آب و نیترات وجود داشت. این مدل به طور قابل ملاحظه‌ای باعث بهبود راندمان و یکنواختی توزیع آب و کود در مقایسه با شرایط مزرعه‌ای شد. راندمان کاربرد آب و نیترات به ترتیب در محدوده ۸۸–۷۲ و ۸۹–۷۰ درصد بدست آمد. همچنین ضریب یکنواختی کریستیانسن برای آب و نیترات به ترتیب درمحدوده ۹۰–۸۰ و ۹۶–۸۶ درصد حاصل شد. بهبود بیشتری در کودآبیاری جویچه‌ای معمولی نسبت به دو تیمار کودآبیاری جویچه‌ای یک در میان مشاهده گردید. پتانسیل مدل شبیه‌سازی–بهینه‌سازی برای بهبود طراحی و مدیریت کودآبیاری جویچه‌ای تاکید می‌شود.

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