INTERNATIONAL
Agrophysics
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Int. Agrophys., 2021, 35, 131-144
doi: 10.31545/intagr/135338

Distribution of soil water and nitrate in furrow irrigation under different plastic mulch placement conditions for a maize crop: Field and modelling study

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Received December 21, 2020; accepted April 1, 2021

Abstract. The use of plastic mulch in furrow irrigation increases irrigation efficiency and improves crop yield. In this study, the effect of the placement of plastic mulch on the furrows and/or on the ridges on reducing water loss and nitrate leaching for furrow-fertigated maize was investigated. Field experiments were carried out including four different treatments which differed according to the placement of plastic mulch on a clay loam soil: plastic mulch on the ridge, plastic mulch on the furrow bed, plastic mulch on the ridge and the furrow bed and control treatment without the mulch. The HYDRUS-2D model was used to simulate water movement and nitrate transfer within the soil. The HYDRUS-2D model was well calibrated and validated using field data. Three irrigation scenarios were also compared including 125, 100 and 75% of the crop water requirement. In the case of using mulch and full irrigation (*i.e.* 100% crop water requirement), nitrate losses compared to the control treatment with 25% over-irrigation decreased by 52, 44, and 30%, in the the treatments of mulch on the furrow bed, mulch on the ridge and mulch on the ridge and the furrow bed, respectively. Deep percolation of irrigation water also decreased by 53, 48, and 41%, respectively. The use of plastic mulch on the furrow bed with less irrigation depth could be used to prevent water and nitrate losses in furrow irrigation.

Keywords: furrow fertigation, plastic mulch, maize, HYDRUS-2D, dryland

INTRODUCTION

In recent years, water resources for irrigated agriculture have declined due to increasing industrial and domestic water consumption. However, an increasing population and the need to produce more food has led to an increase in the consumption of fertilizers and pesticides for food production; therefore water pollution through agricultural activities has become a serious problem around the world. One of the main sources of the contamination of water bodies is nitrate, which pollutes water resources at a high rate because it is so readily soluble in water (Ongley, 1996). Certain approaches to conserving water resources and increasing water use efficiency are essential to tackling the water crisis and the problems of water pollution in arid and semi-arid regions.

Surface irrigation systems are some of the most common irrigation methods in the world. Since furrow irrigation is the most common form of surface irrigation in the world, one of the main goals of the researchers has always been to find a way to simultaneously manage water and fertilizer in furrow irrigation to increase crop yield and reduce fertilizer losses (Barzegari *et al.*, 2017; Bristow *et al.*, 2020; Ebrahimian and Playan, 2014; Mohammadi *et al.*, 2019; Šimůnek *et al.*, 2016). Many researchers have suggested the use of plastic mulch to achieve this goal (Haraguchi *et al.*, 2004; Liu *et al.*, 2014; Qin *et al.*, 2015; Zotarelli *et al.*, 2008).

The use of plastic mulch in furrow irrigation for various plant species is common in many parts of the world for a variety of reasons. One of the reasons is the increase in

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soil temperature in the ridges compared to the case without mulch, thereby promoting the earlier germination of corn seeds (Lamont, 1993). In addition, by preventing the growth of weeds and also reducing evaporation from the soil surface, plastic mulch generally accelerates the ripening of the crop and increases yield in many plant species (Cannington *et al.*, 1975). Moreover, other benefits of plastic mulch include reducing the amount of fertilizer leaching and thus increasing the efficiency of fertilizer application for the plant (Lucasio *et al.*, 1985). Liu *et al.* (2015) evaluated the effects of plastic mulch on urea-N recovery by crops and losses from soil in the furrow-ridge plots, with and without maize cropping in a rain-fed site in China. Their results indicated that plastic mulch increased the total labelled-N remaining in the 0-170 cm depth in cropped soils and unaccounted for labelled-N in non-cropped soils, compared with an absence of mulch. Qin *et al.* (2015) reviewed 1 310 crops and 74 studies in 19 countries and found that using mulch increased water use and nitrogen use efficiency by up to 60%, compared to a mulch-free treatment. Plastic mulch is reported to be better than a straw one due to the higher degree of reduced evaporation, fewer weed problems and more control over soil pests (Lamont, 1993; Yu *et al.*, 2018). The effectiveness of mulching decreases with increasing input water because the excess water is lost through surface runoff or deep percolation. Soil mulch changes the soil surface temperature. Guo *et al.* (2019) performed a field study for the furrow irrigation system by fertilizing the ridges in order to determine the fate and transfer rate of nitrogen fertilizer in the case of using plastic mulch on the ridge compared to the case where mulch was not used. The results showed that maize grain yield and the net economic profit for plastic mulch treatment were significantly higher than was the case with the control treatment. The amount of nitrogen uptake by the plant and the remaining fertilizer at a depth of 120 cm from the soil surface was higher for the treatment with plastic mulch. Therefore, the researchers suggested the use of plastic mulch along with an improvement in nitrogen fertilizer placement to reduce nitrogen fertilizer losses for sustainable agriculture. Bo *et al.* (2019) examined the effects of different placements and durations of plastic mulch on maize height, leaf area index and biomass index related to the aerial part of the plant and grain yield for the plant under a drip irrigation system in a semi-humid area. Three different mulch applications included mulch on the ridge and bottom of the furrow, mulch on the ridge-only and a control treatment, also, the duration of the mulch treatment included the planting, germination and maturation stages of crop growth. The results showed that the application of mulch had a great effect on increasing the height and leaf area index of the plant in the early and late stages of the season when compared to the treatment without mulch. The treatment involving the application of mulch on the ridge and furrow throughout the growing season resulted in the best performance in terms of crop yield. However, the researchers did not carry out a numerical simulation of nitrate leaching and therefore their results may not be generalized.

Simulation models are widely used to improve the design, management, and operation of irrigation systems. Flexibility, affordability, analysis, and the evaluation of different scenarios are some of the advantages of using models. Šimůnek *et al.* (1999, 2006) developed the HYDRUS-2D model to simulate the two-dimensional movement of water, heat, and solute in a porous medium. Abbasi *et al.* (2004) reported that the HYDRUS-2D model (Šimůnek *et al.*, 1999) is capable of accurately simulating water flow and solute transfer in furrow fertigation. A favourable agreement was obtained between simulated and observed soil moisture and solute concentration throughout the cross-section of the blocked end furrow. Ebrahimian *et al.* (2013) simulated water flow and nitrate transfer in the soil in both conventional and alternate (constant and variable) furrow irrigation using the HYDRUS-2D model. Their results showed that the HYDRUS-2D model can accurately simulate water flow and nitrate transfer in both conventional and alternate furrow irrigation.

Iqbal *et al.* (2016) estimated the rate of nitrogen leaching by conducting field experiments and modelling nitrogen transfer within the soil which had been modified with compost under the furrow irrigation system for maize production. The HYDRUS-2D model was calibrated and verified using measured data and used to simulate nitrogen leaching from soil profiles, the model performed well enough to simulate the loss of inorganic nitrogen losses in fertilizer-modified soils. Šimůnek *et al.* (2016) developed a submodel for HYDRUS (2D/3D) to evaluate the effects of different soil surface management methods for furrows and different fertigation schedules on water and solute uptake by plant roots, deep percolation of water and solute leaching. The simulations showed that the lowest loss of solute and deepest percolation of water were obtained for the treatment with plastic mulch on the bottom of the furrow and fertigation at the end of the irrigation event. Overall, the results showed that the new "furrow" submodel, coupled with the HYDRUS (2D/3D) model, was proposed as a powerful tool for analysing water flow processes and solutes transfer in streams and soil profiles. Ranjbar *et al.* (2019), used the HYDRUS-2D model in order to simulate the crop uptake of various forms of nitrogen (such as nitrate and ammonium) and their transfer under the ridges and furrows during the growing period of maize crop under different nitrogen stresses. The results showed that there was a close agreement between the measured and simulated values of the soil water content and nitrate and ammonium concentration, but the model was not able to properly simulate the uptake of nitrate by the plant during the growing season. Lai *et al.* (2020) used the HYDRUS-3D and DNDC (*i.e.* DeNitrification-DeComposition) models to simulate the spatiotemporal variations of nitrate leaching on a tea garden in Taihu Lake Basin, China. Their results showed that the soil water flow and nitrate transport were well simulated by the HYDRUS-3D and DNDC models, respectively.

The management of water and fertilizer consumption along with the use of new approaches such as plastic mulch is one of the important ways to reduce the pollution of groundwater. Nevertheless, limited numerical studies have been conducted to date concerning the effect of different plastic mulch placement in furrow fertigation. Therefore, the present study investigated the effect of plastic mulch placement in furrow fertigation concerning the distribution of moisture and nitrate in the soil profile during the growing season of maize in a semi-arid region. In this study, the HYDRUS-2D model was applied to simulate soil water flow, and soil nitrate movement in furrow irrigation under different placement conditions of plastic mulch.

MATERIALS AND METHODS

The field experiment was carried out to collect field data at the Experimental Station of the College of Agriculture and Natural Resources at the University of Tehran, Karaj, in 2018. The experiment was conducted for conventional furrow irrigation under plastic mulch for maize (*Zea mays*, single cross 704) production. The mulching material consisted of a previously unused transparent LDPE (low-density polyethylene) plastic layer material with a 25 μm thickness and 0.75 m width. The seeds were sown on July 2, 2018. The furrow length and spacing were 4 and 0.75 m, respectively, and the blocked-end furrows were constructed in the direction of the ground slope (about 1%) with a trapezoidal cross-section. In this study, short furrows were selected for greater control and management over irrigation and fertigation practices and the appropriate application of plastic mulch placements. On average, the maximum depth, bottom width, middle width, and top width of the experimental furrows were 12, 10, 25, and 45 cm, respectively (Fig. 1). Four treatments were performed, each of which included three repetitions. As depicted in Fig. 1a, the treatments included mulch only on the ridge (R), mulch only on the bottom of the furrow (F), mulch on the ridge and on the bottom of the furrow (FR), and a control treatment without mulch (C). The mulching material consisted of a previously unused transparent LDPE (low-density polyethylene) material plastic layer with a 25 μm thickness and 0.75 m width. In total, there were 12 plots with each having a 15 m^2 area. The pre-sowing fertilizer application was limited to 10% of the total nitrogen fertilizer requirements (180 kg N ha^{-1} according to the crop and soil characteristics) and was applied the day before sowing using a mechanical spreader. Three nitrogen dressings (with an amount equivalent to 30% of the total fertilizer requirements) were applied at the vegetative (seven leaves on July 31), flowering (September 2), and grain-filling growth stages (September 22) using surface fertigation. The nitrogen fertilizer was applied in the form of potassium nitrate. According to the plot area (15 m^2 each), the total nitrogen fertilizer requirement and nitrogen percentage in the applied fertilizer (14%), a mean amount of 100 g potassium nitrate was applied in each furrow for each fertigation event. The same amount of water and fertilizer was applied to all furrows. To ensure the occurrence of leaching, for each irrigation event, the depth of applied water was set at 125% of the crop water requirement. In order to determine the crop water requirement, meteorological data were received daily from the meteorological station located near the location of the experiment. The maximum and minimum daily mean temperatures during

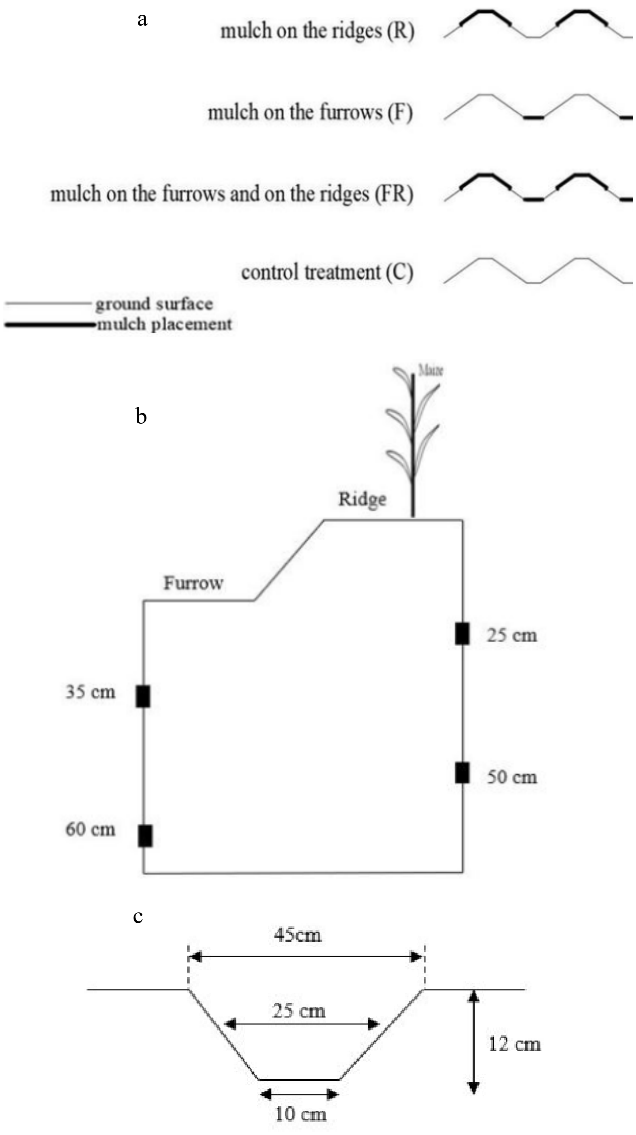

Fig. 1. Schematic view of the different mulch treatments (a), location of the maize crop and soil sampling for the control treatment (b) and experimental furrow cross-section (c).

the experiment were recorded as 40.1 and 27.0°C, respectively. Then, the evapotranspiration rate of the reference crop was obtained using ETo Calculator software (Raes, 2009). The crop coefficient (Kc) related to maize was determined and adjusted according to the FAO 56 guidelines (Allen *et al.*, 1998) for different growth stages. The total depth of irrigation during the growing season was 752 mm and the total number of irrigation events was 17 with a 5 day interval. The volume of irrigation water was determined by multiplication of the irrigation water depth and the plot area. The irrigation water was transferred to each furrow through pipes with a hydrant installed on each inlet. A volumetric flow meter was used to apply an accurately measured amount of water. Figure 2 represents the irrigation (applied) depth, reference evapotranspiration (ETo) and crop evapotranspiration (ETc) during the maize growing period. There was no rainfall during the growing season.

Soil depth was limited to 0.6 m because of the presence of an underlying gravel layer. The soil characteristics of the experimental field are presented in Table 1. Two auger soil samplings were performed for each fertigation event, one day before and three days after the event from the middle of the ridges and the furrows at the 0-25 and 25-50 cm soil layers (Fig. 1b). Spectrophotometric and gravimetric methods were used to measure the soil nitrate concentration and water content, respectively. Sixteen plants from the centre of each plot were harvested on September 29, 2018. After drying at 75°C for 72 h, the dry weights of all samples (as above-ground dry biomass) were recorded. The maize is usually cultivated for forage production in the study area.

HYDRUS-2D uses a numerical solution of the Richards' equation to simulate water flow in a porous medium (Šimůnek *et al.*, 2006). Due to the two-dimensional movement of water and solutes in the furrow irrigation system, the HYDRUS-2D simulation model was used to simulate water and nitrate losses in the soil profile. This model uses the two dimensional form of Richards' equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K_{ij}^A \frac{\partial h}{\partial x_j} + K_{iz}^A\right)\right] - S, \tag{1}$$

where: θ volumetric water content (dimensionless), h pressure head (L), S is a sink term (T^{1}), x_i and x_j = spatial coordinates (L), t – time (T), K_{ij}^A = components of a dimensionless anisotropy tensor K^A, and K unsaturated hydraulic conductivity function (L T^{1}).

The HYDRUS-2D model implements the soil-hydraulic functions proposed by van Genuchten (1980) and Mualem (1976) to describe the soil water retention curve, $\theta(h)$, and the unsaturated hydraulic conductivity function, $K(h)$, respectively:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{(1+|\alpha h|^n)^m}, & h < h_s \\ \theta_s, & h \geq h_s \end{cases} \tag{2}$$

$$K(h) = K_s S_e^l \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2, \tag{3}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad m = 1 - \frac{1}{n} \qquad n > 1, \tag{4}$$

where: θ_r and θ_s denote the residual and saturated water content, respectively (dimensionless), α = inverse of the air-entry value (L^{-1}), K_s = saturated hydraulic conductivity (L T^{-1}), n = pore-size distribution index (dimensionless), S_e = effective water content (dimensionless), and l = pore-connectivity parameter (dimensionless), with an estimated value of 0.5, resulting from averaging conditions in a range of soils (Mualem, 1976).

The plant water uptake is described based on the Feddes *et al.* (1978) model. The parameters of the Feddes model were also determined using the study data of Wesseling *et al.* (1991). The Feddes model is as follows:

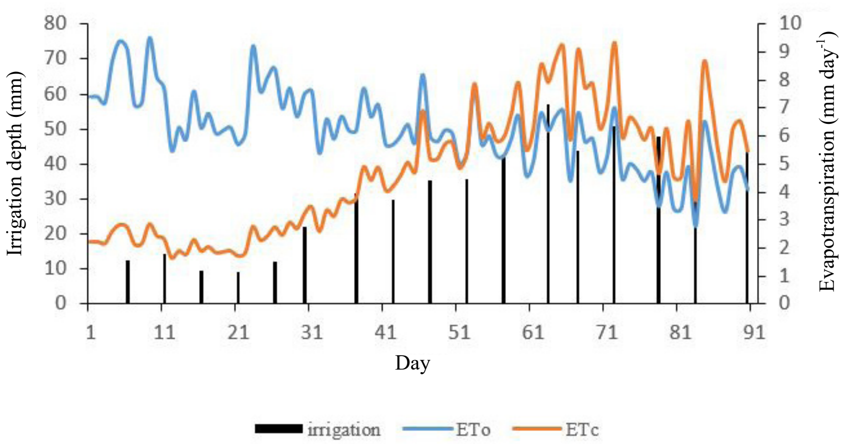

Fig. 2. Irrigation depth and values of reference and maize evapotranspiration from the sowing date (day 1) until the harvest day (day 90).

Table 1. Soil characteristics of the experimental field

Characteristic	Soil depth (cm)		
	0-20	20-40	40-60
Texture classification (USDA)	Clay loam		
Clay (%)	28	31	33
Silt (%)	43	40	46
Sand (%)	29	29	21
Field capacity (cm^3 cm^{-3})	0.29	0.30	0.29
Permanent wilting point (cm^3 cm^{-3})	0.11	0.11	0.09
pH	7.6	7.8	7.7
EC_e (dS m^{-1})	1.2	1.8	1.9
Organic matter (%)	0.85	0.55	0.33
NO_3^- (mg cm^{-3})	0.021	0.006	0.002

$$S\,(h) = \alpha(h)\,S_{max}. \tag{5}$$

where: S_{max} = potential uptake rate (T^{-1}), $\alpha(h)$ is the reduction coefficient of drought stress which varies between 0 and 1.

Regarding solute movement, HYDRUS-2D numerically solves the convection-dispersion equation with zero- and first-order reaction and sink terms.

$$\frac{\partial \theta c}{\partial t} = \frac{\partial}{\partial x_i}\left(\theta D_{ij}\frac{\partial c}{\partial x_j}\right) - \frac{\partial q_i c}{\partial x_i} - SC_s. \tag{6}$$

where: c = nitrate concentration in the soil (M L^{-3}), q_i = ith component of the volumetric flux (L T^{-1}); D_{ij} = dispersion coefficient tensor (L^2 T^{-1}), S = sink term of the water flow in the Richards' equation, and C_S = concentration of the sink term (M L^{-3}). D_{ij} may be defined as follows:

$$\theta D_{ij}^{w} = D_T|q|\delta_{ij} + (D_L - D_T)\frac{q_j q_i}{|q|} + \theta D_w \tau_w \delta_{ij}. \tag{7}$$

where: D_w = molecular diffusion coefficient in free water (L^2 T^{-1}), τ_w = tortuosity factor (dimensionless), δ_{ij} = Kronecker delta function ($\delta_{ij} = 1$ if $i = j$, and $\delta_{ij} = 0$ if $i \neq j$), D_L = longitudinal dispersivity (L), and D_T = transverse dispersivity (L). In this study, only the nitrate (NO_3^-) transfer was simulated by solving the equation above.

The Galerkin finite-element method is used in this model to solve the governing equations and subjected to the appropriate initial and boundary conditions. The nitrate concentrations and soil water contents measured before the first fertigation event were used as initial conditions within the flow domain. The boundary conditions considered in furrow irrigation for all treatments are shown in Fig. 3. The flux boundary conditions were set on the soil surface. The ridge surface and the unsubmerged sides of the ridge and also the surface covered by plastic mulch were specified as atmospheric boundaries, while the surface of the submerged sides and the bottom of the furrow (where they were not covered with plastic mulch) were specified as variable flux boundaries with flux values equal to the atmospheric fluxes between irrigation events and irrigation rates during each irrigation event. The durations of irrigation and the amounts of applied water were assigned in the HYDRUS-2D simulations based on the irrigation schedule used in the field experiments. Free drainage conditions were set up at the bottom of the simulated domain, assuming that the groundwater level did not affect the water flow within the domain. A no-flux condition was assigned to the vertical boundaries assuming that both water and nitrate flux were compensated for by outflux through these boundaries. A third type of boundary condition was used at both the top and bottom boundaries for solute transport. To reduce the computational time, a symmetry mode was considered in the definition of the geometric dimensions of the furrow and ridge cross sections. The HYDRUS utilizes the ROSSETA-based pedotransfer functions to estimate soil hydraulic parameters with easily measurable variables. Thus, the water flow parameters (θ_s, θ_r, K_s, n, and α) were estimated using ROSSETA and easily measurable soil physical properties (particle fraction, bulk density, field capacity and permanent wilting point in Table 1) as initial values. The initial values of θ_s, θ_r, K_s, n, α and l were 0.440, 0.046 cm^3 cm^{-3}, 21.5 cm day^{-1}, 1.48, 0.007 (1/cm) and 0.5, respectively.

Plant information included water uptake model parameters, evapotranspiration, root distribution depth, and fertilizer uptake by the plant. The parameters of the root water uptake model were determined for maize according to Wesseling *et al.* (1991). In the model, the two-dimensional root distribution function of Vrugt *et al.* (2001) is used to describe the spatial distribution of the roots. The 40-30-20-10 % pattern was considered for water uptake by plant roots. The maximum values of the roots in the vertical and horizontal directions were considered to be 60 and 37.5 cm, respectively. The spatial distribution of the roots was considered to be constant over time. The total maize evapotranspiration (ET_c) was calculated through the dual crop coefficient approach during the growing season as 564 mm in 2018, using the FAO 56 method (Allen *et al.*, 1998). It consisted of the basal crop coefficient (K_{cb}) and soil evaporation coefficient (K_e) which were used to describe the transpiration (T) and evaporation (E) components of ET_c, respectively (ET_c = [K_{cb} + K_e]. ET_o, ET_o is the reference crop evapotranspiration). According to Allen *et al.* (1998), the standard maize K_{cb} values for the initial, middle, and late season stages were found to be 0.15, 1.15, and 0.3, respectively. The K_{cb} values were then adjusted for the study region (Karaj) climate based on crop height, wind speed, and minimum relative humidity for the study period. The K_e values were calculated using the method proposed

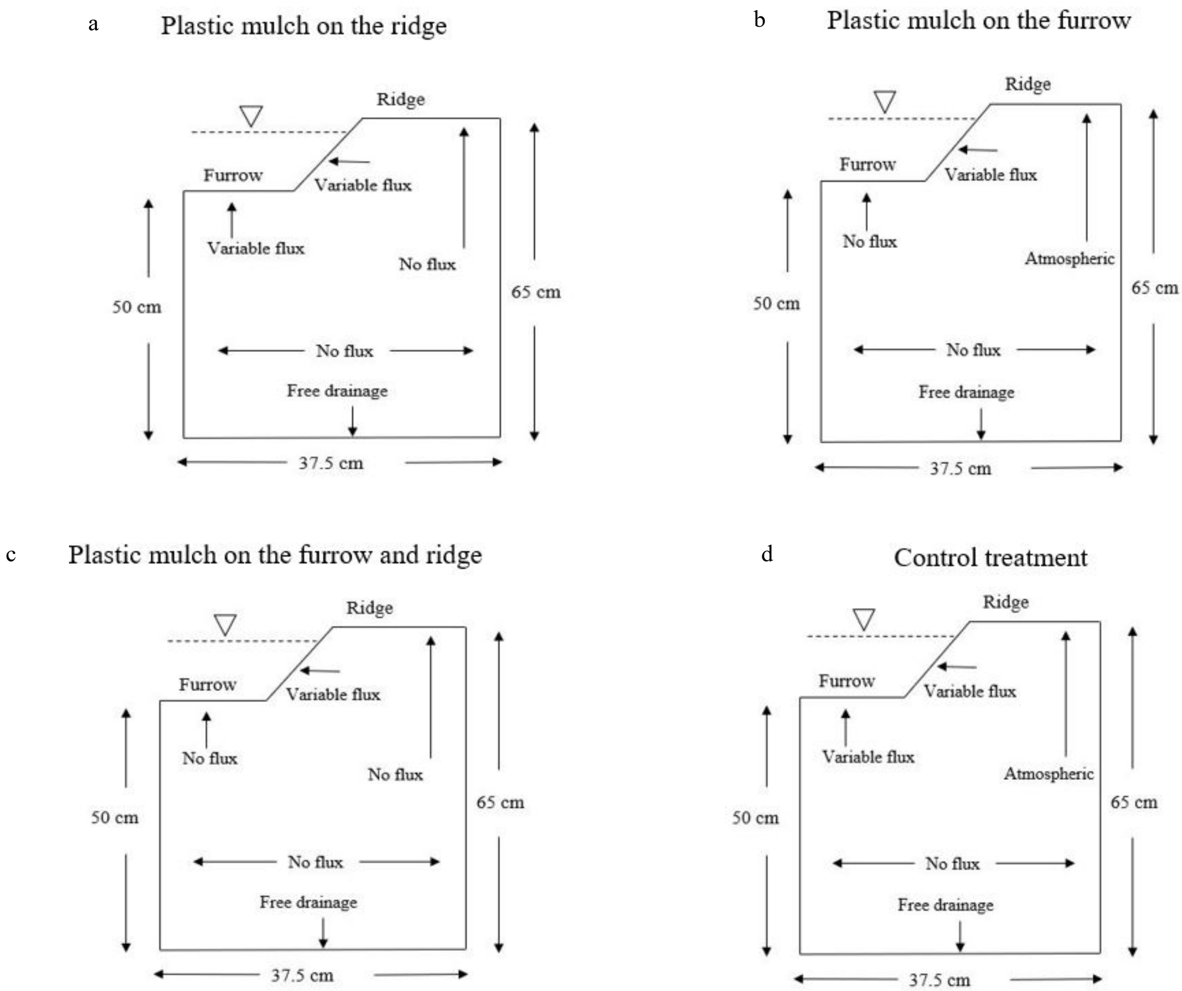

Fig. 3. Schematic view of the boundary condition related to the plastic mulch on the ridge (a), plastic mulch on the furrow (b), plastic mulch on the ridge and the furrow (c) and the control (d) treatments defined in HYDRUS-2D model.

by Allen *et al.* (1998) which gives the potential evaporation rates. The actual evaporation rates were calculated by the model.

The solute transfer parameters used in this study include longitudinal dispersivity (D_L), transverse dispersivity (D_T), the molecular diffusion coefficient in free water (D_w) and the concentration of the sink term (C_s). Using the results of similar research conducted previously (Ebrahimian *et al.*, 2013) on the same farm, the initial values of longitudinal and transverse dispersivity (D_L and D_T) were considered to be 12 and 1.2 cm, respectively, and the nitrate diffusion coefficient in free water is 1.64 cm^2 day^{-1} and also the initial value of was considered to be 0.35 mg cm^{-3}.

The data collected from the control treatment were used for model calibration. A total number of 144 soil samples collected from the control treatment were used for the calibration stage. 72 of them were used to measure the soil water content and the rest were used to measure the soil nitrate concentration. The measured soil water content and nitrate concentration for the day before the first fertigation event was used as the initial condition. Since the properties of all three soil layers in the root zone were very similar to each other, they were considered to be a single profile with a 60 cm thickness to determine the hydraulic parameters of the soil. In the first step, an inverse analysis was performed for a homogeneous soil profile (*i.e*., a single 0.6 m layer) in order to optimize the parameters of the model. A number of water flow and nitrate transport parameters were estimated using an inverse solution procedure implementing the Levenberg-Marquardt optimization module which was added to HYDRUS-2D software (Šimůnek *et al*., 2006). The inverse method is based on the minimization of a suitable objective function, which expresses the discrepancy between the observed and model-predicted values. The objective function was defined as the sum of the squared residuals (*SSQ*):

$$SSQ = \sum_{j=1}^{n} v_j \sum_{i=1}^{n} w_{ij}\left[q_j^*(x,z,t_i) - q_i(x,z,t_i,b)\right]^2, \quad (8)$$

where: n = number of measurements for the jth measurement set (water contents, concentrations, …), $q_j^*(x, z, t_i)$ = measurement at time t_i, location x, and depth z, $q_i(x, z, t_i, b)$ = corresponding model prediction obtained with the vector of optimized parameters $b = (\theta_s; K_s, D_L, …)$ and v_j and w_{ij} = weights associated with a particular measurement set or point, respectively. The weighting coefficients were assumed to be equal to 1 in all cases. The quality of the parameter estimation was assessed using two dimensionless indicators: the coefficient of determination (R^2) and *SSQ*.

The inverse approach has been successfully applied by several researchers (Abbasi *et al.*, 2003, Crevoisier *et al.*, 2008; Ebrahimian *et al.*, 2013; Ranjbar *et al.*, 2019; Verbist *et al.*, 2009) to estimate soil-hydraulic and solute transport parameters. In this paper, the inverse estimation was applied to three water flow parameters, including K_s (saturated hydraulic conductivity), θ_s (saturated soil water content), and (corresponding to the van Genuchten water retention function), and two nitrate transport parameters, including D_L (longitudinal dispersivity), D_T (transverse dispersivity). The soil-hydraulic and solute transport parameters were simultaneously estimated. The inverse optimization method simultaneously uses all measured data, *i.e.* water contents and nitrate concentrations, and yields a superior estimation when compared to sequential optimization because it considers the interactive effects between the water flow and solute transport parameters (Abbasi *et al.*, 2003; Ebrahimian *et al.*, 2013; Šimůnek *et al.*, 2002).

After model calibration, HYDRUS-2D was run for other treatments using optimized parameters from the control treatment in order to validate the model.

In order to examine the different conditions in water and fertilizer management, for the purposes of achieving a more appropriate situation with regard to using plastic mulch to prevent fertilizer losses in real farm conditions, two distinct scenarios were applied to the model. The first scenario was to apply 100% of the crop water requirement, without considering the 25% of excess water used in the field study to ensure that leaching occurred. The second scenario was to apply 75% of the crop water requirement during the season. The deep percolation of irrigation water and the amount of leached nitrate were calculated for both scenarios and then compared with the field conditions (*i.e.* applying 125% of the crop water requirement).

In order to evaluate the performance of the model, the simulated values of soil water content and nitrate concentration below the furrows and ridges were compared with the measured values for all treatments. The correspondence between the simulated and observed data was evaluated using the coefficient of determination (R^2), mean bias error (*MBE*), and the normalized root mean square error (*NRMSE*). The *NRMSE* is expressed as a percentage and gives an indication of the relative difference between the model and observation (Jamieson *et al.*, 1991):

$$R^2 = \left(\frac{n(\sum O_i P_i) - (\sum O_i)(\sum P_i)}{\sqrt{[n \sum O_i^2 - (\sum O_i)^2][n \sum P_i^2 - (\sum P_i)^2]}} \right)^2, \tag{9}$$

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}} \times 100}{\bar{O}}, \tag{10}$$

$$MBE = \frac{\sum_{i=1}^{n} (P_i - O_i)}{n}, \tag{11}$$

where: O_i are the observed values, P_i are the predicted values, $\bar{O}$ is the mean of the observed values and n is the number of observations.

RESULTS AND DISCUSSION

The mean values and the standard deviation (red bars) of the measured soil water content and nitrate concentrations for all treatments are shown in Figs 4 and 5, respectively. According to Fig. 4, the average soil water content under the ridges at both sampling depths for the RF treatment was clearly higher than it was for other treatments. After the second fertigation, the average soil water content under the ridges became closer to each other in soils covered with mulch. The reason for this could be the significant reduction in the amount of evaporation due to maize growth in comparison with the early growth stage when the canopy cover was much less than the full canopy cover after the second fertigation. Thus, the presence of plastic mulch on the ridges also plays an important role in maintaining soil moisture on the ridges, especially in the early stages of plant growth when the ground surface is not yet covered by foliage. Between the first and third sampling events, when the crop was still in its early growth stage and canopy cover was relatively sparse, there is a significant difference in soil moisture under the ridges between the covered ridges treatments with mulch (R and FR) and the treatments without ridge cover (F and C treatments) because of the higher rate of evaporation in the treatments without mulch on the ridges. However, this difference for the F treatment was less than that for the C treatment. In addition, the results indicated that for the treatments with furrows covered with mulch (FR and F), the mean soil water content was significantly higher than it was for the two other treatments with bare furrows. Moreover, the range of change in the water content below the furrow was smaller for the FR and F treatments than it was for the R and C treatments. The maize yield (dry biomass) of the R, F, FR and C treatments were 20.3, 26.5, 27.0 and 16.9 t ha^{-1}, respectively. The measured values of the biomass in the treatments with mulch (particularly FR

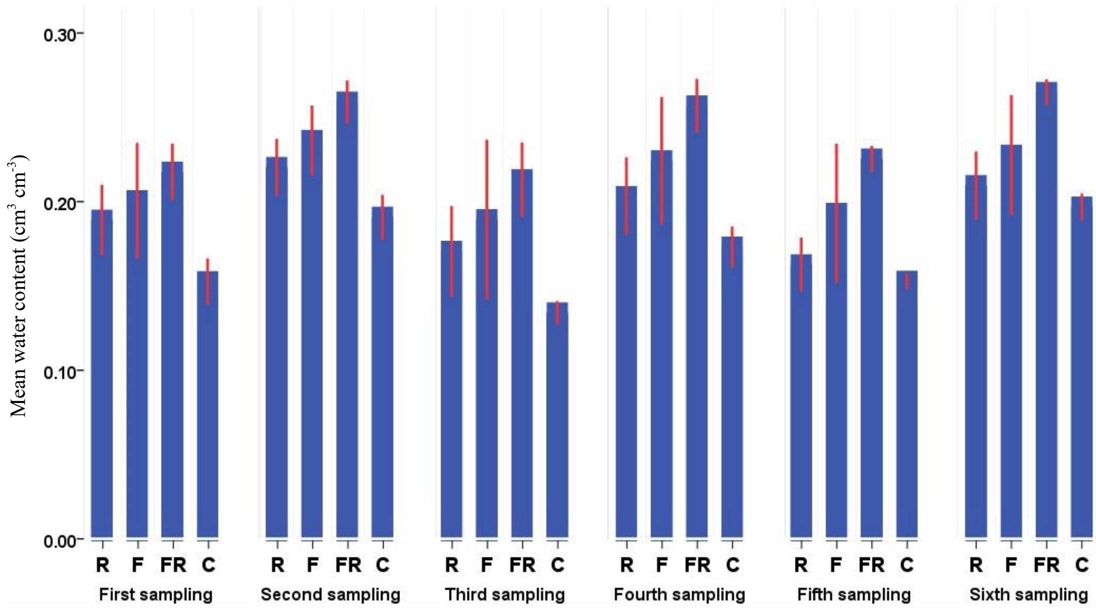

Fig. 4. Mean soil water content and the standard deviation (red bars) for all treatments before and after each fertigation event (R – mulch on the ridge, F – mulch on the furrow, FR – mulch on the furrow and the ridge and C – control treatment).

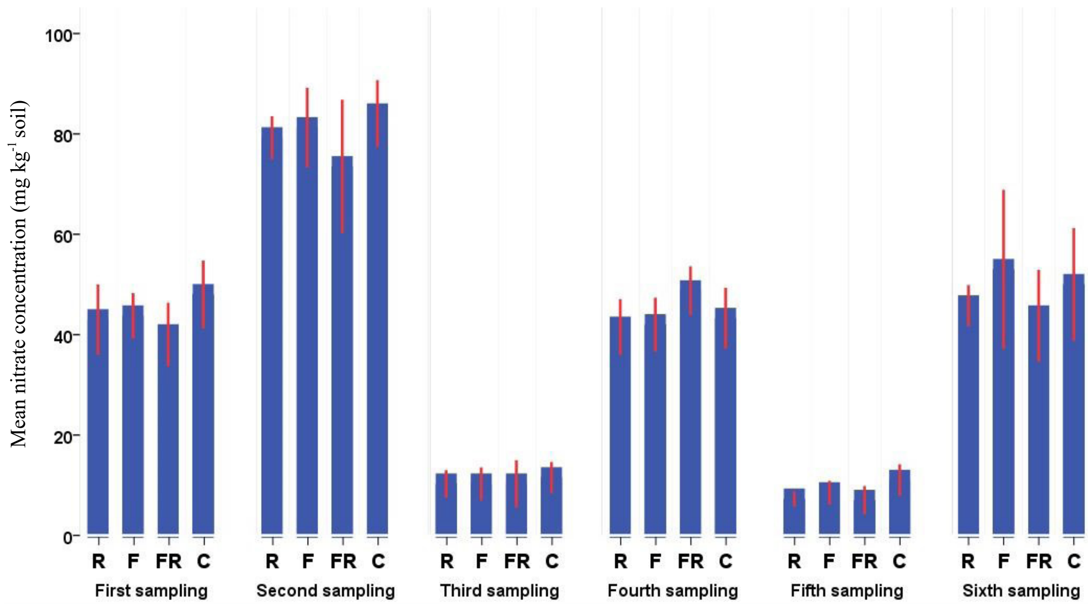

Fig. 5. Mean soil nitrate concentration and the standard deviation (red bars) for all treatments before and after each fertigation event. Explanations as in Fig. 4.

and F) were greater than in the control treatment. Higher soil water content (close to field capacity, FC) in the root zone might be the reason for this result.

According to Fig. 5, the reduction in soil nitrate concentration between the two successive fertigations was observed for all treatments. Additionally, the soil nitrate concentration before each fertigation event was higher for the C treatment compared to the others. In general, it appears that the lowest fertilizer loss occurred for the C treatment and that the F, R, and FR treatments are ranked next, respectively. The reason for this could be the equal amount of irrigation water that was applied to all treatments without considering the effect of the plastic mulch on soil moisture retention due to the significant reduction in evaporation. As mentioned previously, the soil moisture levels in the treatments with plastic mulch were higher than the level measured for the C treatment, and therefore excess water may have been lost through deep percolation, leading to further nitrate leaching. The difference in soil nitrate concentration between the FR and C treatments was greater

Table 2. Values of parameters before and after the inverse solution for the control treatment

Parameters	θ_S (cm^3 cm^{-3})	n (-)	K_s (cm day^{-1})	D_L (cm)	D_T (cm)
Initial	0.44	1.48	21.5	12.0	1.2
Optimized	0.38	2.66	13.67	8.82	0.36
95% confidence interval	(0.301-0.477)	(1.30-2.74)	(11.12-22.31)	(7.38-13.20)	(0.24-1.3)

Table 3. Values of model evaluation indicators in simulating soil water content and nitrate concentration in the calibration stage (control treatment)

Nitrate concentration			Water content		
R^2 (-)	*MBE* (mg cm^{-3})	*NRMSE* (%)	R^2 (-)	*MBE* (cm^3 cm^{-3})	*NRMSE* (%)
0.96	0.019	14.7	0.81	-0.003	12.9

than it was for the two other treatments, and the amount of soil nitrate concentration in the FR treatment was less than it was for the other mulch covered treatments. This is due to the fact that more soil is covered with plastic mulch, especially at the beginning of the growing season when less ground is covered by foliage and the losses due to evaporation for this treatment are much less than they were for other treatments. The amount of water applied to the soil throughout the season was 25% higher than the crop's water requirement, which actually indicates that this excess water in the treatments with mulch may have caused more soil nitrate leaching than in the control treatment. Another important point is the closeness of the soil nitrate concentration between the F and R treatments. For all samples, the soil nitrate concentration in the F treatment is slightly higher than in the R treatment.

The initial and optimized values of the soil hydraulic parameters are presented in Table 2. In addition, the values of the model evaluation indicators in simulating soil water content and nitrate concentration using optimized parameter values are presented in Table 3. The optimum values of the parameters are reasonable and fit within the common ranges reported in previous studies (Ebrahimian *et al.*, 2013 and Ranjbar *et al.*, 2019). The values of and other evaluation indicators for the calibration stage are reasonable. The model slightly under-estimated and over-estimated the soil water content and nitrate concentration, respectively. The accuracy of the model in simulating water content was somewhat better than its performance with regard to simulating nitrate concentration.

The numerical solutions were compared with the observed data one day before and three days after all three fertigations in the validation stage. The values of the model evaluation indicators for water flow and nitrate transfer simulation are presented in Table 4. According to the values of the evaluation indicators, the accuracy of the model in soil moisture simulation and nitrate concentration was satisfactory (10%< *NRMSE*< 20%), and the measured results were close to the results simulated by the model. The negative value of the *MBE* index indicates that the model under-estimated soil nitrate concentration by a slight margin.

The simulated values of soil nitrate concentration and water content were compared with the measured values for all treatments in Figs 6 and 7, respectively. The values for the F, R, FR, and C treatments were 0.76, 0.96, 0.87 and 0.97, respectively, for water content and 0.96, 0.97, 0.97 and 0.96, respectively, for nitrate concentration. There is a fair correlation between the simulated and measured values. These results show that the calibrated model simulated water flow and nitrate transport in soil profiles to a fair extent. The HYDRUS-2D model had a higher accuracy in simulating nitrate concentration compared to water content. These results are in contrast to those obtained by Ebrahimian *et al.* (2013) and Ranjbar *et al.* (2019).

Since the HYDRUS-2D model had relatively favourable accuracy in the validation stage, this model was used to estimate the deep percolation of irrigation water and nitrate leaching, the results are presented in Table 4. Water and nitrate balance components for the simulation period are presented in Tables 5 and 6, respectively.

As expected, the FR and C treatments had the highest and lowest fertilizer losses through the leaching process, respectively, according to the results of soil water content and nitrate concentration which were discussed. The R and

Table 4. Deep percolation of irrigation water and nitrate leaching throughout the simulation period

Treatment	Nitrate leaching	Deep percolation of water
	(%)	
Mulch on the ridge (R)	34.4	30.8
Mulch on the furrow (F)	32.2	30.4
Mulch on the furrow and the ridge (FR)	37.8	32.4
Control (C)	29.3	28.8

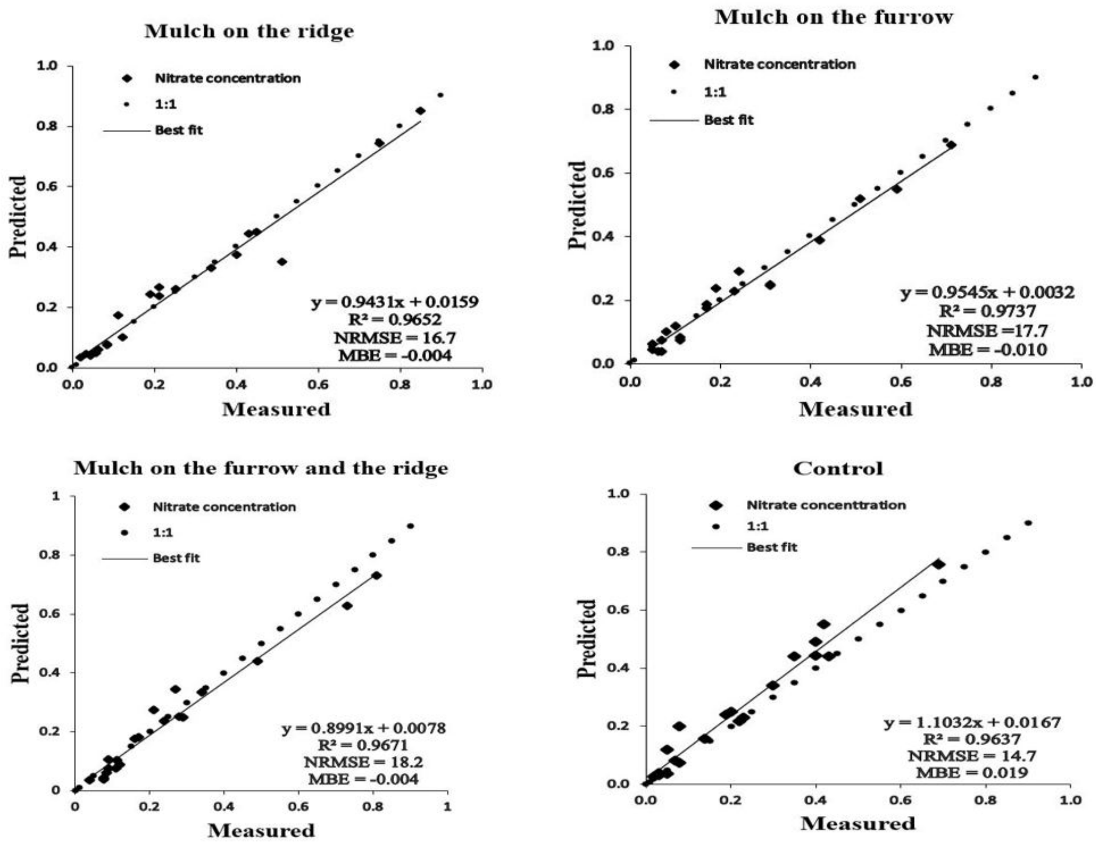

Fig. 6. Observed and simulated (HYDRUS-2D) soil nitrate concentration (mg cm^{-3}) for each treatment.

F treatments are similar in terms of deep percolation and nitrate leaching. The water and nitrate losses were greater than 25% under 25% over-irrigation conditions because soil water content was increased by using mulch through a reduction in evaporation. On the other hand, to a slight extent the model over-simulated deep percolation and nitrate leaching in which the simulated value of water deep percolation and nitrate leaching for the C treatment was 28.8 and 29.3%, respectively, which was greater than 25%.

In order to investigate the effect of plastic mulch in different irrigation management conditions, the model was run for complete irrigation and 25% deficit-irrigation conditions. The results of the deep percolation of irrigation water and nitrate leaching are presented in Table 6. The results of the simulation of 25% excessive irrigation are also given in order to obtain an improved evaluation and comparison in this table. Moreover, for the purposes of making a better comparison, the effect of different irrigation management techniques on plant water uptake is given in Table 7.

The results indicated that by using plastic mulch and full irrigation compared to irrigation with 125% of water requirement and without using mulch, more water would be saved and soil nitrate leaching would also be significantly reduced. According to Table 8, in the case of full irrigation with plastic mulch, there was no decrease in root water uptake compared to over-irrigation, while in the control treatment (C), root water uptake decreased by approximately 7.3%. The reason for crop uptake decrease in this treatment may be attributed to water stress due to a relatively high irrigation interval during the maximum crop water requirement. In other words, the use of mulch and full irrigation will save water (without causing drought stress for the crop) and reduce soil nitrate losses through leaching compared to the case without the use of mulch under over-irrigation conditions. The simulation results for treatments with mulch under full irrigation conditions, as was the case with 25% over-irrigation, showed that the lowest losses of water and nitrate were related to the F treatment followed by the R treatment with a minor difference between them.

Under the conditions of 25% deficit irrigation, the losses of water and nitrate in all treatments were very small. However, in this case, the results of plant root water uptake shows that the uptake rate was reduced in all treatments. This reduction in water uptake for the C treatment was much more severe than it was for the mulch-treated treatments. Under 25% deficit irrigation, crop water uptake was reduced to 15.1, 20.3 and 10.3% for the F, R and FR, respectively. This finding shows the effect of plastic mulch in maintaining soil moisture. However, by reducing the

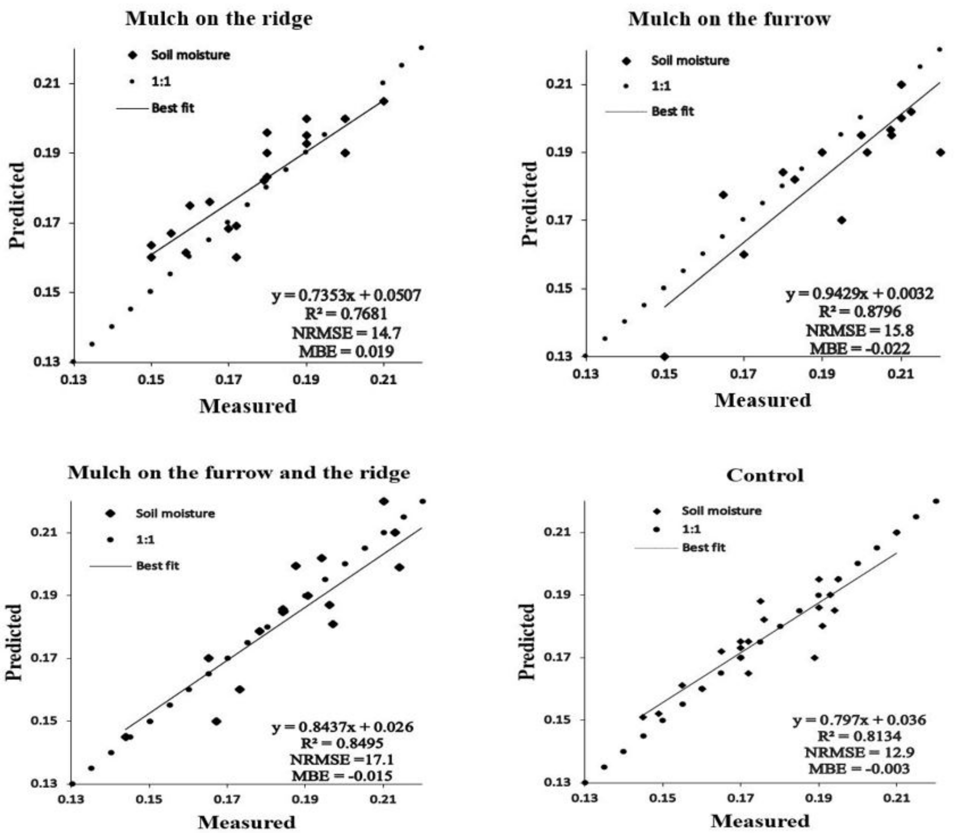

Fig. 7. Observed and simulated (HYDRUS-2D) soil water content (cm^3 cm^{-3}) for each treatment.

Table 5. Water balance components throughout the simulation period

Treatment	Irrigation depth	Evapotranspiration	Root water uptake	Soil moisture storage changes	Deep percolation
	(mm)				
R	429	321	232	65	132
F	429	321	232	67	130
FR	429	321	232	58	139
C	429	321	232	74	123

Table 6. Soil nitrate balance components throughout the simulation period for each furrow

Treatment	Total nitrate input	Total nitrate uptake by maize	Nitrate storage changes	Nitrate leaching
	(g)			
R	88	46	12	30
F	88	46	14	28
FR	88	44	11	33
C	88	49	13	26

amount of irrigation water, the effect of mulch on the loss of nitrate is more visible. Furthermore, higher water uptake by the plant in the FR treatment than in the other treatments with mulch shows that this placement of plastic mulch may serve to retain more moisture in the soil than other treatments with mulch. In general, according to the results, by using plastic mulch and applying less irrigation water, it is possible to save water without creating crop water stress, as well as reducing water and nitrate losses, thereby leading to a more sustainable model of agriculture. In the case of

Table 7. Deep percolation of irrigation water and nitrate leaching in different scenarios and treatments

Irrigation depth	Deep percolation of water (%)				Nitrate leaching (%)			
	R	F	FR	C	R	F	FR	C
125% CWR*	30.8	30.4	32.4	28.8	34.4	32.2	37.8	29.3
100% CWR	14.8	13.4	16.8	10.4	15.6	13.2	19.7	12.5
75% CWR	1.8	1.4	2.8	0.8	4.7	3.1	6.5	0.0

*CWR – crop water requirement.

Table 8. Maize water uptake at different levels of irrigation depth during the growing season (mm)

Irrigation depth	Treatment			
	R	F	FR	C
125% CWR*	232	232	232	232
100% CWR	232	232	232	215
75% CWR	185	197	208	164

*Explanations as in Table 7.

using plastic mulch and full irrigation compared to the control (mulch-free) treatment and 25% over-irrigation, without causing drought stress to the crop, nitrate leaching and the deep percolation of the irrigation water decreased 52, 44, and 30% and 53, 48, and 41% for the F, R, and FR treatments, respectively. Moreover, when the issue of preventing nitrate leaching is of great importance, it would be advisable to use the F and FR treatments with reduced irrigation water and accepting a slight reduction in crop yield in order to reduce fertilizer losses to almost zero. However, in order to determine the optimal scenario, it is necessary to evaluate net income while considering the crop yield and costs for water, fertilizer and mulch.

Finally, the use of plastic mulch on the furrow bed (the F treatment) produced the best performance in reducing nitrate and water losses. Bristow *et al.* (2020) confirmed the use of soil surface management approaches to reducing water and fertilizer losses. Moreover, considering the soil moisture storage and the solute balance, the use of plastic mulch treatment in furrow irrigation was suggested as a favourable approach in water and soil management by Yang *et al.* (2018).

In this study, short furrows were selected for more precise control and management of both irrigation and fertigation practices and the appropriate application of plastic mulch placements, although longer furrows are usually used in reality. In short furrows, it may be assumed that the infiltration depth along the furrow was the same. However, the advance and recession times on different sections of a longer furrow supposes that the infiltration depth in each section of the furrow may be different. Therefore, it is difficult to extrapolate the results of this study to longer furrows. Thus the necessity of considering a hydrodynamic model on the soil surface along with the HYDRUS-2D model to take into account the different infiltration depths along the long furrow. Moreover, carrying out similar field studies for longer furrows is recommended.

CONCLUSIONS

1. In this study, the effect of the placement of plastic mulch on reducing water loss and nitrate leaching in furrow-fertigated maize was investigated. The HYDRUS-2D model was used to simulate water movement and nitrate transfer within the soil.

2. Soil water content was increased with the use of plastic mulch in furrow irrigation which reduced the negative impact of crop water stress under deficit irrigation. This finding indicates the importance of using mulch under drought conditions, particularly with regard to the treatments of mulch on the furrow bed and mulch on the ridge and the furrow bed.

3. The results of the model calibration and validation show that the model had a relatively good performance in simulating soil water content and nitrate concentration. Under 25% over-irrigation conditions, nitrate and irrigation water losses for the treatments with mulch were higher than those of the control treatment. Thus, it was concluded that through the practice of using plastic mulch, conventional water management will lead to an increase in soil moisture and fertilizer leaching.

4. In the case of using plastic mulch and full irrigation compared to the treatment without mulch and with 25% over-irrigation, nitrate leaching and deep percolation of the irrigation water decreased by 52, 44, and 30% and by 53, 48, and 41% for the treatments of mulch on the furrow bed, mulch on the ridge and mulch on the ridge and the furrow bed, respectively.

5. Finally, numerical simulations indicated that the use of plastic mulch on the furrow bed with less irrigation depth (or moderate deficit irrigation) produced the best performance in terms of reducing water and nitrate losses.

6. The application of plastic mulch should take place with an appropriate level of consideration concerning extra precautions about its long-term impact on various soil properties and the environment due to microplastic residues. In recent years, a variety of biodegradable (Bio) plastics has been introduced to farmers to reduce the microplastic pollution of the ecosystem. The use of biodegradable forms of plastic mulch is suggested.

ACKNOWLEDGMENTS

We thank to Mr. Shayan Khanaki for his great assistance to our field experiments and lab measurements.

Conflict of interest: The authors declare no conflict of interest.

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