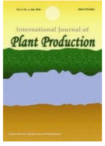

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Modification of a maize simulation model under different water, nitrogen and salinity levels

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Abstract

Irrigation, salinity and nitrogen (N) are the three major limiting environmental factors in maize yield potentials especially in arid and semi-arid regions. An integrated water and N Maize Simulation Model (MSM) was modified for salinity conditions using 2009-2010 field experiments data in southwest of Iran. Irrigation levels were: $I_1=1.0ET_c+0.25ET_c$ as normal leaching amount, $I_2=0.75I_1$ and $I_3=0.5I_1$, salinity of irrigation water: $S_1=0.6$, $S_2=2.0$ and $S_3=4.0$ dS m^{-1} and N fertilizer rate: $N_1=0$, $N_2=150$ and $N_3=300$ kg N ha^{-1}. Data of the first and second year were used to calibrate and validate the modified model, respectively. The MSM model was modified by including the combined effects of water and salt stresses using different water uptake functions. Furthermore, N uptake *via* mass flow process was also modified. By this modification, the soil salinity was also estimated by the model. Calibration/validation results showed that the water uptake function of Homaee and Feddes led to a better estimation of all parameters than those obtained by other water uptake functions. Based on the NRMSE and d indices, the modified MSM model presented a very good to fair estimation of soil water content, salinity and N, evaporation, transpiration, evapotranspiration, leaf area index, total dray matter, N uptake and grain yield. Besides, under saline irrigation water there was much higher risk to the groundwater contamination by nitrate leaching.

Keywords: Deficit irrigation; Nitrogen uptake; Nitrate leaching; MSM model; Water uptake models.

Introduction

Maize (*Zea mays* L.) is an important food/feed crop with a substantial cultivated area in I.R. of Iran. In many regions of Iran, water shortage and salinity are the main problems for farmers producing maize. In arid and semi-arid climate, irrigation water and N fertilizer should be applied efficiently. Because of suitable weather conditions for growth of maize and scarcity of fresh water in southern parts of Iran, it is necessary to manage the agricultural lands properly using crop simulation models. Many investigators studied the effects of irrigation water, its salinity levels and their interaction on maize growth and yield (Katerji et al., 2003; Amer, 2010). Furthermore, the effect of N fertilizer application rate along with irrigation water levels on yield has been reported for maize (Pang and Letey, 1998; Zand-Parsa and Sepaskhah, 2001; Tafteh and Sepaskhah, 2012).

Water and N effects on plant growth were considered in some models such as Crop-Environment-Resource-Synthesis (CERES) for maize (Jones and Kiniry, 1986), Ground Water Loading Effects of Agricultural Management Systems (GLEAMS) (Leonard et al., 1987), Environmental Productivity Integrated Climate (EPIC) (Williams et al., 1989), Leaching Chemistry Estimation and Chemistry Model (LEACHM) (Hutson and Wagenet, 1992) and Root Zone Water Quality (RZWQ) model (Great Plains System Research, 1992), WOFOST (van Ittersum et al., 2003), STICS (Brisson et al., 2003), CropSyst (Stockle et al., 2003). Watts and Hanks (1978) presented a mechanistic model describing the soil N budget for maize crop that effectively accounts for N movement and transformation in the soil.

The effect of water and salt stress has been considered in a model for yield prediction of some crops including maize (Sepaskhah et al., 2006). The SALTMED was developed by Ragab (2001) to simulate crop response to environmental stresses, e.g. drought and salinity. This model was evaluated well by Rameshwaran et al. (2013) for pepper under drip irrigation for predicting dry matter, soil water content and salinity.

Triple combined effect of water, salinity and N on maize yield has been considered in ENVIRO-GRO model (Pang and Letey, 1998). This model did not use a mechanistic approach for simulation of maize N uptake, diurnal distribution of soil temperature, evapotranspiration (ET) and dry matter (DM) production. In the MSM as described by Zand-Parsa et al. (2006), dynamic flow of water, N movement and heat flow through the soil were simulated in unsteady state conditions by numerical analysis in soil depth from 0–1.8 m in sprinkler irrigation system. The MSM model was modified by Majnooni-Heris et al. (2011) and Nehzati-Paghaleh (2008) for furrow irrigation and different plant densities, respectively.

The objectives of this study were to modify the MSM model for predicting maize growth and yield under saline water application at different levels of irrigation water and N fertilizer in furrow irrigation. Furthermore, water uptake functions of Maas and Hoffman (1977) and Homaee and Feddes (1999) were used in the model modification for their suitability.

Materials and Methods

Description of the MSM model

The MSM model is a multi-component model for maize growth that simulates hourly top DM production. The MSM model has a main program and nine subroutines. These subroutines were described in details by Zand-Parsa (2001) and Zand-Parsa et al. (2006) for sprinkler irrigation and modified for furrow irrigation by Majnooni-Heris et al. (2011). The model used by Majnooni-Heris et al. (2011) is described in this section.

Dry matter is produced by interaction between different parameters such as intercepted solar radiation by plant leaves, meteorological parameters especially air temperature, irrigation water and soil nutrients. In the model, hourly potential top DM production ($HDMP^{j+1}$) is calculated by the multiplication of the radiation use efficiency (K_{DM}) and hourly corrected intercepted radiation ($RSLT^{j+1}$) as:

$$HDMP^{j+1} = 0.01 K_{DM} RSLT^{j+1} \tag{1}$$

where j is the hour after planting, K_{DM} is the radiation use efficiency (g MJ^{-1}) of maize plant which is defined by the field experiment under no water and nitrogen deficit as 0.0146 (Zand-Parsa et al., 2006). The parameter of corrected intercepted radiation ($RSLT^{j+1}$) that is the multiplication of hourly intercepted radiation (RSL_j) and temperature effect factor is calculated using the hourly solar radiation, hourly intercepted and corrected intercepted solar radiation at j+1 h after planting which has been described in detail by Zand-Parsa et al. (2006). Therefore, relationship between the accumulated potential top DM production (DMP^{j+1}, Mg ha^{-1}) without water and nitrogen deficiency and the accumulated hourly temperature corrected radiation intercepted by plant leaves ($SRSLT^{j+1}$, MJ m^{-2}) is shown as follows:

$$DMP^{j+1} = 0.01 K_{DM} SRSLT^{j+1} \tag{2}$$

Plant growth is highly affected by the supply of N. The concentration of N in plant tissue also changes as the plant ages. The minimum and maximum above ground plant-N concentration (PN_{min} and PN_{max}, respectively) can be obtained by the results of maize field experiments as a function of relative growth stage (the ratio of days after planting to total days of growth period).

When plant-N concentration was equal to PN_{min}, then, hourly top and root DM production by photosynthesis is decreased to the value of N uptake in previous hour divided by PN_{min}, otherwise, hourly top and root DM production are equal to the amount of their potential values. Hence, top DM production is estimated by Equation (1). Therefore, the value of actual accumulated top DM (DMA^{J+1}, Mg ha^{-1}) at J+1 hour after planting will be as follows:

$$DMA^{j+1} = \sum_{jt=0}^{jt=j+1} HDMA^{jt} \tag{3}$$

where $HDMA^{jt}$ is the actual hourly top DM production at jt hours after planting (Mg ha^{-1}). When time increases after emergence, DMA^{j+1} and leaf area index (LAI^{j+1}) increase. However, after tasseling, LAI^{j+1} decreases, due to leaves senescence. As plants grow, DMA^{j+1} and LAI^{j+1} are increased up to a time of t_{max} after planting that LAI^{j+1} reaches a maximum. When the days after planting is less than t_{max}, the relationship between DMA^{j} and LAI^{j+1} for all treatments is shown as a Polynomial function of DMA^{j}.

$$LAI^{j+1} = f(DMA^{j}) \tag{4}$$

This function is determined using field experimental data. When the number of days after planting are greater than t_{max}, the LAI^{j+1} is decreased and finally approaches zero at harvest. This trend is described as a quadratic equation depending on the cumulative and corrected solar radiation (Zand-Parsa et al., 2006).

In the MSM model after reading input data, transformation of N was computed at the first hour of each day. The values of soil water content at layer i and j hour after planting (θ_i^j), soil temperature (T_i^j) and soil nitrate concentration (CN_i^j) were known in different soil layers from soil surface to maximum root depth (1.8 m) at j hours after planting. Plant N uptake was calculated during previous hour. The values of radiation parameters (extraterrestrial, solar, plant intercepted, long wave and sky), potential evaporation (E) and potential transpiration (T) are calculated between j and j+1 hours for the experimental conditions. The values of soil water content (θ_i^{j+1}), T_i^{j+1} and CN_i^{j+1} are simulated at each soil layer i at j+1 hour after planting by considering soil water redistribution, N movements and its uptake by plant and heat transfer during previous hour. Then, the values of soil heat flux (G^{j+1}), actual E (Ea^{j+1}) and T (Ta^{j+1}) are simulated during j and j+1 hours. Dry matter production is calculated during j and j+1 hours based on the N uptake during j-1 and j hours. These processes will be continued until day of harvest. The value of HI will be calculated at harvest after calculation of total seasonal plant N uptake. Grain yield is obtained by multiplication of HI and total seasonal DM production.

In this model root N uptake was determined based on soil water pressure head and van Genuchten parameters of soil water retention curve (van Genuchten, 1980). GY prediction was based on the seasonal plant top N uptake and grain N concentration. The relationship between grain-N uptake (GN, kg ha^{-1}) and plant top N uptake (NU, kg ha^{-1}) was determined as follows:

$$GN = a(NU) + b \tag{5}$$

Then the relationship between the measured GN and grain N concentration [GNP, the ratio of grain-N (GN) to gain yield, %] for combined data was given as:

$$GNP = c(GN) + d \tag{6}$$

where a, b, c and d in Equations (5) and (6) are regression constants. Therefore, Majnooni-Heris et al. (2011) concluded that grain yield (GY, Mg ha^{-1}) can be predicted by dividing grain N uptake [predicted using Equation (5)] by grain N concentration [predicted using Equation (6)], shown as follows:

$$GY = 0.115\frac{GN}{GNP} \tag{7}$$

where GY is the grain yield (Mg ha^{-1}) at 15% grain moisture content and the value of 0.115 is the multiplication of 0.1 (unit conversion) by 1.15.

Modification of the MSM model for salinity conditions

When saline irrigation water is applied, the salts accumulate in the soil. Therefore, soil osmotic potential is decreased. Crop water uptake is consequently reduced in lower osmotic potential conditions. In the modified MSM model, osmotic potential was calculated using the soil solution salinity. Soil salinity was estimated by salt balance method. Two cases were presumed to estimate the salinity of each soil layer:

(i) when leaching was occurred from a given soil layer due to higher applied water than the soil water holding capacity. In this case, salts were leached to the next layer. To estimate the salinity in each soil layer, it is assumed that total remained salt from previous irrigation event is dissolved in the entered water into the soil layer and resulted in a uniform salt solution. Therefore, salinity of deep percolated water from a given layer is equal to its electrical conductivity of soil solution (EC^j_{ssi}). The electrical conductivity of soil solution in a given layer is calculated as follows:

(ii)

$$EC^j_{ssi} = \frac{\dfrac{((EC^j_{ssi-1} \times 640 \times DP^j_{i-1} + EC^{j-1}_{ssi} \times 640 \times \theta^{j-1}_i \times \Delta z}{DP^j_{i-1} + \theta^{j-1}_i \times \Delta z}}{640} \tag{8}$$

Where EC^j_{ssi} is the electrical conductivity of soil solution of layer i in hour j (dS m^{-1}), EC^j_{ssi-1} is the electrical conductivity of water that is entered into the layer from the upper layer that is equal to the electrical conductivity of soil solution in the upper layer (dS m^{-1}), EC^{j-1}_{ssi} is the electrical conductivity of soil solution in the layer from previous irrigation event (dS m^{-1}), θ^{j-1}_i is the soil volumetric water content (m^3 m^{-3}) in layer i at hour j, DP^j_{i-1} is the depth of water entered each soil layer in hour j from upper layer (i-1) (mm), 640 is the conversion coefficient of the electrical conductivity of soil solution (dS m^{-1}) to salt concentration (mg L^{-1}) (Richards, 1954) and Δz is the layer thickness (mm).

(iii) In second case, water is entered to a soil layer but leaching is not occurred from the layer. Therefore, soil salinity is calculated as follows:

$$EC^j_{ssi} = EC^{j-1}_{ssi} + \frac{\dfrac{(EC^j_{ssi-1} \times 640 \times DP^j_{i-1})}{\theta_{si} \times \Delta z}}{640} \tag{9}$$

Where θ_{si} is the saturation soil water content of layer i (m^3 m^{-3}).

After estimation of the soil salinity, osmotic potential (h_o) of the soil water was estimated by the following equation (Richards, 1954):

$$h_o = -360 EC_e \tag{10}$$

where h_o is the osmotic potential (cm) and EC_e is the electrical conductivity of soil saturation extract in dS m^{-1} which is derived from EC_{ss} multiplying by 0.70. The salinity of soil saturation extract is lower than that for soil water at field capacity due to dilution effect. Therefore, 0.7 was used to convert the the EC_{ss} to EC_e (Smedema and Rycroft, 1983). Similar equations [Equations (8) and (9)] were used by Dominguez et al. (2011) in a salt model. However, they used DP/2 instead of DP. This is due to the fact their model calculated daily mean soil salt content, while in our model it is calculated on hourly basis. Therefore, it is not needed to multiply DP by 0.5.

Root water uptake is reduced by water and salinity stresses. In these conditions, during an irrigation interval, ET depletes the soil water content and consequently the matric and osmotic potential of the soil water are reduced and these factors reduce root water uptake. Hence, root water uptake under coupled water and salinity stresses was determined as follows (Richards, 1931):

$$S = S_{\max}\alpha(h,h_o) \tag{11}$$

where S_{max} is the maximum root water uptake rate (under no stress conditions) that is equal the potential crop transpiration and α (h,h_o) is the water uptake reduction function that is a function of soil water pressure (h) and osmotic potential (h_o). Two available functions for water uptake reduction function based on the combined stresses are as follows:

$$\alpha(h,h_o) = \frac{h-h_4}{h_3-h_4}\left[1-\frac{b}{360}(h_o^*-h_o)\right] \tag{12}$$

Maas and Hoffman (1977)

$$\alpha(h,h_o) = \frac{h-(h_4-h_o)}{h_3-(h_4-h_o)}\left[1-\frac{b}{360}(h_o^*-h_o)\right] \tag{13}$$

Homaee and Feddes (1999)

where h^*_o is the threshold soil water osmotic potential corresponding to the threshold soil water salinity, h_o is the soil osmotic potential corresponding to the soil water salinity, h is the soil matric head corresponding to the soil water content, h_3 is the soil water pressure head threshold and h_4 is the soil water pressure head at wilting point and b is the dry matter reduction per unit increase in saturated soil extract salinity under full irrigation conditions. These parameters were reported for maize by Azizian and Sepaskhah (2014b) and used in this study. Equations (12) and (13) were determined for each layer at each hour and used to calculate the actual transpiration. After modifying water uptake, the nitrogen uptake by plant *via* mass flow process was also modified. Then, DM production and finally GY were determined based on the modified relationships [Equations (5)-(7)]. Furthermore, the model was modified based on Equations. (12) and (13) and results were compared to choose the one with the most accurate results.

In the modified MSM model, dynamic flow of water through the soil were simulated in unsteady state conditions by numerical analysis in soil depth of 0-1.8 m. Hourly potential ET for maize field was estimated directly by Penman-Monteith method (Allen et al., 1998) that has been modified for local conditions. Hourly potential soil surface E (E_p) was estimated based on hourly potential ET and canopy shadow projection. Actual E of soil surface was estimated based on its potential value, relative humidity of air, water pressure head and temperature at soil surface layer (Stockle and Campbell, 1985). Actual T was estimated based on the soil water content and root distribution at each soil layer and water uptake reduction function under combined water and salt stress in the presented modified version.

In the modified MSM model, soil depth was divided into 5 cm-thickness layers. Besides, Richards' equation was used for simulation of water flow through the soil

(Zand-Parsa et al., 2006). The van Genuchten soil hydraulic parameters, irrigation depth and initial soil water contents at different depths at planting were required for prediction of soil water content. The values of soil E from top layer, T by absorbing water from root depth, redistribution of soil water and deep percolation at soil bottom layer at the depth of 1.8 m were simulated by the modified MSM model. Soil water content at each layer was hourly determined. Then, the soil water contents at different 30 cm-soil layers were daily averaged in the root zone.

Soil saturation extract was prepared by the method as described by the U.S. Salinity Laboratory Staff (Richards, 1954) to determine the soil salinity. In the modified MSM model, the electrical conductivity of soil solution for each layer was determined based on Equations (8) or (9). In this estimation, both initial electrical conductivity of soil solution and irrigation water were required. Soil salinities at different soil layers were averaged in the root zone.

Dynamic flow of N movement through soil in the modified MSM model is described by the convection-dispersion equation. In this analysis, different forms of N transformation were considered. The main transformations of N are: (1) urea hydrolysis, (2) mineralization of organic N to inorganic N, (3) immobilization or transformation of inorganic N to organic form, (4) nitrification or transformation from ammonium to nitrate, (5) denitrification or reduction of nitrate to gaseous products including NO, N_2O and N_2 (Zand-Parsa et al., 2006). In the modified MSM model, the values of root N uptake was considered as convective flow (mass flow) and diffusion based on the values of soil N supply and plant stover N contents.

The mass flow of N is the movement of nitrate through the soil toward the root in the convective flow of water that is caused by plant water absorption. The amount of nitrate movement from soil to plant by mass flow is related to the plant water uptake and nitrate concentration in soil water. As plant water uptake (T) was modified under water and salt stress [Equations (11)-(13)], mass flow nitrogen uptake was simultaneously modified. The portion of N uptake by diffusion process does not need to be modified in the modified MSM model.

In the modified MSM model, grain yield is affected by quantity and quality of irrigation water, N fertilizer, soil and meteorological conditions. The modification of Majnooni-Heris et al. (2011) was used for GY estimation from DM production. In the modified MSM model, plant top N uptake is simulated on an hourly basis during the growing season influenced by combined water and salinity stresses.

Field experiments

Two independent field experimental data set were used for modification and validation of the MSM model, respectively. The experiments were conducted in 2009 and 2010 at the Agricultural Experiment Station, College of Agriculture located at Bajgah with 29° 56’ N latitude, 52° 02’ E longitude and 1810 m above the mean sea level, in southwest of Iran with a semi-arid climate. Long-term mean air temperature, precipitation and relative humidity of the region are 13.4 °C, 387 mm and 52.2%, respectively. Most root activity of maize usually is occurred in 0-0.60 m soil layer. Therefore, soil properties of the experimental site for this layer were determined. The soil is classified as silty clay loam for 0-0.60 m of top soil profile. Physico-chemical properties of the soil and chemical analysis of the fresh and saline irrigation water are presented in Table 1.

Table 1. Physico-chemical properties of the soil used in the experiment (average of two years).

Characteristic	Amount		
	Depth (cm)		
Soil analysis	0-30	30-60	
Texture	SCl*	SCl	
Clay (%)	52.5	53.8	
Silt (%)	34.0	35.5	
Field capacity (-0.03 MPa) (%)	31	30	
Permanent wilting point (-1.5 MPa) (%)	18	19	
Bulk density (Mg m^{-3})	1460	1560	
EC (dS m^{-1})	0.65	0.55	
pH (saturated past)	7.50	7.45	
Organic matter (%)	0.7	0.5	
Total Nitrogen (%)	0.021	0.009	
NO_3-N (mg L^{-1})	4.6	6.0	
Available P (mg L^{-1})	21.0	11.0	
Available K (mg L^{-1})	343.0	315.0	
Water analysis	Fresh water	Saline water	
EC (dS m^{-1})	0.60	2.00	4.00
pH	7.80	7.70	7.80
Cl^{-1} (meq L^{-1})	1.81	17.27	40.37
Na^+ (meq L^{-1})	1.74	18.9	30.3
Ca^{2+} (meq L^{-1})	2.15	16.17	39.41
Mg^{2+} (meq L^{-1})	2.00	2.00	2.00
HCO_3^- (meq L^{-1})	1.97	4.99	4.64

* Silty Clay Loam

For calibration of the model, potential crop evapotranspiration of maize (ET_c) was calculated by multiplying reference evapotranspiration (ET_o) and crop coefficient (K_c) (Allen et al., 1998). ET_o in the study area was calculated using modified FAO-Penman-Monteith method (Razzaghi and Sepaskhah, 2012) with collected meteorological data in a standard weather station at the Agricultural College located nearby the experimental field. For K_c the modified crop coefficient of maize in the study area was used (Shahrokhnia and Sepaskhah, 2013).

Maize (cv SC704, a late maturity hybrid) was planted on May 21, 2009 and May 25, 2010 using furrow irrigation system. Length and spacing of the furrows were 5 and 0.75 m, respectively and there were five furrows in each plot. Final maize density after thinning was 88888 plants ha^{-1} with on-row spacing of 15 cm. There was no precipitation or groundwater contribution (groundwater depth >40 m) during the growing seasons. Phosphorus in the form of triple super-phosphate was applied at a rate of 200 kg ha^{-1} (as 92 kg P_2O_5 ha^{-1}) before planting.

After sowing, the field was adequately watered in the first and second irrigation event for different irrigation treatments (after sowing to three-leaf stage of plant) with 200 mm of water. This practice guaranteed seed germination for a rigorous stand. After first irrigation a 1.5 m length aluminum access tube was installed at the center of the plots in two replications for measuring soil water content using neutron scattering method. Salinity and irrigation treatments were initiated at the third irrigation (3-4 leaf stage of maize). Treatments were three levels of irrigation water, salinity of irrigation water and nitrogen fertilizer rate. Irrigation was scheduled with 7-day interval (Sepaskhah et al., 1993; Zand-Parsa and Sepaskhah, 2001) and ET_c was considered as full plant water requirement for upcoming 7-day. The irrigation treatments were I_1 ($1.0ET_c$ $+0.25ET_c$ as leaching fraction), I_2 ($0.75I_1$) and I_3 ($0.5I_1$). Nitrogen (as urea) levels were 300, 150 and 0 kg N ha^{-1} as N_3, N_2 and N_1, respectively. Seventy percent of the N fertilizer was applied at 3rd week and the rest was applied at10th week after planting in both years. Salinity treatments were denoted as S_3, S_2 and S_1, equivalent to 4, 2 and 0.6 (groundwater salinity) dS m^{-1}. The S_3 and S_2 treatments were obtained by adding NaCl and $CaCl_2$ salts to the irrigation water with equal proportion. The experimental design was a split-split plot arrangement with three replications. Water, salinity and nitrogen treatments were considered as the main- sub- and sub-sub factor, respectively. The irrigation water was applied using a volumetric measuring device. After first year, the field was leached using two heavy irrigation events to reduce soil profile salinity during winter season. The arrangement of the experimental treatments in the field in second year (2010) was the same as that in the first year.

Volumetric soil water contents in different irrigation treatments were monitored by neutron scattering method (neutron meter, Model CPN, 503DR) up to 1.5 m depth with 0.30 m intervals before every irrigation event. The crop evapotranspiration for irrigation intervals (ET, mm) was estimated by the water balance procedure using the following equation (Jensen, 1973):

$$ET=I+P-D\pm(\textstyle\sum_{i=1}^{n}(\theta_1-\theta_2)\Delta S_i) \qquad (14)$$

Where I is irrigation amount (mm), P is precipitation (mm), D is deep percolation (mm) from the bottom of root zone, n is the number of layers, ΔS is the thickness of each soil layer (mm) and θ_1 and θ_2 are volumetric soil water contents (cm^3 cm^{-3}) before two consecutive irrigations. Cylindrical micro-lysimeter (PVC), 20 cm deep and 10.5 cm internal diameter, was used to measure the soil evaporation (E). They were placed along the furrows, between two rows of crops (the area that wetted by irrigation). The cylinders were filled with disturbed soil from the surrounding field at the sowing day and they were weighed before and after each irrigation event during the growing season. Soil evaporation was calculated as the decrease in micro-lysimeter weights in two consecutive irrigation events. Furthermore, crop transpiration was determined by subtracting soil evaporation from crop evepotranspiration.

Plant height, leaf area index (LAI) and dry matter (DM, oven dried at 70 °C until constant weight) production were measured from 3-6 plants during the growing season at 30-day intervals. Simultaneously, soil samples of each 0.30 m increment up to 1.5 m depth, were taken, air dried and passed through 2 mm sieve for chemical analysis including electrical conductivity of soil saturation extract (EC_e) using the methods described by the U. S. Salinity Laboratory Staff (Richards, 1954) and soil NO_3-N using the method presented by Chapman and Pratt (1961).

Plants were harvested on October 11 in both years from three middle rows of each plot with length of 4 m and oven dried afterward at 70 °C until constant weight. Total DM and grain yield (GY, at 15% moisture content) were measured. Nitrogen contents of grain and stover were determined by the Kjeldahl method (Chapman and Pratt, 1961). Harvest index (HI, as GY/DM), was also determined. Data of the first year was used to calibrate the model and data of the second year was used to validate the model.

Statistical analyses

To evaluate the results, Normalized Root Mean Square Error (NRMSE) and index of agreement (d) were determined as follows:

$$NRMSE = \frac{\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}}{\overline{O}} \tag{15}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|)^2} \tag{16}$$

where, P_i and O_i are the predicted and measured values of a parameter, respectively, n is the number of measurements and $\overline{O}$ and $\overline{P}$ are the means of measured and predicted values, respectively.

Results and Discussion

Model modification

Evapotranspiration, transpiration and evaporation

Results showed that the water uptake reduction function of Homaee and Feddes (1999) [Equation (13)] was more appropriate for estimation of ET, T and E since the NRMSE and d of the results of this model were lower and higher than those values of Mass and Hoffman (1977) equation [Equation (12)], respectively (Table 2). The same result was obtained for other traits that were obtained from the model. Therefore, Equation (13) was selected for the model. Relationship between the predicted and measured values of ET, T and E are presented in Figure 1. The values of NRMSE and d indicated that the modified MSM model could estimate these three parameters with acceptable accuracy, especially in the ET. Azizian and Sepaskhah (2014b and c), Sepaskhah and Yarami (2010) and Shabani et al. (2013) also showed that Homaee and Feddes (1999) equation predicted ET/T of maize, saffron and rapeseed, respectively, with more accuracy in comparison with other water uptake reduction functions.

Soil water content and salinity

Relationship between the measured (at 13, 63 and 119 day after planting) and predicted soil water content in the root zone was determined (Figure 2a). The NRMSE and d for this comparison were 0.13 and 0.741, respectively indicated an acceptable estimation of soil water content by the model.

Relationship between the measured and predicted soil salinity was presented in Figure 2(b). The value of NRMSE was 0.225 that showed a fair estimation of soil salinity by the modified MSM model; however, the d value was 0.940 which indicated an accurate estimation of soil salinity. The presented results of soil water content and soil salinity were based on the Homaee and Feddes (1999) equation [Equation (13)] which showed a better estimation compared with Maas and Hoffman (1977) function [Equation (12)] in calibration stage (Table 3).

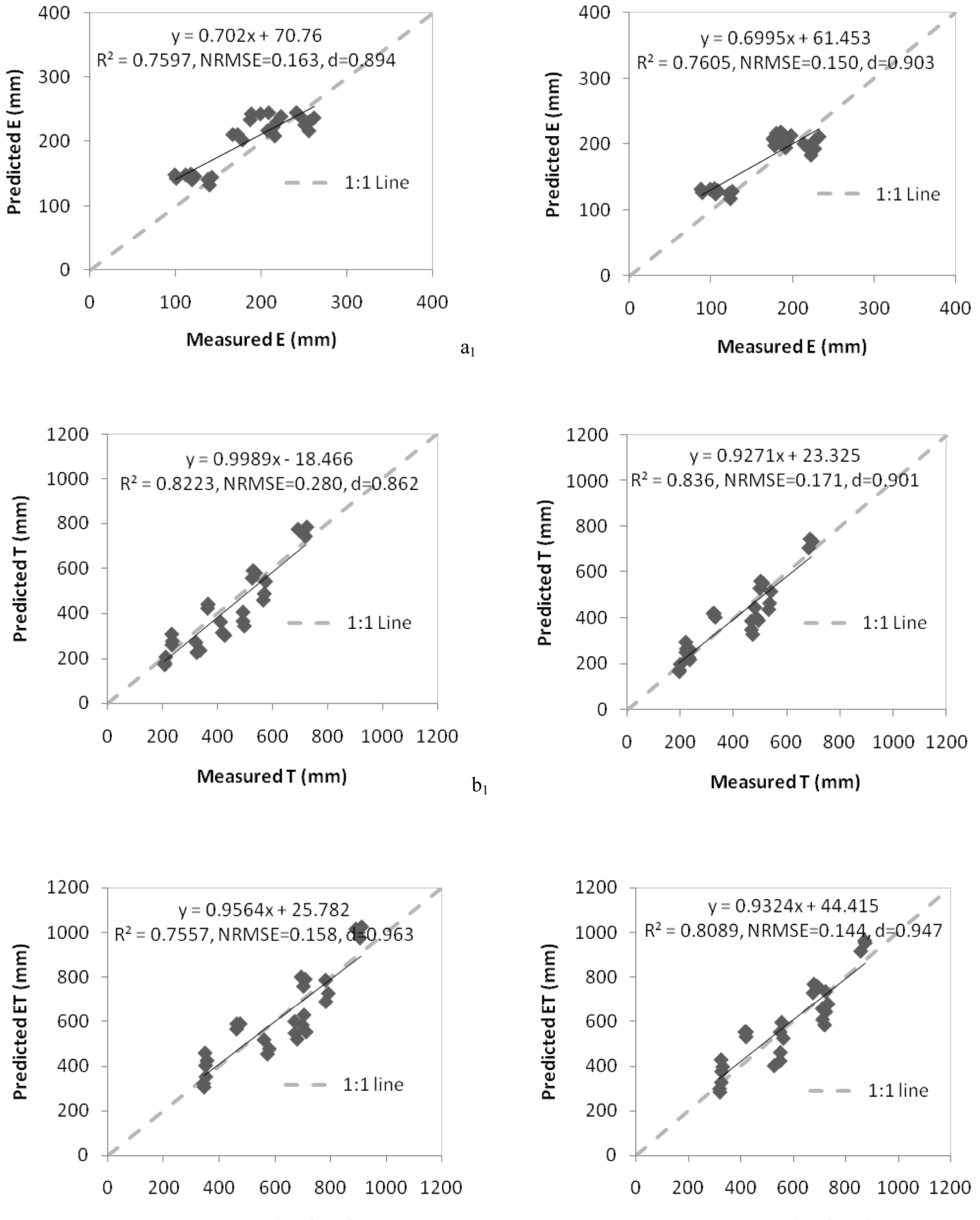
Table 2. Relationship between the predicted and measured actual evapotranspiration (ET_a), transpiration (T_a), evaporation (E_a), soil water content (ϴ), electrical conductivity of soil water extract (EC_e), leaf area index (LAI), top plant nitrogen uptake (TopN), top dry matter (DM) and grain yield (GY) based on two soil water uptake reduction functions (calibration).

Water uptake reduction function	Predicted-measured relationship	R^2	NRMSE[1]	d[2]
Maas and Hoffman (1977)	$E_{ap} = 0.666(E_m) + 91.300$[3]	0.628	0.203	0.790
Homaee and Feddes (1999)	$E_{ap} = 0.702(E_m) + 70.760$	0.760	0.163	0.894
Maas and Hoffman (1977)	$T_{ap} = 0.899(T_m) – 19.40$	0.762	0.320	0.812
Homaee and Feddes (1999)	$T_{ap} = 0.999(T_m) – 18.470$	0.822	0.280	0.862
Maas and Hoffman (1977)	$ET_{ap} = 0.819(ET_m) + 18.210$	0.716	0.218	0.913
Homaee and Feddes (1999)	$ET_{ap} = 0.956(ET_m) + 25.780$	0.756	0.158	0.963
Maas and Hoffman (1977)	$\Theta_p = 0.773(\Theta_m) + 0.0560$	0.611	0.182	0.725
Homaee and Feddes (1999)	$\Theta_p = 0.787(\Theta_m) + 0.051$	0.626	0.130	0.741
Maas and Hoffman (1977)	$EC_{ep} = 1.051(EC_{em}) + 0.202$	0.781	0.259	0. 890
Homaee and Feddes (1999)	$EC_{ep} = 1.039(EC_{em}) + 0.163$	0.879	0.225	0.940
Maas and Hoffman (1977)	$LAI_p = 0.907(LAI_m) + 0.423$	0.740	0.264	0.949
Homaee and Feddes (1999)	$LAI_p = 0.924(LAI_m) + 0.382$	0.756	0.215	0.925
Maas and Hoffman (1977)	$TopN_p = 0.800(TopN_m) - 3.615$	0.552	0.316	0.817
Homaee and Feddes (1999)	$TopN_p = 0.843(TopN_m) – 3.891$	0.587	0.295	0.814
Maas and Hoffman (1977)	$DM_p = 1.286(DM_m) - 1.059$	0.788	0.309	0.920
Homaee and Feddes (1999)	$DM_p = 1.106(DM_m) - 1.471$	0.883	0.271	0.962
Maas and Hoffman (1977)	$GY_p = 1.014(GY_m) - 1.541$	0.710	0.281	0.809
Homaee and Feddes (1999)	$GY_p = 1.004(GY_m) - 1.283$	0.779	0.235	0.895

[1] NRMSE: normalized root mean square error.

[2] d: index of agreement.

[3] p and m subscripts represent predicted and measured parameters, respectively.



a_1 a_2 b_1 b_2 c_1 c_2

Figure 1. Relationship between the predicted and measured (a) actual evaporation (E), (b) transpiration (T) and (c) evapotranspiration (ET) (1: calibration and 2: validation).

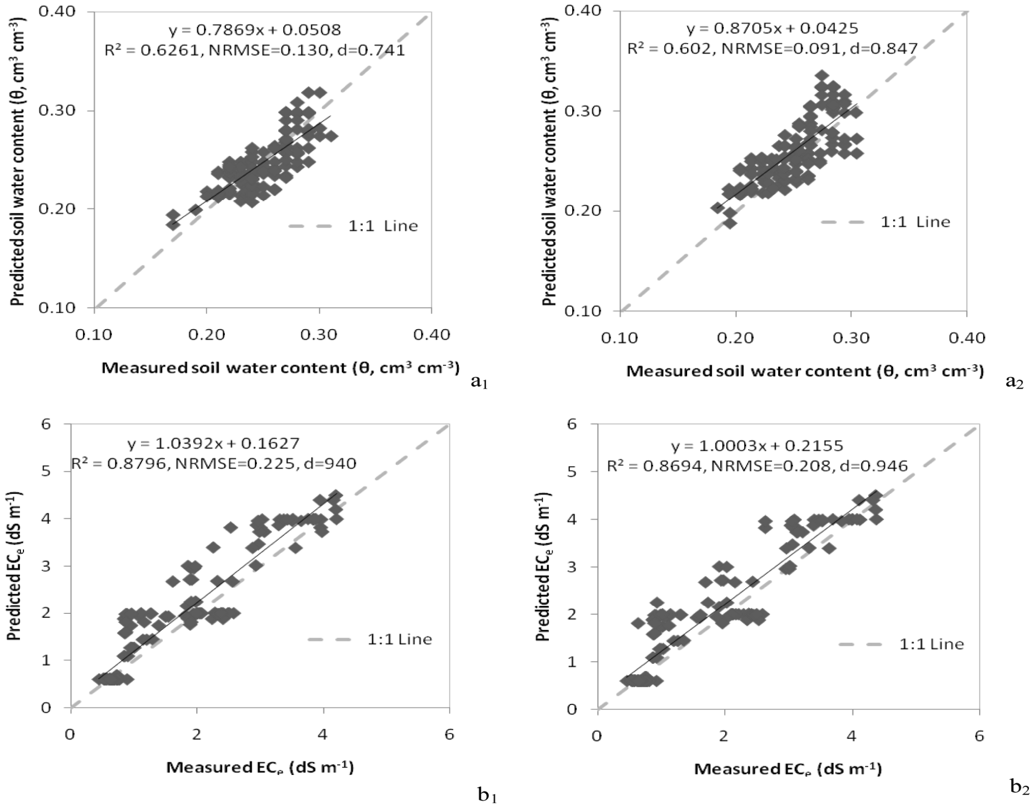


Figure 2. Relationship between the measured and predicted (a) soil water content (θ) and (b) soil saturation electrical conductivity (EC_e) (1: calibration and 2: validation).

Table 3. Relationship between the predicted and measured actual evapotranspiration (ET_a), transpiration (T_a), evaporation (E_a), soil water content (Θ), soil saturation extract salinity (EC_e), leaf area index (LAI), top plant nitrogen uptake (TopN), top dry matter (DM) and grain yield (GY) based on two soil water uptake reduction functions (validation).

Water uptake reduction function	Predicted-measured relationship	R^2	NRMSE[1]	d[2]
Maas and Hoffman (1977)	$E_{ap} = 0.556(E_m) + 61.33$[3]	0.728	0.193	0.880
Homaee and Feddes (1999)	$E_{ap} = 0.699(E_m) + 61.45$	0.761	0.150	0.903
Maas and Hoffman (1977)	$T_{ap} = 0.884(T_m) + 29.40$	0.772	0.240	0.892
Homaee and Feddes (1999)	$T_{ap} = 0.927(T_m) + 23.33$	0.836	0.171	0.901
Maas and Hoffman (1977)	$ET_{ap} = 0.879(ET_m) + 48.21$	0.756	0.188	0.903
Homaee and Feddes (1999)	$ET_{ap} = 0.932(ET_m) + 44.42$	0.809	0.144	0.947
Maas and Hoffman (1977)	$\Theta_p = 0.812(\Theta_m) + 0.036$	0.591	0.152	0.825
Homaee and Feddes (1999)	$\Theta_p = 0.871(\Theta_m) + 0.043$	0.602	0.091	0.847
Maas and Hoffman (1977)	$EC_{ep} = 1.071(EC_{em}) + 0.130$	0.781	0.292	0.910
Homaee and Feddes (1999)	$EC_{ep} = 1.0003(EC_{em}) + 0.216$	0.869	0.208	0.946
Maas and Hoffman (1977)	$LAI_p = 0.887(LAI_m) + 0.400$	0.740	0.214	0.909
Homaee and Feddes (1999)	$LAI_p = 0.942(LAI_m) + 0.372$	0.776	0.171	0.948
Maas and Hoffman (1977)	$TopN_p = 0.710(TopN_m) - 12.65$	0.702	0.296	0.817
Homaee and Feddes (1999)	$TopN_p = 0.898(TopN_m) - 13.409$	0.711	0.265	0.861
Maas and Hoffman (1977)	$DM_p = 1.286(DM_m) - 1.150$	0.848	0.298	0.942
Homaee and Feddes (1999)	$DM_p = 1.124(DM_m) - 1.283$	0.882	0.276	0.961
Maas and Hoffman (1977)	$GY_p = 1.179(GY_m) - 0.123$	0.799	0.220	0.914
Homaee and Feddes (1999)	$GY_p = 1.085(GY_m) - 0.296$	0.808	0.211	0.936

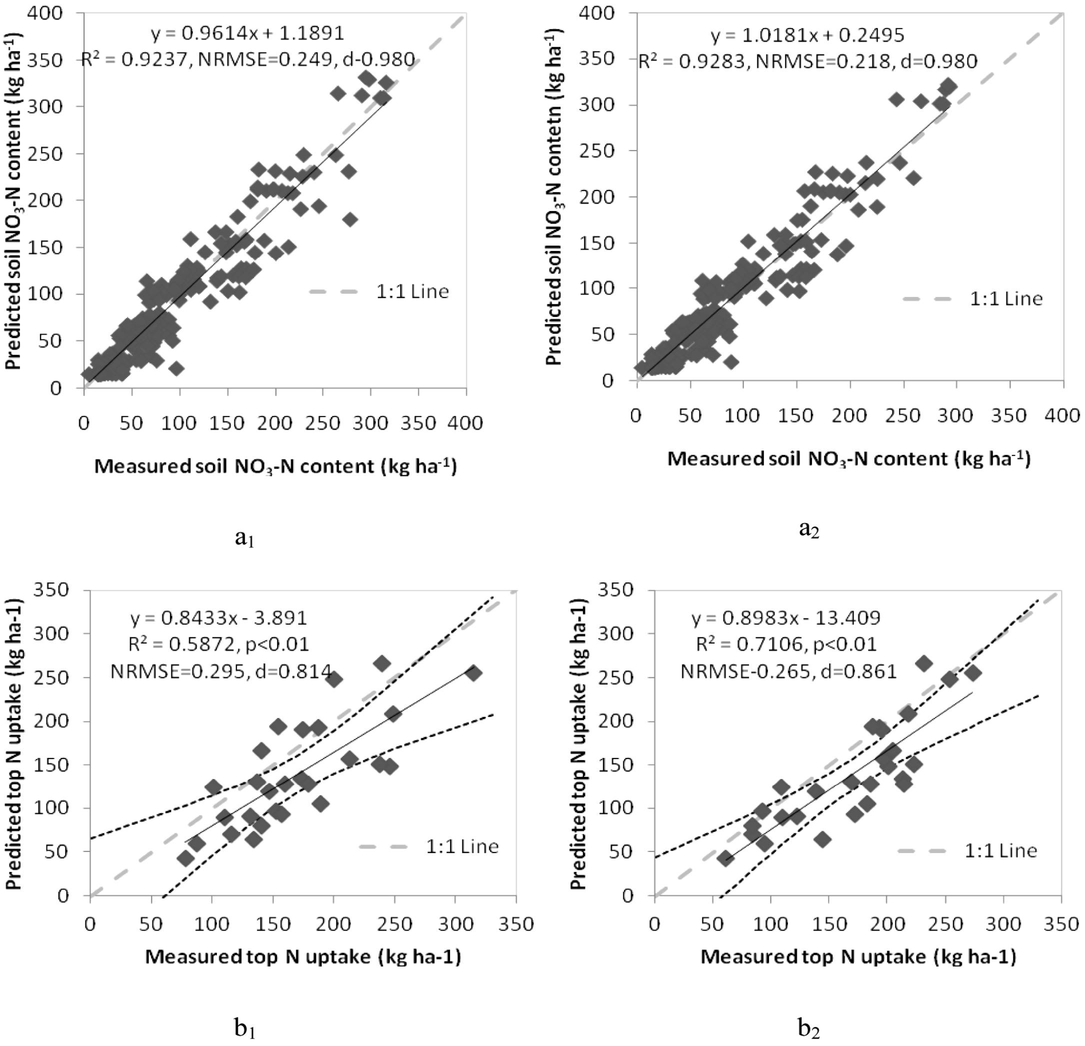
[1] NRMSE: normalized root mean square error.

[2] d: index of agreement.

[3] p and m subscripts represent predicted and measured parameters, respectively.

Soil nitrate content and plant top nitrogen uptake

Relationship between the predicted and measured soil nitrate contents and maize top N uptake are presented in Figure 3. The values of NRMSE and d for these relationships indicated a fair estimation of soil nitrate content and plant top N uptake by the modified MSM model in calibration stage. Results showed that water uptake reduction function as described by Homaee and Feddes [1999, Equation (13)] resulted in more acceptable estimation of soil and plant nitrogen as compared with those obtained by Maas and Hoffman (1977) equation (Table 3).



a_1 a_2

b_1 b_2

Figure 3. Relationship between the measured and predicted (a) soil NO_3-N content and (b) maize top nitrogen (N) uptake (1: calibration and 2: validation). Fine dashed lines in the b-pictures represent the 95% confidence interval of the regression line.

Leaf area index and top dry matter

The values of leaf area index (LAI) were determined after emergence for all treatments in 4-week intervals. When the day after planting is less than t_{max} (the time at which maximum leaf area index occurred), relationship between top DM production

(DMA) and LAI for all treatments is obtained by multiple regression analysis as follows:

$$LAI=9\times10^{-6}DMA^{6}-0.0005DMA^{5}-0.0094DMA^{4}+0.0958DMA^{3}+0.5355DMA^{2}+1.8468DMA \quad (17)$$

$R^2=0.8491$, $n=243$, $SE=0.416$, $P<0.0001$

Such a high order of polynomial relationship between LAI and DMA for maize was reported by Zand-Parsa et al. (2006). Relationship between LAI and DMA for all treatments up to t_{max} is shown in Figure 4(a). When the days after planting are greater than t_{max}, the LAI is decreased. This trend is described by a quadratic equation between LAI and cumulative corrected solar radiation with air temperature (Zand-Parsa et al., 2006). The predicted and measured LAI was compared in Figure 4(b). The NRMSE and d values of this comparison were 0.215 and 0.925 indicated an acceptable estimation of LAI by the modified MSM model in the calibration stage.

In the modified MSM model, hourly top DM was simulated by considering corrected intercepted solar radiation with air temperature by maize leaves, root N uptake and radiation use efficiency (Zand-Parsa et al., 2006). Top DM of plant was measured monthly after planting. Comparison between the predicted plant top DM by the modified MSM model and the measured values for different treatments are shown in Figure 4(c). The NRMSE (0.271) and d (0.962) values of the comparison indicated an acceptable estimation of maize top DM in the calibration stage. These results were based on the Homaee and Feddes (1999) equation [Equation (13)] which was more acceptable that those of Maas and Hoffman (1977) equation (Table 3).

Grain yield

Relationships between grain-N and plant top N uptake obtained by using the data for calibration (Figure 5a) were as follows:

$$GN = 0.681NU - 1.876 \quad (18)$$

$R^2=0.818$, $n=81$, $SE=19.05$, $P<0.0001$

Then the relationship between measured GN and grain N concentration [GNP, the ratio of grain-N (GN) to gain yield, %] for combined data (Figure 5b) was given as:

$$GNP = 0.004GN - 1.166 \quad (19)$$

$R^2=0.178$, $n=81$, $SE=0.319$, $P=0.0001$

Therefore, GY (Mg ha^{-1}) was predicted by using Equation (8). The predicted and measured maize GY was compared in Figure 5(c). The NRMSE and d values of this comparison (0.235 and 0.895, respectively) indicated that the modified MSM model estimated GY of maize with acceptable accuracy. This result was obtained on the basis of Homaee and Feddes (1999) water reduction function [Equation (13)] which was more acceptable in GY estimation than that of Maas and Hoffman (1977) equation (Table 3).

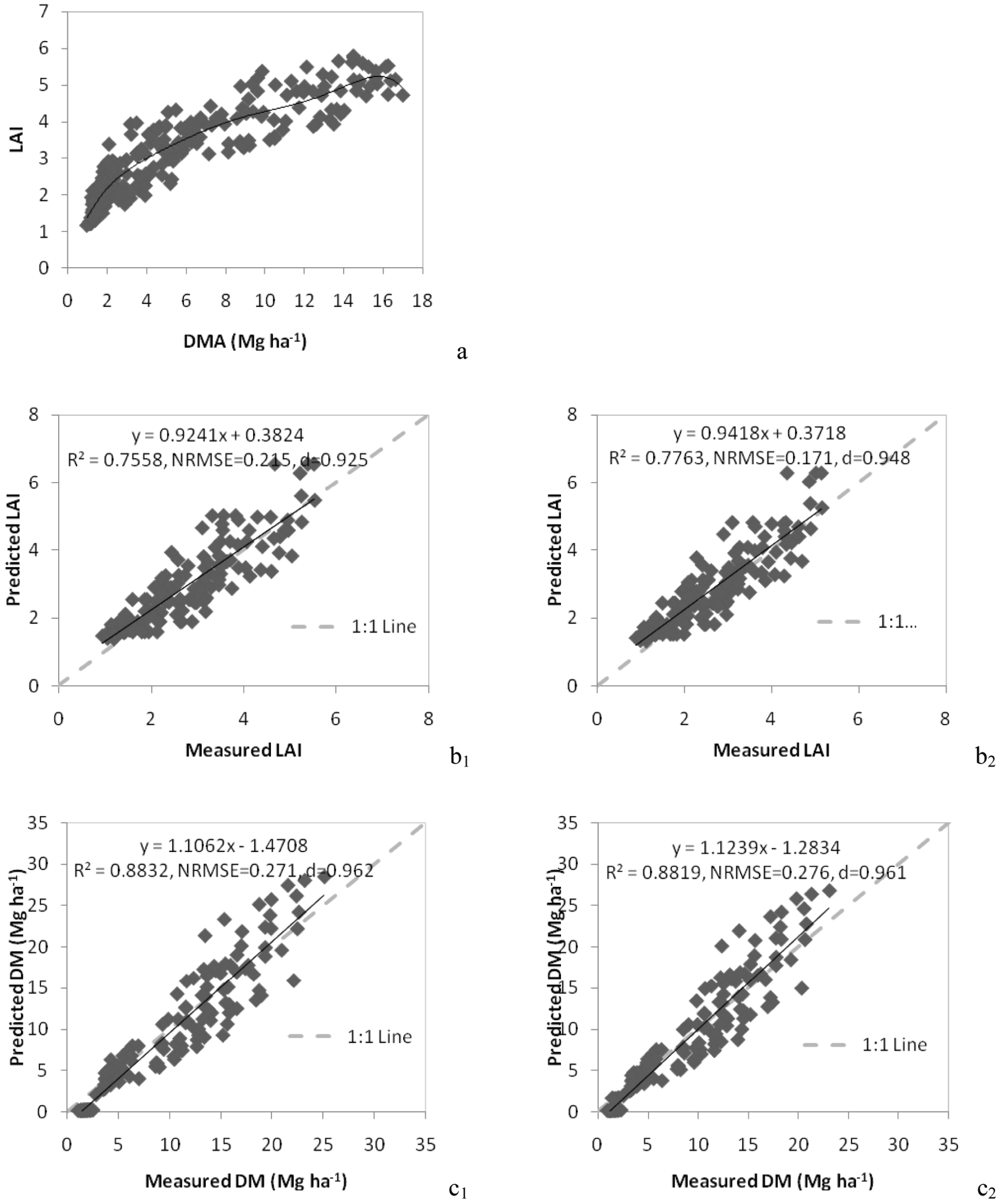


Figure 4. (a) Relationship between leaf area index (LAI) and dry matter production (DMA) for all treatments (b) relationship between the measured and predicted LAI and (c) relationship between the measured and predicted maize top dry matter (DM) (1: calibration and 2: validation).

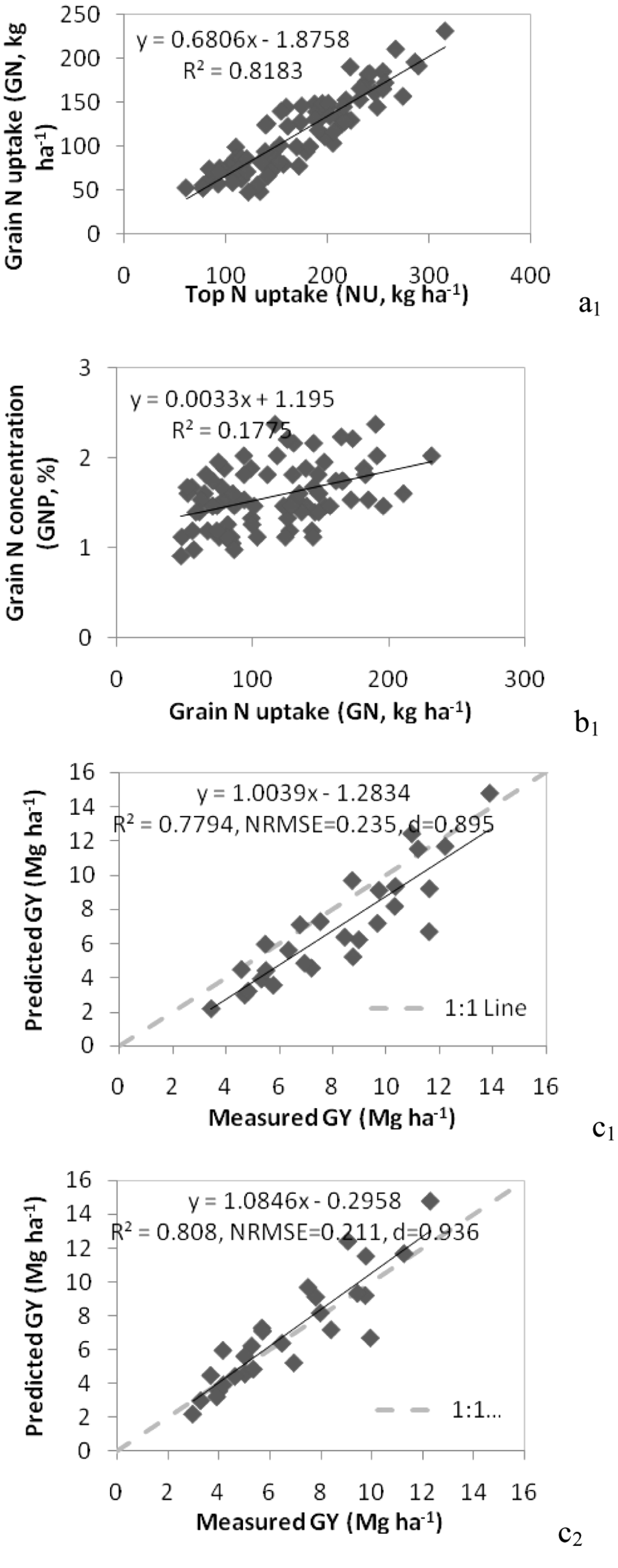


Figure 5. Relationship between (a) maize top (stover and grain) N uptake and grain N uptake, (b) grain N uptake and grain N concentration and (c) the measured and predicted maize grain yield (GY) (1: calibration and 2: validation).

Model validation

Evapotranspiration, transpiration and evaporation

Relationships between the estimated and measured E, T and ET by the modified MSM model in validation stage based on two water reduction functions are presented in Table 3. Results indicated that Homaee and Feddes (1999) equation [Equation (13)] was more appropriate than Maas and Hoffman (1977) function in validation stage, since they showed a lower NRMSE and higher d values. Results based on Homaee and Feddes (1999) equation are presented in Figure 1. The NRMSE values for E, T and ET were <20% indicated a good estimation of these parameters by the modified model (10%<NRMSE<20%). Furthermore, the values of d index were >0.9 indicated a very accurate estimation by the model. Maximum values of the measured ET and T were 873 and 694 mm in $I_1S_1N_3$ treatment. However, the corresponding predicted values were 961 and 744 mm, respectively at the same treatment that are close to each other. Minimum values of the measured and predicted ET/T were 320/196 and 282/164 mm respectively, in $I_3S_3N_1$ treatment that are close to each other. Maximum values of the measured/predicted E were 232/211 mm in $I_3S_3N_3$ treatment, whereas the corresponding minimum values were 88/65 mm in $I_3S_1N_3$ treatment that are close to each other.

Soil water content and salinity

Relationships between the predicted and measured soil water contents and salinities are presented in Figure 2. The NRMSE of these comparisons are 9.1% and 20.8%, respectively indicated that the modified MSM model accurately estimated the soil water content (NRMSE<10%); however, the model estimation for soil salinity was fair (20%<NRMSE<30%). The values of d index indicated an acceptable estimation of these two parameters by the modified model. Variations of the predicted and measured soil water contents and EC_e at soil depths for some treatments during the growing season are also presented in Figure 6. Results showed that the measured values of soil water contents were generally higher in comparison with the predicted values. This may be as a result of measurement error obtained by neutron scattering method. The presented results of soil water content and EC_e were obtained based on Homaee and Feddes (1999) equation [Equation (13)] that resulted in a better estimation of these two parameters in validation stage (Table 3).

Soil nitrate content and plant top nitrogen uptake

Results for the soil nitrate content and also top plant N uptake based on water uptake reduction function of Homaee and Feddes (1999) [Equation (13)] were more accurate than those of Maas and Hoffman model in validation stage (Table 3). Relationship between the predicted and measured soil nitrate content and plant top N uptake based on Homaee and Feddes (1999) equation are presented in Figure 3. The NRMSE and d values of the comparison were 0.218 and 0.980 for soil NO_3-N content and 0.265 and 0.861 for plant top nitrogen uptake, respectively indicated fair estimation of these two parameters by the modified MSM model. Variations of the soil NO_3-N content in depth of 0-30 and 30-60 cm during the growing season for some treatments are also presented in Figure 7. The substantial rapid increase in soil NO_3-N content that observed on day

30 after sowing was due to N fertilize application in 3rd week after planting. Furthermore, an increase in soil nitrate in N_1 treatment might be due to mineralization of organic N arising from soil organic matter. Figure 7 also showed that NO_3-N could be accumulated in deeper soil layer (i.e. 30-60 cm) under deficit irrigation (I_3). Similar results were previously reported by Azizian and Sepaskhah (2015 and 2014a).

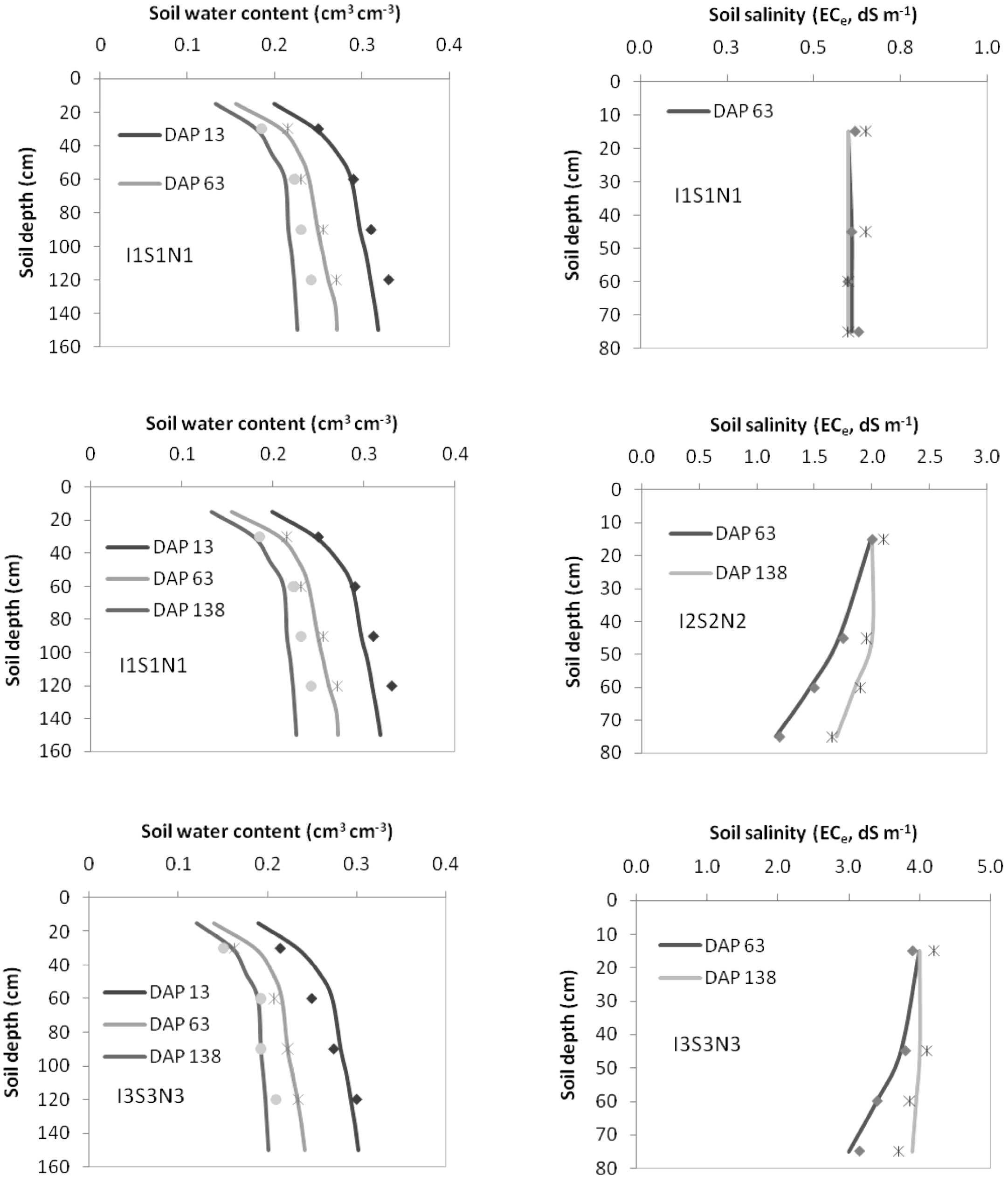


Figure 6. Measured (points) and predicted (curves) soil water content (left hand side) and soil salinity (EC_e, right hand side) at different days after planting (DAP) for some irrigation (I_1=1.25ET_c, I_2=0.75I_1 and I_3=0.5I_1), salinity (S_1=0.6, S_2=2.0 and S_3=4.0 dS m^{-1}) and nitrogen (N_1=0, N_2=150 and N_3=300 kg ha^{-1}) treatments (validation).

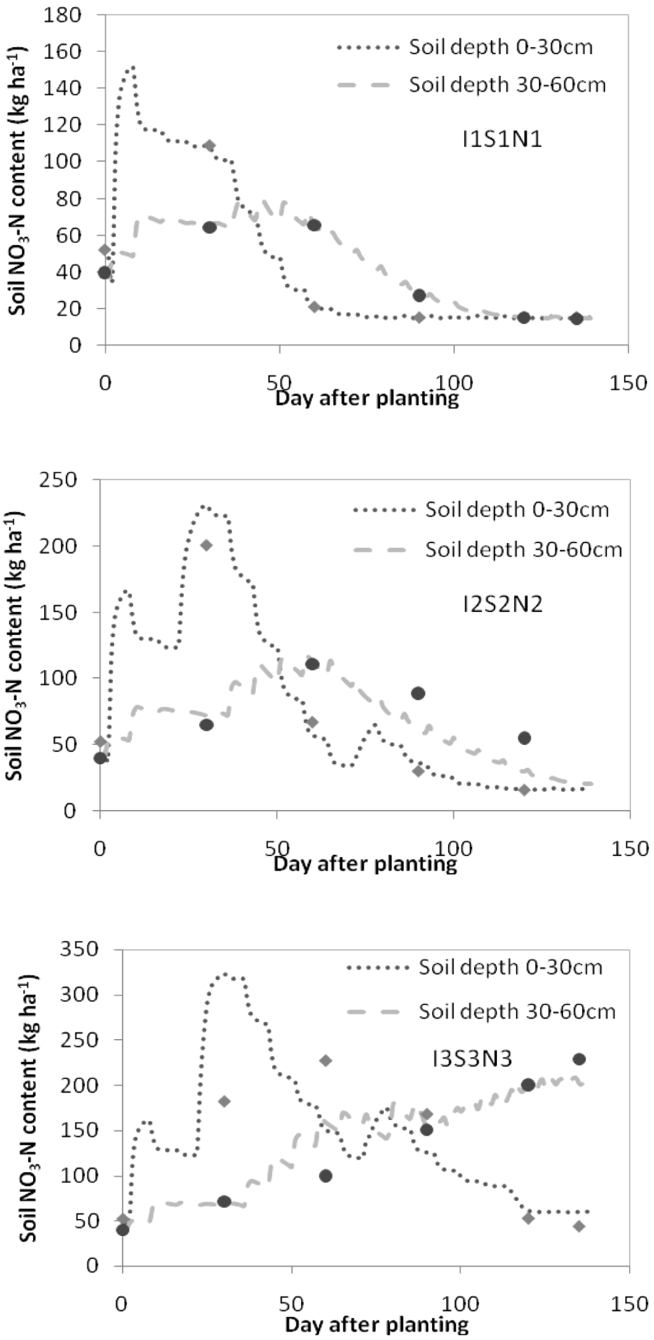


Figure 7. Measured (points) and predicted (curves) values of soil NO_3-N content at soil depth of 0-30 and 30-60 cm during the growing season for some irrigation (I_1=1.25ET_c, I_2=0.75I_1 and I_3=0.5I_1), salinity (S_1=0.6, S_2=2.0 and S_3=4.0 dS m^{-1}) and nitrogen (N_1=0, N_2=150 and N_3=300 kg ha^{-1}) treatments (validation).

Simulated nitrate leaching by the modified MSM model is presented in Figure 8. Results indicated that NO_3-N losses in I_1 and I_2 treatments were 108 and 63% higher than that value in I_3 treatment, respectively. Furthermore, under I_1 treatment the leaching of NO_3-N in S_3 was 3.5 times higher than that value in S_1 (no saline condition) treatment. The corresponding values under I_2 and I_3 treatments were 3.48 and 3.49. However, results of the modified MSM model indicated that a higher application rate of N fertilizer above its optimum level under saline irrigation water enhance the risk of groundwater N contamination. In other words, it is concluded that N fertilizer should be applied more precisely under limited fresh water for maize production. Similar results were reported by Pang and Letey (1998) by ENVIRO-GRO model for maize.

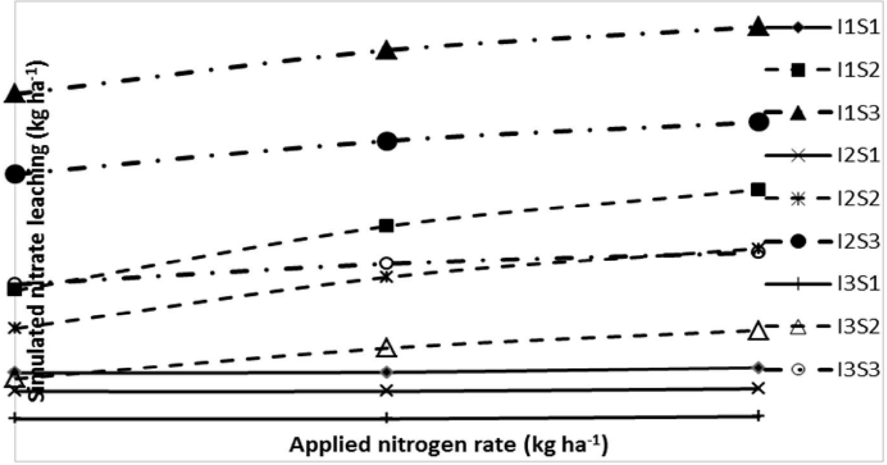


Figure 8. Simulated interactions between irrigation, salinity and nitrogen on soil nitrate leaching.

Leaf area index and top dry matter

Results for the predicted and measured LAI and DM based on water uptake reduction function of Homaee and Feddes (1999) [Equation (13)] that is more accurate than those of Maas and Hoffman equation (Table 3) are presented in Figure 4. The values of NRMSE for these comparisons indicated good and fair estimation of LAI and DM, respectively by the modified MSM model in the validation stage. Furthermore, the d values showed an accurate estimation of these two traits. Figure 9 showed the variation of LAI and DM accumulation during the growing season for some treatments. Maximum values of the predicted and measured DM were 27.0 and 25.1 Mg ha^{-1} for $I_1S_1N_3$ treatment, respectively. However, the minimum values were 12.30 and 10.40 Mg ha^{-1} for $I_3S_3N_1$ treatment, respectively. The corresponding values for maximum LAI were 6.48 and 5.52 and for minimum LAI were 3.62 and 3.06, respectively for the same treatments.

Grain yield

The predicted and observed maize GY based on water uptake reduction function of Homaee and Feddes (1999) [Equation (13)] were closer to each other in comparison with those obtained on the basis of Maas and Hoffman equation (Table 3). Comparison of the predicted and measured values of GY is presented in Figure 5. The NRMSE and d values of the comparison were 0.211 and 0.936 indicated an acceptable estimation of maize GY by the modified MSM model under salinity conditions in validation stage. Therefore, the modified MSM model could be applied for maize GY prediction under deficiency of fresh water and different amount of N fertilizer. Maximum values of the predicted and measured maize GY were 14.80 and 12.31 Mg ha^{-1} for $I_1S_1N_3$ treatment, respectively. However, the minimum values were 2.20 and 3.00 Mg ha^{-1} for $I_3S_3N_1$ treatment, respectively.

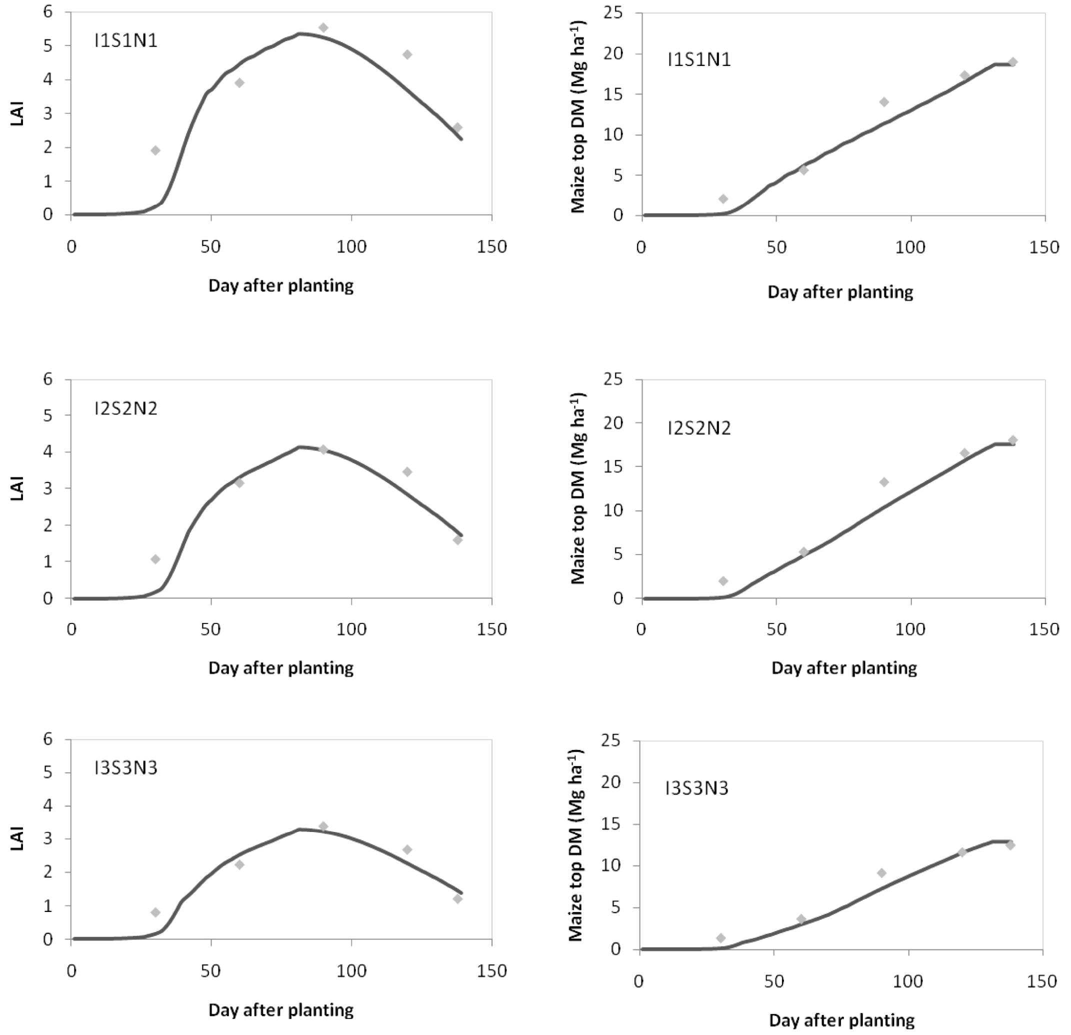


Figure 9. Measured (points) and predicted (curves) leaf are index (LAI, left hand side) and dry matter (DM, right hand side) during the growing season for some irrigation (I_1=1.25ET_c, I_2=0.75I_1 and I_3=0.5I_1), salinity (S_1=0.6, S_2=2.0 and S_3=4.0 dS m^{-1}) and nitrogen (N_1=0, N_2=150 and N_3=300 kg ha^{-1}) treatments (validation).

Conclusions

The MSM model could be applied under saline irrigation water application by modifying the subroutines of water uptake based on different water uptake reduction functions. Results of this modification showed that water uptake reduction function of Homaee and Feddes (1999) led to a better estimation of traits of interest in the calibration and validation stages. Based on the NRMSE index, results showed that the modified MSM model presented very good estimation of soil water content; good estimation of E, T, ET and LAI and fair estimation of EC_e, soil NO_3-N content, plant N uptake, DM and GY. However, based on the d index, the modified MSM model estimated the mentioned parameters very good (d>0.90) or good (0.80<d<0.90). The modified MSM model is also capable to evaluate the potential environmental risk regarding N leaching from the soil profile. Furthermore, the modified MSM model showed that saline irrigation water application exposed the groundwater to higher danger of N contamination.

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