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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Monitoring and modeling root-uptake salinity reduction factors of a tomato crop under non-uniform soil salinity distribution

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Abstract

This study has investigated the possibility for monitoring simultaneously and continuously the relationship between the macroscopic crop response and the evolution of water content, electrical conductivity and root density along the soil profile during the whole growing season of a tomato crop under different salinity treatments. Water storages measured by TDR sensors were used for calculating directly the actual water uptake by the root system along the whole soil profile under the different salinity levels imposed during the experiments. It was observed that during irrigation with saline water the salt content increased along the whole profile but that it tended to accumulate quite uniformly below the 20 cm in the case of the 4 dSm^{-1} treatment and at depth between 15 and 25 cm in the case of the 8dSm^{-1} salinity treatment. Compared to the reference freshwater treatment, the evapotranspiration under salinity treatments started to decrease at a threshold value of the time-depth average electrical conductivity (EC) of soil water of about 3dSm^{-1}. Based on the results of soil and plant monitoring, the root uptake process was simulated by using a model for water and solute flow in the soil-plant-atmosphere continuum. This way, the root activity reduction at each depth-node was calculated as a function of the salinity (and eventually water) stress. This enabled relating the distribution of higher/lower activity of root uptake along the soil profile in response to the actual distribution of salts.

Keywords: Soil salinity, soil electrical conductivity, sink term, soil hydraulic properties, Time Domain Reflectometry (TDR).

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1. Introduction

Irrigation has significantly increased crop yields worldwide. However, irrigation systems may be particularly susceptible to salinization, especially in arid and semiarid areas. FAO (2002) [1] estimated that about 20-30 ha of irrigated land are seriously damaged (0.25-0.5 million ha/year are lost from production) by the build-up of salts. Soil salinity may be particularly high in arid and semiarid areas with shallow, saline groundwater tables. Under these conditions, the evapotranspiration rate is very high due to the high evaporative demands of arid climates. The high evapotranspiration induces an upward soil water flow, which transports a large amount of salt to the root zone.

Salinity generally slows the rate of crop growth, resulting in plants with smaller leaves, shorter stature and reduced economic yield [2]. On the one hand solutes tend to be sieved out by root membranes; on the other hand they may be actively taken up by the plant. The inherent ability of crop plants to withstand the effects of elevated solute concentrations in their root zone solutions still produce a measurable agricultural product defines the magnitude of crop tolerance salinity.

Crop salt tolerance information is abundant in the literature. An abundance of data exists for the whole plant salt tolerance as a function of root-zone average salinity [3; 4; 5; 6]. Nevertheless, the accuracy of many of the data is questionable. In general, the data does not include information about soil and other environmental factors which are known to affect root water uptake and, thus, crop salt tolerance. Besides changes in solute concentrations, many other crop-environment interactions may cause variations in salinity-yield relationships, such as those involving temperature, radiation, humidity, atmospheric pollutants, wind, soil fertility, soil water content. Maas and Hoffman (1977) [3] themselves observed that their data serves only as a guideline and that the absolute tolerance of crops to salinity may vary with climate, cultural practices and soil conditions. As pointed out by Maas (1990) [4], the widely cited tables describing the relationship between relative yield and electrical conductivity of saturated extract, averaged over the root zone as well as the entire growing season are quite approximate and carry significant uncertainty.

Actually, much of the crop response under saline irrigation depends on the root distribution over the root zone. In turn, this largely depends on whether the root system preliminary developed into a saline or non-saline profile. In heterogeneously distributed soil salinity, roots do not penetrate readily into high saline depths, but once established in non-saline soil, imposing salinity does not drastically change the root distribution.

The salt distribution in the root zone depends, besides management practices and other environmental factors, on the complex non-linear processes of water flow and solute transport in soil determining variable distributions and storage of solutes and water along the whole root-zone, as well as their upward and downward fluxes. The effect of all these processes on the response of a crop to irrigation with saline water cannot be assessed without a detailed spatio-temporal monitoring of water contents and solute concentrations in soils during irrigation with saline water.

An answer may be a methodology coupling adequate soil monitoring to numerical models simulating the transfer of water and solutes in the soil-plant-atmosphere continuum. A detailed monitoring allows following continuously the evolution of the local processes of water and salt storage and transport which mainly influence root uptake. By integrating such a database in numerical models, insights may be gained on the effects of the main physicochemical interacting processes affecting root-zone salinity and root uptake response to increasing osmotic potentials. Nevertheless, proper modeling and parameterization of the root water uptake as a function of water and salinity stresses remain one of the main challenges. The main reason for this is that the required data cannot be obtained easily and with the necessary detailed spatial and temporal resolution. In fact, it involves a number of problems to be solved concerning the selection of appropriate soil-water sensors and their placement, which essentially depends on the distribution of the roots and their activity. These, in turn, are affected by the specific soil-water-salt conditions which become established in the root zone according to the local soil physical-hydrological characteristics. Additionally, an accurate transpiration rate is required when validating the prediction capacity of the sink term functions in the numerical models.

With such premises, the aim of this paper is mainly setting up a methodology for monitoring continuously the local processes of water and salt accumulation and transport which mainly influence the evapotranspiration (thus the root uptake) processes. The methodology will be principally based on Time-Domain reflectometry (TDR) as a non destructive technique for rapid, reliable, and routine measurements of water content and electrical conductivity of soil. Water storages measured by sensors will be used for calculating directly the actual water uptake by the root system along the whole soil profile under the different salinity levels imposed during the experiment.

2. Materials and methods

2.1. The experimental layout

The experiment was carried out at the research station of the Mediterranean Agronomic Institute (Bari–Italy) in the south-east of Italy. The soil is pedologically classified as Colluvic Regosol consisting of a silt loam layer of an average depth of 60 cm on a fractured calcarenite rock.

The experimental area in the field was about 18m×24m; i.e. 432 m². A randomized complete block design with three replicates was used in this study (Figure 1).

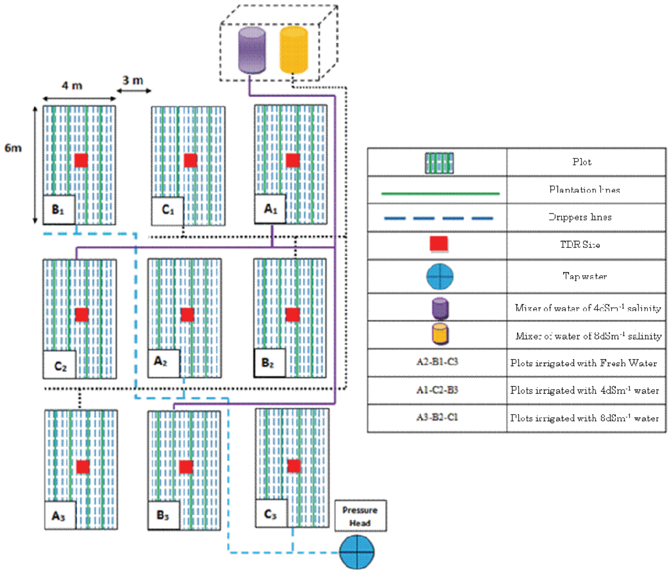

Fig. 1. Schematic view of experimental field.

The treatments consisted of three irrigation salinity inputs (fresh water-FW; 4dSm^{-1}; 8dSm^{-1}). Water salinity was induced by adding NaCl and $CaCl_2$ to the tap water. Overall, nine plots of about 24 m² were set up. The irrigation volumes were estimated according to the Penman-Monteith equation by using the meteorological data collected by an automated weather station located close to the experimental field. The same total irrigation input was provided to all the plots every two days. Irrigation volumes allowed keeping soil water content under optimal conditions. This way, the eventual reduction of root uptake may only be induced by osmotic stress. An irrigation system was set up consisting of 15 dripper lines, 600 cm length and drippers 25 cm apart per plot. The pressure self-compensating drippers deliver discharge rates of 4 l/h. Four tomato lines were planted 100 cm apart. A total of 24 plants were planted for each line.

Each of the nine plots was equipped with TDR probes and tensiometers: TDR probes were spread at six depths (0, 15, 25, 35, 45, 55 cm), in the middle of each plot in two adjacent sites (in-line and between the line); two tensiometers were installed at 50cm and 60cm depth among the last TDR probe. A total of 108 TDR probes and 36 tensiometers were installed in the field.

Undisturbed soil samples were collected from each plot in the neighborhood of the monitoring sites and analyzed in the laboratory for physical and hydraulic properties.

Also, TDR probes were calibrated in the laboratory for the relationship ECb-ECw-θ among bulk EC, the soil water EC and the water content θ [7] for monitoring soil water electrical conductivity under transient conditions.

2.2. Calculating evapotraspiration from TDR soil water contents

As mentioned, water storages measured by TDR probes were used for calculating directly the actual water uptake by the root system along the whole soil profile under the different salinity levels imposed during the experiments. This is the main difference between this experiment and the traditional ones where the evapotranspiration has been generally estimated from meteorological data [8; 9; 10] or by a water balance method [11]. There are also researchers who used a constant transpiration rate [12; 13; 14; 15]. Evapotranspiration was calculated by volumetric soil water content monitored by using TDR probes at different depths. The water content integrated along the whole soil profile (0-55 cm) represents the water storage, W, at a given time. The TDR measurements were taken just before and (1-2 h) after each irrigation. By using soil measurements, evapotranspiration may be estimated by applying the water conservation equation and by assuming that water flows only in the vertical direction. This let us consider a volume of soil of unit cross-sectional area in the horizontal plane, bearing vegetation, with a lower boundary at z=L=55cm and an upper boundary at the soil surface at z=0. Water flow through the roots plus water flow through the soil surface (J_w (z=0)) can then be calculated as:

$$\int_0^L S(z,t)dz + Jw(0,t) = Jw(L,t) - \frac{\partial}{\partial t}\int_0^L \theta(z,t)dz \tag{1}$$

with $\int_0^{z=L=55cm} \theta(t)dz = W(t)$, *S(z)* the sink (by roots) at z and J_w the water flux in the soil.

The depletion fluxes along the soil profile (the second term on the right side of the conservation equation) may be partly due to the evapotranspiration and partly to the eventual downward or even upward fluxes at the profile bottom (J_w (z=55cm)). The up/downward fluxes at the profile bottom may be easily calculated by applying the Darcy's law between the 50 and 60 cm depth and using the potential gradients measured by tensiometers. Alternatively, these gradients may be obtained by measuring water contents at 50 and 60 cm and thus converting these values to the corresponding water potentials by using the measured water retention and hydraulic conductivity curves.

As already mentioned, TDR probes were installed at different depths in two sites located in the middle of each plot, one along the dripper line and another between lines. The ET for each plot was calculated as the average of the in-line and between lines measurements. This average ET thus accounted for both root uptake from the crop row and the crop inter-row.

2.3. Calculating the sink term

The maximum root water uptake is simulated macroscopically according to the method of Feddes et al. (1978) [16], which distributes potential transpiration (T_p) over the root zone (Dr) on the basis of a normalized root density distribution. Assuming that the specific water extraction rate is proportional to the root density, RD (gcm^{-3}), for optimal soil water conditions [16] we calculated the normalized root density, f (z) (cm^{-1}), as:

$$f(z) = \frac{RD}{\int_0^{Dr} RDdz} \tag{2}$$

Any root density distribution may be used according to specific crop being simulated. In this paper, and based on the RD actually observed in the field, we used a logistic-derivative description of the f (z):

$$f(z) = \frac{abc\exp(cz)}{b + \exp(cz)^2} \tag{3}$$

with a, b and c being empirical parameters to be estimated by fitting the logistic to the measured f(z) and z the depth. Thus, the maximum sink term S_{max} is calculated as:

$$S_{\max} = f(z) \times T_p \tag{4}$$

with $T_p(t) = \int_0^{Dr} S_{\max}(z,t)dz$

Low water contents and/or the presence of soluble salts in the soil lower the total hydraulic head and may reduce the root water uptake. Reduction coefficients to decrease the maximum water uptake according to the water and osmotic stresses may be calculated independently and multiplied to calculate the actual root uptake as [17]:

$$S = \alpha_{rw}\alpha_{rs}S_{\max} = f(z) \times \alpha_{rw}\alpha_{rs} \times T_p \tag{5}$$

with α_{rw} and α_{rs} being the reduction factors due to the water and osmotic stresses, respectively. Accordingly, $T_a(t) = \int_0^{Dr} S(z,t)dz$, with T_a being the actual transpiration rate.

2.4. Calculating the salinity reduction factor α_{rs}

Several functional forms that have been proposed for uptake reduction are based on the whole-plant response and water and salt stress relationships. Assuming that a proportional relationship exists between the ratio of yield to potential yield and the ratio of transpiration to potential transpiration [18; 19; 20; 21], it follows that:

$$\frac{Y_a}{Y_p} = \frac{T_a}{T_p} = \frac{\int_0^{Dr} S(z,t)dz}{\int_0^{Dr} S_{\max}(z,t)dz} = \alpha_{rw}\alpha_{rs} \tag{6}$$

Note that the magnitudes of T_p and Y_p differ from year to year according to the prevailing meteorological conditions, and that relative yield is related to water availability as well as to salinity stress. The yield reduction due to salinity stress also leads to a reduction of the water uptake. In absence of a water stress, the reduction of transpiration may be only ascribed to salinity stresses (α_{rw}=1).

Accordingly, the α_{rs} factors for each treatment and for each plot were calculated as the ratio T_a of each treated plot (4dSm^{-1} and 8dSm^{-1}) to the T_p of the control plot obtained as the average over the three FW plots. T_a for each plot was obtained by applying the Beer's law [22] to the measured ET by using the information on the leaf area index (LAI) measured on that plot:

$$\begin{aligned} E &= ET \times e^{-k \times LAI} \\ T &= ET - E \end{aligned} \tag{7}$$

with k being an extinction coefficient set to be 0.5. The response function can be written in terms of concentration, or electrical conductivity (see Figure 4) of either the soil water or the soil saturation extract, or osmotic pressure head [23; 4; 24; 3; 25]. In terms of osmotic pressure heads, the Maas and Hoffman [3] model for crop salt tolerance, the effects of salinity stress on root water uptake can be described using the piecewise linear (threshold-slope) function:

$$\alpha_{rs} = \alpha(h_o) = \begin{cases} 1, & a \le h_o \le 0 \\ 1 + b(h_o - a), & a > h_o > a - \frac{1}{b} \\ 0, & h_o \le a - \frac{1}{b} \end{cases} \tag{8}$$

where a and b are adjustable parameters, often referred to as the salinity threshold and slope, respectively.

The osmotic potential, expressed as osmotic head h_o, assumed to be a linear function of soil solution salinity ECw according to U. S. Salinity Laboratory Staff (1954) [26]:

$$h_o = -360 ECw \tag{9}$$

360 is a factor to convert the salinity-based values to cm osmotic head.

Alternatively, nonlinear S-shaped and exponential yield response functions due to salinity stress were proposed and tested by Van Genuchten and Hoffman (1984) [25]. The S-shaped salinity-stress yield reduction function is given by:

$$\alpha(h_o) = \frac{1}{1 + \left(\frac{h_o}{h_{o,50}}\right)^{p_2}} \tag{10}$$

where p_2 and $h_{0,50}$ are the adjustable parameters, the latter being the osmotic pressure head where uptake is halved.

3. Results and discussion

3.1. Water content by measuring by TDR in the field

The time-evolution of the bulk water content (corrected for stones) at different measurement depths are averaged over the three plots for each salinity treatment (data not shown).

It has observed that the water content tends to be constant at the soil surface under all the three treatment conditions while it decreases deeper because of the increasing root expansion (deepening) with time. The decrease is quite gradual in the FW treatment. By contrast, it is sharper in the other two treatments because of a larger variability among the three plots in both the 4 dSm^{-1} and 8 dSm^{-1} salinity conditions. In all the three treatments, a clear double-layer soil profile (tilled 0-20 cm and untilled 20-60 cm) be observed, with higher water contents in the untilled layer. It is worth noting the large increase in the water content at 25 and 35 cm depths under both the 4 dSm^{-1} and 8 dSm^{-1} salinity conditions. This may be explained by looking at the corresponding increase in the soil Exchangeable Sodium Adsorption ratio (ESP) (data not shown) which induces a partial occlusion of pores (and thus a decrease of the soil hydraulic conductivity) at the interface with the untilled layer. This, in turn, induces water stagnation and slows down the salt leaching which accumulates progressively at the interface, especially in the 8 dSm^{-1} treatment plots.

3.2. Average electrical conductivity in the soil surface

The ECw of the soil solution were deduced from the ECb values according to the calibration procedure described in the section 2.1. The graph in figure 2 shows the evolution of the ECw averaged over the whole soil profile and over the three plots of each salinity treatment.

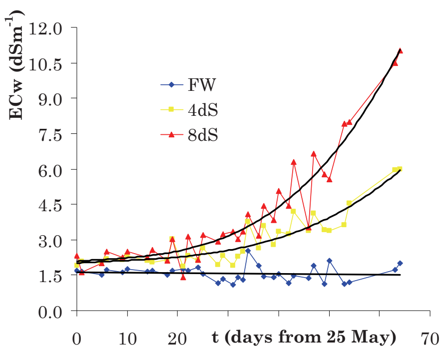

Fig. 2. Evolution of ECw averaged over the whole soil profile and over three plots of each salinity treatment.

In the graph, the line interpolates the ECsw data measured for each treatment. The increasing slope is consistent with the increasing salt content, in the sense that the ECsw increases more rapidly with the higher salt concentration of the irrigation water. The average ECw measured at the end of the monitoring period was of about 11dSm^{-1}, 6dSm^{-1} and 1.5dSm^{-1} for the 8dSm^{-1}, 4dSm^{-1} and FW treatment, respectively. The oscillatory behavior of the ECw values is related to irrigations.

In any case, and interestingly, the average ECw hides the real distribution of the salts along the soil profile. The figure 3 shows the ECw distribution with depth for two different days of the growing season. It may be seen that the salt content increases along the whole profile but that it tends to accumulate quite uniformly below the 20 cm in the case of the 4 dSm^{-1} treatment and at a depth between 15 and 25 cm in the case of the 8 dSm^{-1} salinity treatment.

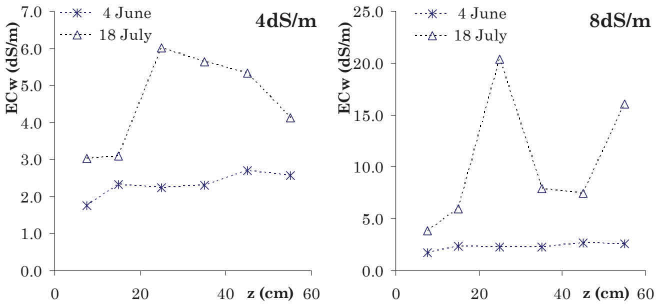

Fig. 3. ECw distribution with depth for two different days of the growing season.

The two behaviors are representative of two different hydraulic properties of the soil profile. In both cases, the first 20 cm have been tilled and are quite homogeneous in the whole experimental field. The soil there is relatively more conductive and the salts are leached out by the continuous irrigations. Deeper, the soil become less conductive and the salts tend to accumulate. However, the behavior of the ECw in the 8 dSm^{-1} treatment suggests an abrupt increase of the hydraulic impedance of the second untilled layer in that case, inducing the solute to concentrate at the interface. This behavior is directly reflected in the root uptake distribution calculated by the simulation model.

3.3. Average electrical conductivity in the soil surface

As mentioned, the α_{rs} factors for each treatment and for each plot were calculated as the ratio of the T_a averaged on the three plots for each salinity treatment to the T_p of the control plot obtained as the average of the three FW plots. The graph in the figure 4 shows the ratio of the average T_a/T_p for both the 4 dSm^{-1} (yellow symbols) and 8 dSm^{-1} (red symbols) treatments as a function of the ECw of the soil solution averaged over the 0-55 cm soil profile as well as the time from the beginning of the experiment.

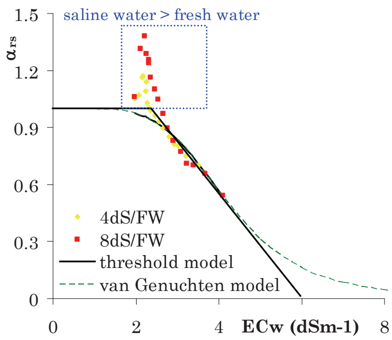

Fig. 4. Salinity reduction factors αrs as a function of ECw for two salinity treatment.

It may be seen that the two dataset practically coalesce thus suggesting that given two different salinity treatments, one may expect the same reduction factor once the time average of the soil EC is the same. In other words, the graph is telling us that the reduction factor only depends on the time average EC and is practically independent on the specific process evolution leading to that time average soil EC.

The data were described by alternatively using a so-called threshold model (the solid line in the graph) and the S-shaped model proposed by van Genuchten (the dashed line in the graph). Interestingly, both the models identify a critical ECw value (or critical ECw values interval) from which the ET starts to decrease which is practically that identified by looking at the ET graphs in the next section (figure 5), thus implying a clear robustness of the measurements and of the data elaboration methods used in this work.

However, it is clear that the data are not enough for discriminating between the two models. Either model could describe the data equally well. In general, it seems that transpiration data alone are not sufficient for discriminating among different functional forms for the reduction functions used here, as well as others containing additional parameters.

Nevertheless, it should be noted that the threshold model identifies a zero-transpiration at an ECw value of about 6dSm^{-1}, which seems really underestimated. To the contrary, the S-shaped model would provide more reasonable results, by identifying a zero-T_a at about ECw=12 dSm^{-1}.

3.4. Comparison between cumulative evapotranspiration, irrigation volumes and LAI

As already mentioned, the TDR probes were installed at different depths in two sites located in the middle of each plot, one along the dripper line and between lines.

The ET for each plot was calculated as the average of the in-line and between lines measurements. This average ET thus accounted for both root uptake from the crop row and the inter-row. Subsequently, the three averages ET of each salinity treatment were further averaged for giving the ET representative of that treatment (treatment EC). The figure 5 depicts the evolution of the cumulative treatment EC for each salinity level (treatment EC FW, EC 4dS, EC 8dS).

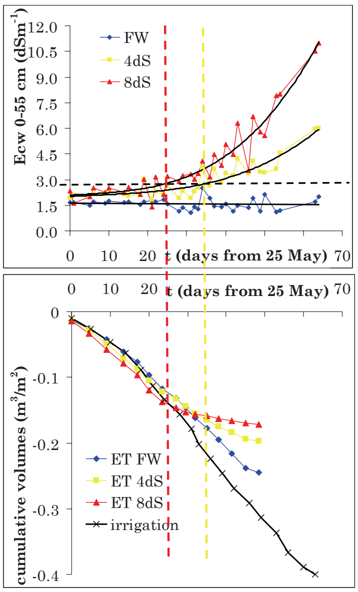

Fig. 5. Evolution of cumulative irrigation volume, cumulative ET and cumulative ECw for each salinity level.

The three ECs are compared to the cumulative irrigation volumes supplied during the experiments. As the salinity irrigations started on approximately half of May, all the measurements shown refer to the period from 25 of May to the end of the experiment. The graph of ET and irrigation volumes is compared to that of the ECw described above.

Firstly, it may be seen that the irrigation volumes calculated according to the Penman-Monteith method follow perfectly the measured cumulative ET values (note that the two ETs come from independent methods) more or less till half of the growing season. Later, starting from the 25th day (about 18 June) the irrigation volumes are systematically higher than the measured ET. In this second stage, a leaching of part of the salts downward is obviously expected. It is more or less at that time that the cumulative ET evolution for the 8dS treatment changes its trend by decreasing respect to both the 4dS and the FW treatments. Looking at the upper part of the figure, this change corresponds to an average value of the ECw of about 3.0 dSm^{-1}.

Interestingly, looking at the ET evolution for the 4 dSm-1 treatment, it is apparent that it starts to decrease approximately at the same value of EC. In practice, this ECw≅3 identifies the threshold value above which the ET (and thus the root uptake) starts to decrease. The figure 6 showing the LAI evolution averaged over the three plots for each treatment confirms the results concerning the ET. A clear significant LAI reduction may be observed on the 25th day.

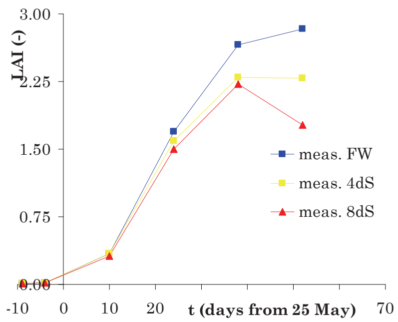

Fig.6. LAI evolution averaged over three plots and three salinity treatment.

Starting from this point, the decreasing law of the ET with increasing ECw in the soil may be deduced by looking at the reduction factors of root uptake (Figure 4).

4. Conclusions

In this work we proposed a methodology for monitoring the transfer of water and solutes in the soil-plant-atmosphere continuum, with the main objective of understanding the effect of the main physico-chemical interacting processes affecting the root-zone salinity and the root uptake response to increasing osmotic potentials.

The Time Domain Reflectometry-TDR-technique was used for monitoring continuously and simultaneously the water content and electrical conductivity along the soil profile during the whole growth season. Water storages measured by sensors were used for calculating directly the actual water uptake by the root system along the whole soil profile under the different salinity levels imposed during the experiments.

As expected, the ECsw increased more rapidly with the higher salt concentration of the irrigation water. Nevertheless, it was also observed that the salt content increases along the whole profile but that it tends to accumulate quite uniformly below the 20 cm in the case of the 4 dSm^{-1} treatment and at a depth between 15 and 25 cm in the case of the 8 dSm^{-1} salinity treatment.

The methodology allowed identifying an ECsw threshold value above which the crop transpiration started to decrease under both the salinity treatments. Of course, the transpiration reduction was accelerated in the case of the 8 dSm^{-1} treatment compared to the 4 dSm^{-1} treatment.

The transpiration reduction factor was calculated as a function of the soil water EC averaged over the whole soil profile and over time. The van Genucthen model for interpreting the experimental reduction factors was found to be more realistic than the traditional threshold model proposed formerly by Maas and Hofmann.

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