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Assessing salt accumulation in the root zone of tomato plant through using ordinary kriging interpolation technique under deficit irrigation regime

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Ö Z E T / A B S T R A C T

Aims: Deficit irrigation might be a remedy to increase water use efficiency in water scarce areas albeit it may cause to: a) increase salt accumulation in the root-zone, b) decrease crop yield. Therefore, monitoring and assessment of salt accumulation in the root-zone is necessary in deficit irrigation practices. Primary objectives of this work were to: a) assess salt accumulation in the root-zone of tomato crop irrigated with conventional deficit irrigation (DI-50) through using ordinary kriging interpolation technique, and b) compare it with full irrigation (FI) treatment.
Methods and Results: To this end, soil electrical conductivity (EC in dS m-1) measurements were conducted under emitters, between emitters and plant, and under plant on right and left side of root-zone by using an EC probe. In order to assess spatial and temporal changes of salt accumulation in the root-zone of tomato crop, EC lectures were done: a) at the beginning crop growth stage, b) in the middle, and c) at the end of growing season. In order to generate salinity maps in the root-zone, geostatistical interpolation techniques have been utilized. Geostatistical analysis has been realized by using “Jeostat-2017” software. Geostatistical analysis results indicated that the most suitable theoretical semivariogram model to the experimental semivariogram was Gaussian and/or Spherical model. Cross validation analysis revealed that kriging interpolation errors were fitted to the normal distribution, indicating that theoretical semivariogram model and its parameters as well as kriging search parameters are representative for the study site. Kriging errors helped us to evaluate efficiency of sampling design for salinity assessment.
Conclusions: In this regard, results showed that salt accumulation was concentrated in the root-zone just beneath the plant. This finding can be explained by the heavy texture of soil, which obstructs the leaching operation also by the high root density of tomato under this profile. Soil salinity maps reveal that salt accumulation in the root-zone gets more and more as the growing stage progress.
Significance and Impact of the Study: Deficit irrigation treatment reduce the amount of total salt accumulated in the root zone compared with the full irrigation treatment due to the fact that the amount of water applied with deficit irrigation is half of the full treatment, hence salt accumulation.

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INTRODUCTION

Salinization of soil and water resources jeopardize food security as well as regular societal advancements. Among these, soil salinity in semi-arid regions -where crop water requirements are augmented by irrigation supplies- is a major concern for the sustainability of irrigated agriculture (Letey et al., 2011). Salinization occurs inevitably because all irrigation waters contain more or less salt. Crops take up nearly pure water for transpiration (nutrients and some specific salts are taken up by the roots) and therefore salts remain behind and concentrate in the root zone (Handson et al., 2009). The evaporation of water from the soil surface is another cause of salinization (Karlberg & de Vries, 2004) as pure water is evaporated, salts are left behind. Decreasing irrigation water requirement through the use of new irrigation technologies is of utmost importance in water-scarce regions. Among the likely problems which may degrade soil fertility, soil salinity most commonly develops under mismanaged irrigation schemes and it may cause permanent loss of soil fertility if timely corrective measures are not taken (Burt el al., 2009). Salinity development in the root zone may be visually delineated by generating salinity maps. In this regard, a number of spatial interpolation methods have been developed for mapping purposes. Prominent among these ones are different versions of geostatistical techniques such as simple kriging, ordinary kriging, universal kriging, etc. Hence, there are a large number of studies which apply geostatistical techniques to natural resource distributions (Vanderborght et al., 2007). Geostatistical tools such as variogram modeling and kriging have also been need for environmental applications and agriculture application (Amezketa et al., 2007; Aragués et al., 2011) to monitor soil quality and its affects by irrigation water quality. Primary objectives of this work were to: *a)* assess salt accumulation in the root-zone of tomato crop -irrigated with conventional deficit irrigation (DI-50) which targets at supplying 50% of total crop water requirement- through using ordinary kriging interpolation technique, and *b)* compare it with full irrigation (FI) treatment, which targets at providing 100% of crop water requirement. The results were discussed in view of whether the salt accumulation would reach to plant salt tolerance threshold levels.

MATERIALS and METHODS

Characteristics of Study Area and Experimentation

The study was carried out under greenhouse conditions (9m×44m) at the experimental station of Researches Regional Center on Horticultural and Organic Agriculture of Chott-Mariem, Sousse, Tunisia (Latitude:35°55'16.36'' N, Longitude:10°34'09.49'' E). Chott-Mariem belongs to the *Sahel* of Tunisian governorate of Sousse, limited to the north by *Hergla*, in south by *Hammam Sousse*, in east by the *Mediterranean Sea* and on west by *Akouda*. Study area is characterized by a semi-arid climate. Average temperature in summer is approximately 25°C, and average temperature in winter is about 12.5°C, observed during December and January. The average annual rainfall is about 410 mm. The relative humidity increases during winter months and reaches at 75%. In addition, the wind speed ranges between 10-15 km/h (Sayari et al. 2016).

Experiment was conducted from January to June 2018. Seeds of the processing tomato "*Sehli*" were sown on 15 December 2017. Forty days after seeding, uniform plants were transplanted into 8 rows with 3 replicates per row. The ground was covered by a black plastic mulching for diminishing the evaporation of water from soil surface and fight against adventitious weed development, diseases and pests.

The experimental soil in the greenhouse is "*sandy-clay*" composed with 28% of clay, 5% of silt and 68% of sand. Initial electrical conductivity "*EC*", the organic matter content and the *pH* are in the order of 1.25 $dS\ m^{-1}$, 2.1% and 7.8, respectively. The apparent *field capacity* "θFC" and *permanent wilting point* "θPWP" are 32% and 15%, respectively. Soil *bulk density* for 0-20 cm, 20-40 cm, 40-60 cm and 60-80 cm depths were 1.36, 1.48, 1.65 and 1.82 $g\ cm^{3}$, respectively. A drip irrigation system with laterals laid down along the rows was used for irrigation. The two laterals with drippers of 4 $l\ h^{-1}$ flow rate and spaced at 1 *m* were arranged in a such way that one dripper centered between the two plants, but installed alternately on the separate laterals.

Water requirements of greenhouse's tomato were estimated by using evapotranspiration of the culture "ETc" calculated according to the Eq. 1 of Allen (2003);

$$ETc = Kc \times ET_0 \qquad \text{(Eq. 1)}$$

Soil Salinity Samples

Soil electrical conductivity (*EC* in dS m^{-1}) measurements were recorded by using EC probe, which provides EC values at different soil depths with 0, 5, 10, 20, 30 and 50 cm under emitters, between emitters and plant, and under plant on right and left side of root-zone with three replications per measurement. EC lectures, based on the sampling scheme given in the Fig 1, were recorded directly after irrigation to get the right measures.

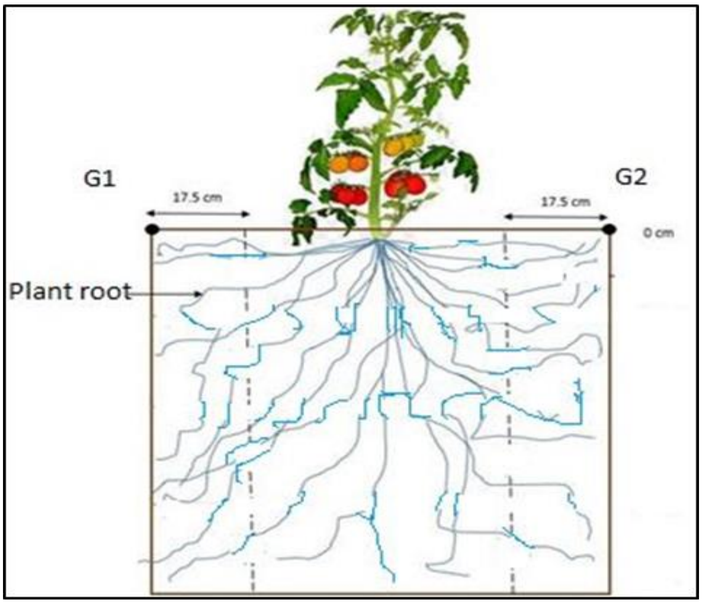

Fig 1. Soil sampling points with reference to crop and emitters (G1 and G2)

Mapping Spatial And Temporal Variability Of Soil Salinity

By using Surfer®, which is considered a useful tool to create, manipulate and display the spatial data, maps of EC development under full (FI) and deficit (DI-50) irrigation regimes have been prepared in the rooting depth of tomato plant. Concerning the mapping procedure, the point themes were generated through the use of geo-referenced EC readings. The Jeostat®-2017 (Mert & Dag, 2017) software was used in semivariogram modeling and ordinary kriging interpolation of EC data. The software also enables the user to make cross-validation tests for the fitted theoretical semivariogram models. Furthermore, numerical values of any point in the map can be controlled by using text boxes, so it allows the kriging interpolation technique in assessing, predicting and mapping soil salinity.

In order to generate EC maps in the Surfer, geostatistical analysis and estimations were made by using Jeostat®, and estimated data were then transferred to Surfer's mapping platform. In line with this target, sequential geostatistical analyses were done as the following:

a) Experimental and theoretical semivariogram analysis,

b) Gridding study area for kriging estimations,

c) Kriging estimations at the grid nodes and generating maps.

Basics of Geostatistical Estimations

The semivariogram is a plot of semivariances, denoted by γ(h), as a function of distances between the observations (Cressie, 1991). In order to plot experimental semivariogram, firstly, maximum number of sample pairs, consisting of N(N-1)/2, are formed from the N observations (Cetin & Kirda, 2003) and Euclidean distances (h_{ij}) and direction angle (α) between pairs are calculated by the following Eq. 2 and Eq. 3.

$$h_{ij} = |u_i - u_j| = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad \text{(Eq. 2)}$$

$$\alpha = \text{arctangent}\left(\frac{y_i - y_j}{x_i - x_j}\right) \quad \text{(Eq. 3)}$$

where; u_i and u_j are observation locations; x_i and y_i are easting and northing, respectively, i.e. metric coordinates of the sampling locations. Secondly, observation pairs are classified based on distances between pairs and direction angles. The semivariance values for each pair with h_{ij} distances are calculated by using Equation 4 (Clark ve Harper, 2000; Cetin ve Kirda, 2003).

$$\gamma^*(h_{ij}) = \frac{1}{2N(h_{ij})} \sum_{i=1}^{N(h_{ij})} [z(x_i) - z(x_i + h)]^2 \quad \text{(Eq. 4)}$$

Where; $z(x_i)$ is an observed value at a particular location of x_i, and $N(h_{ij})$ is total number of pairs separated by h_{ij} distance vector (Fortin, 1999). Finally, the calculated semivariance values are plotted against the h_{ij} distances and experimental semivariogram graph is obtained. Then, the user examines visually the graph so as to determine the likely theoretical semivariogram model and its parameters for kriging estimations. In this regard, theoretical model parameters consisting of nugget (unaccountable) variance [C_0] and stochastic (accountable) variance [C_1], sill value (total variance) [$C= C_0 + C_1$], range of influence [R or α] are determined accordingly (Cetin et al., 2003). In this study, adopted theoretical semivariogram model and its parameters are used interactively in the Jeostat program to estimate unknown values of soil salinity (EC) at unsampled locations. In another saying, ordinary kriging technique explained well enough in Webster et al. (2001) was used as a best linear unbiased estimator in the present study.

RESULTS and DISCUSSION

Exploratory data analysis of soil salinity (EC)

Descriptive statistics of soil salinity, EC in dS m^{-1}, obtained from EC probe for the treatments of full (FI) and conventionally deficit (DI-50) irrigation practices. Results showed both temporal and spatial variability between different treatments. EC values increased from first stage to the third one for both treatments. As it is seen in Table 1, soil salinity ranged from 1.43 to 5.01 dS m^{-1}, and from 1.45 to 4.22 dS m^{-1} for FI and DI, respectively. Descriptive statistical analysis results showed that soil salinity accumulation under DI regime is less than FI.

The values of kurtosis and skewness are not high for all the treatments. However, it might be concluded that data were characterized by a left skewed distribution albeit the skewness is low in comparison with the value of normal distribution that is equal to zero. On the other hand, Table 1 is far from giving any indication on how the salinity varies spatially in the rooting depth of tomato crop. Therefore, spatial behavior of the data might be exerted by geostatistical analysis, in particular experimental semivariogram analysis and mapping.

Semivariogram Analysis Results

It is not crucial to have a normal distribution for kriging, except for if one plans to use the kriging standard deviation to create confidence intervals of the estimated value. In this study, no-transformation was made to make salinity data normal. Hence, the semivariogram analysis was carried out directly on the observed (raw) data by using Jeostat-2017 software. In a geostatistical study, finding out the theoretical semivariogram model and its parameters are among the staple objectives. Fig. 2 depicts experimental semivariograms for the two irrigation treatments with three-replication and theoretical semivariogram types fitted to the experimental ones.

It is clear from Fig 2 that there is no masking effect on the spatial structure of the data regardless of type of the experiment. Table 2 shows theoretical semivariogram models and their parameters determined.

Directional experimental semivariogram graphs of each variable revealed neither zonal nor geometric anisotropy. Therefore, omnidirectional semivariograms were given in Fig. 2. All the experimental semivariograms were found to be bounded with the sill value, which indicates stationarity in soil salinity, fluctuating more or less around sample variance (Fig. 2 and Table 2).

Visual examination of experimental semivariograms suggested that the theoretical Gaussian and spherical models are in good agreement with the data. The theoretical model was plotted on the experimental ones. Except for the theoretical model of FI2, all the theoretical models for the treatments and replications resulted in no nugget effect component (Table 2).

As pointed out by Myers (1997), the larger the nugget effect the model has, the more it dampens the decluttering effect of kriging interpolation technique. In addition, the sill value of the theoretical models of each variable was found to be the very close to the variance of the variable. In conclusion, semivariogram analysis results revealed that sampling design is reasonable and/or consistent, and the distance between samples is small enough to determine the spatial dependence structure of the salinity data.

Table 1. Descriptive statistics of EC data (dS m^{-1}) from two treatments with three replications

Statistics	FI1	FI2	FI3	DI1	DI2	DI3
Mean	0.79	2.81	2.95	0.82	2.89	2.73
Standard Deviation	0.29	0.97	0.97	0.27	0.65	0.73
Median	0.77	3.03	3.08	0.81	2.95	2.81
Variance	0.09	0.95	0.94	0.07	0.42	0.53
Skewness	0.35	-0.33	-0.53	0.55	-0.2	-0.28
Kurtosis	-0.63	-0.17	-0.05	-0.47	0.49	-0.001
Maximum	1.43	4.92	5.01	1.45	4.02	4.22
Minimum	0.3	1.05	1.09	0.41	1.1	1.23
Range	1.13	3.87	3.92	1.04	2.92	2.99
Coefficient of variation	0.37	0.35	0.33	0.34	0.22	0.26

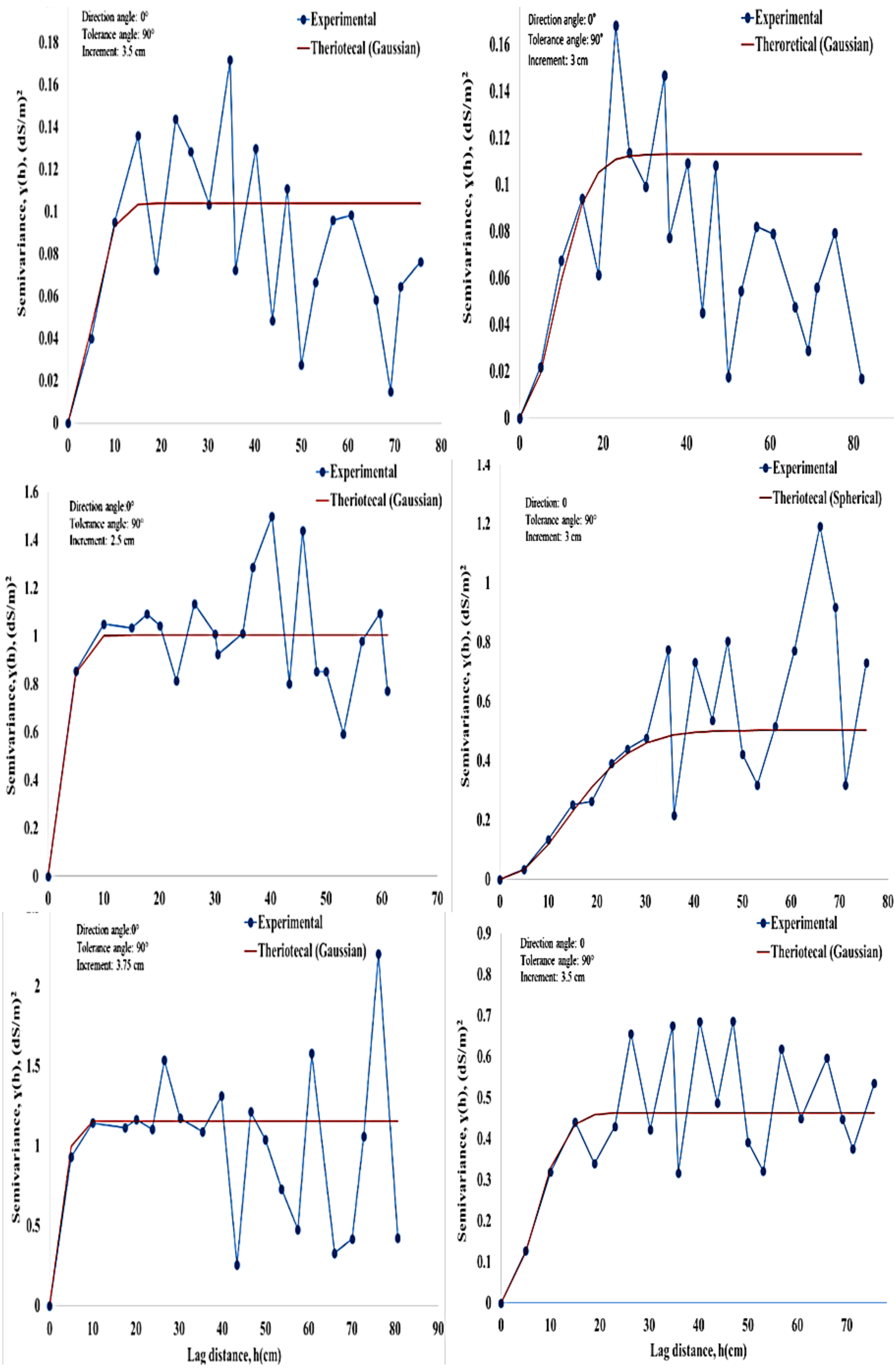

Fig. 2. Experimental and theoretical semivariograms of a) FI1, b) FI2, c) FI3, d) DI1, e) DI2, f) DI3

Table 2. Theoretical semivariogram models and respective parameters of treatments

Treatment	Model	Nugget Effect (C_o)	Sill (C)	Range (a, cm)
FI1	Gaussian	0	0.104	11.5
FI2	Gaussian	0.38	0.625	7.4
FI3	Gaussian	0	1.155	6.1
DI1	Gaussian	0	0.503	23.4
DI2	Spherical	0	0.174	43.7
DI3	Gaussian	0	0.464	15.5

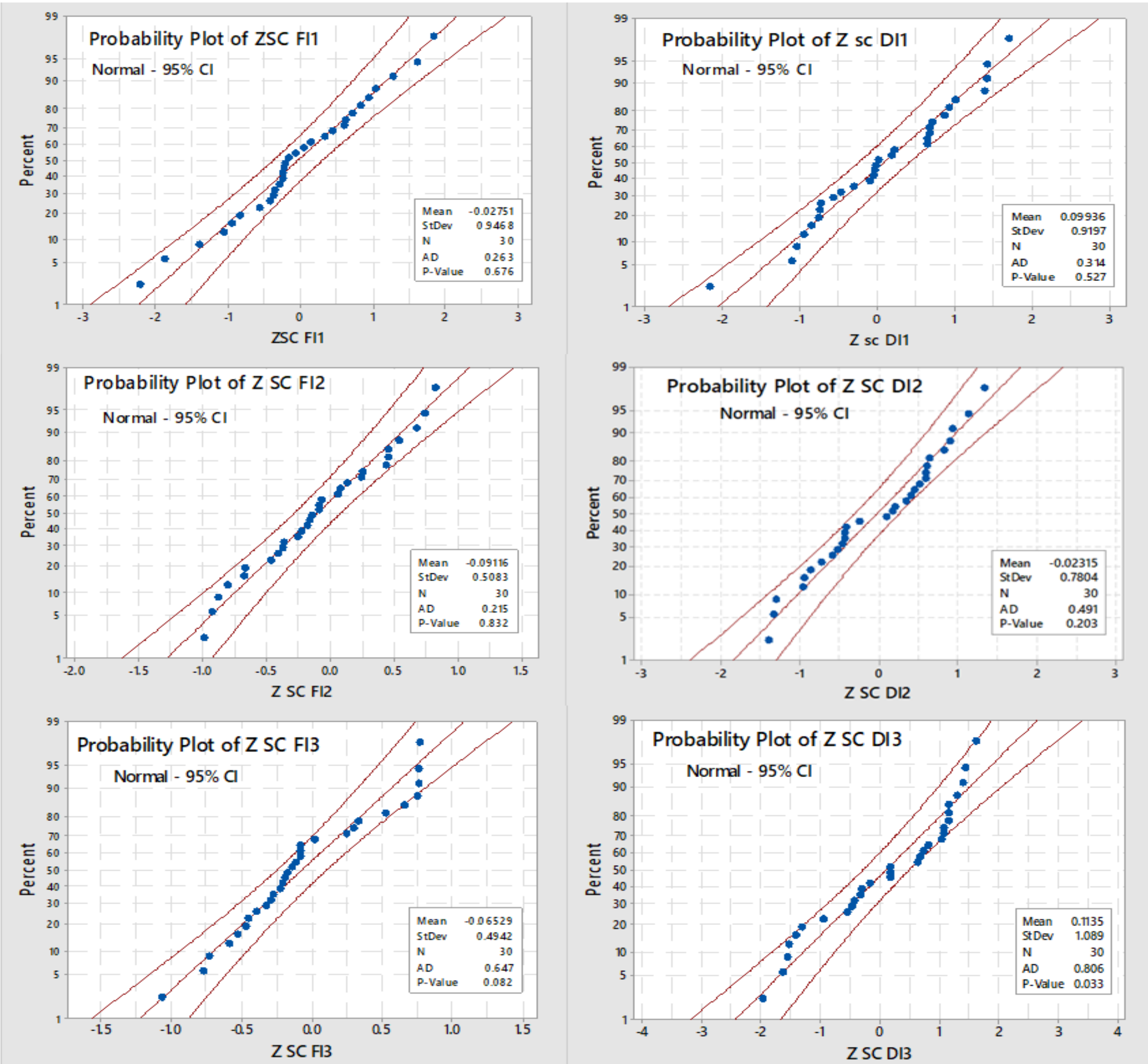

Fig 3. Probability plot of standard errors of kriging estimates with some statistics and Anderson-Darling (AD) goodness-of-fit test results

Cross validation analysis is necessary in order to decide that theoretical semivariogram models are representative for the variable being analyzed. To this end, kriging interpolation errors were standardized and then tried to fit to the normal distribution as seen in Figure 3.

Anderson-Darling (AD) goodness of fit statistics indicated that theoretical semivariogram model and its parameters as well as kriging search parameters are representative for the study site. In fact, the probability plot of kriging estimation errors, i.e. *Zscores (Z SC* in Figure 3*)*, of all the treatments, except for DI3 treatment, highlighted a normal distribution (probability of *AD*≫5%) of *Zscores* and produced the most favorable results. The higher the *P-Value* of *AD* statistics, the closer are the observed frequencies to the theoretical normal distribution line. Type of probability distribution model of kriging errors is important to calculate confidence limits for the kriging estimates.

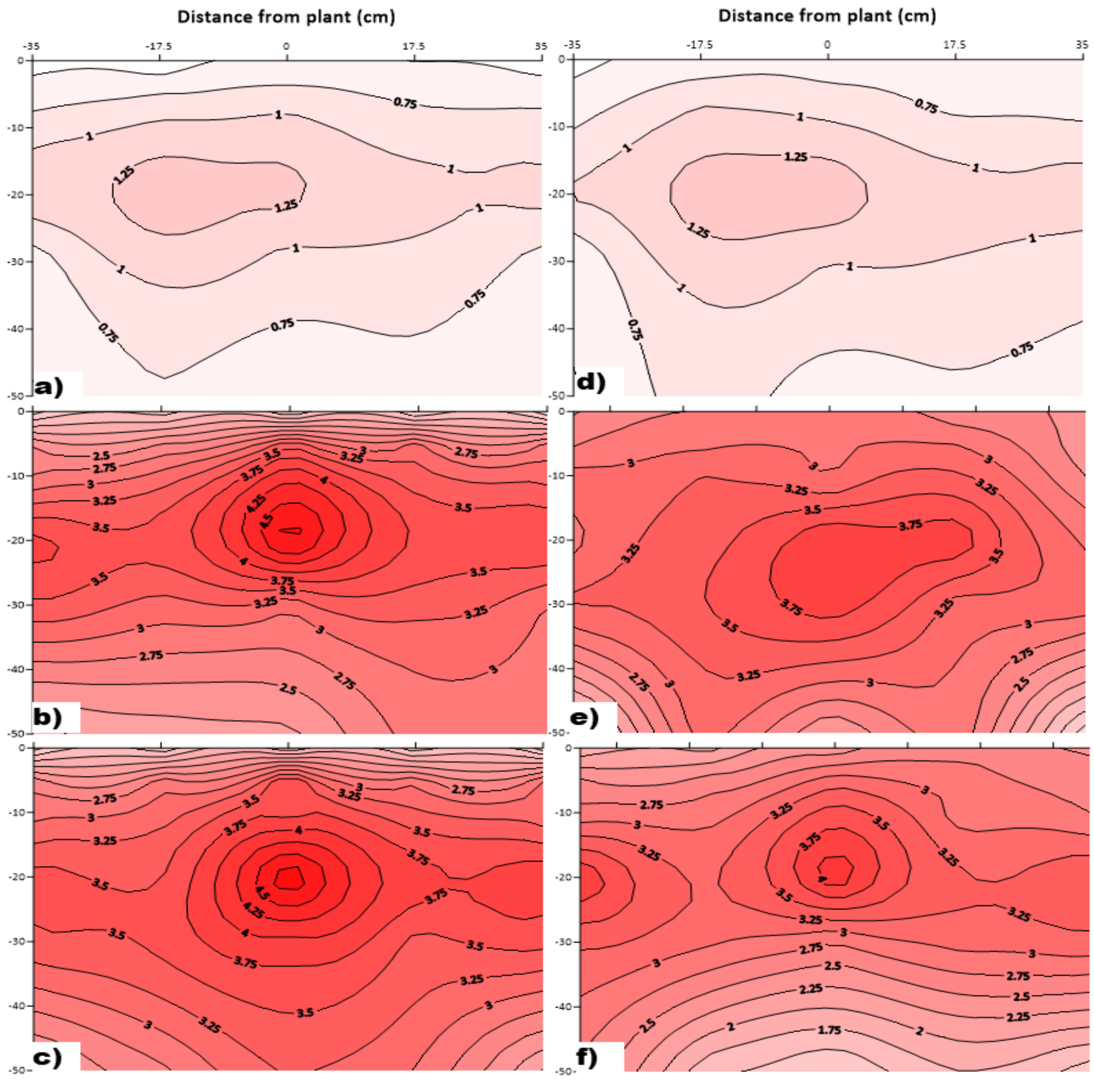

Fig. 4. Salt accumulation and distribution pattern under irrigation treatments in progress of time: At the stage of planting (FI(a), DI(d)), fruiting (FI(b), DI(e)), end season (FI(c), DI(f))

Mapping

In the study area, grid nodes of 560 points, i.e. 28 along easting and 20 along northing (depth), with 2.5 cm by 2.5 cm size, were established. The salinity values at the 560 grid nodes of each element were estimated by ordinary kriging method by using Gaussian and spherical semivariogram models and their parameters (Fig. 4). To this end, kriging search parameters were incorporated with semivariogram models, too.

Fig. 4 shows the EC distribution in the root zone by treatments. EC showed spatial and temporal salt accumulation process in the root-zone of tomato crop. In this regard, results showed that salt accumulation was concentrated in the root-zone just beneath the plant. This finding can be explained by the heavy texture of soil, which obstructs the leaching operation also by the high root density of tomato under this profile. Moreover deficit irrigation treatment reduce the amount of total salt accumulated in the root zone compared with the full irrigation treatment due to the fact that the amount of water applied with deficit irrigation is half of the full treatment. Accordingly, salt accumulation in the root zone is less under deficient irrigation practice, compared to the full irrigation. Salinity distribution pattern in the root zone was found to be in accord with the findings by Kaman et al. (2006).

Soil salinity maps reveal that salt accumulation in the root-zone gets more and more as the growing stage progress. As seen in Fig. 4a and 4d, salinity distribution pattern in the root zone is more ore les the same in the plots of FI and DI treatments in the beginning. However, while approaching to the fruiting stage, salinity development started to differ with irrigation treatments, resulting in favor of deficit irrigation practice (Figure 4b and 4e). At the end of growing season, full irrigation practice resulted in more salt accumulation in the root zone compared to the deficit irrigation, particularly beneath the tomato stem at the depth of about 20 cm (Fig. 4c for FI, 4f for DI).

CONCLUSION

The ordinary kriging interpolation technique under different irrigation regimes was an efficient tool to assess salt accumulation in the root zone of tomato plant. In fact, visual assessment of salinity development maps proved that putting the tomato plant in the middle between the two emitters caused to accumulate more salt under the plant, especially at the horizon 20-40 cm due to the heavy texture of soil and the root condensation. At the beginning, soil salinity distribution pattern for both treatments was almost the same in the root zone. In the course of time, EC in the soil profile was higher under FI than DI. Consequently, our conclusion was that salt accumulation in the root zone under deficit irrigation applications was remarkably marginal compared to the full irrigation practices.

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CONFLICTS of INTEREST
The author(s) declare no conflict of interest for this study.

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