Influence of soil hydraulic variability on soil moisture simulations and irrigation scheduling in a maize field

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Hydrological models play a crucial role for their ability to simulate water movement from soil surface to groundwater and to predict onset of stress conditions within agricultural fields. However, optimal use of mathematical models requires intensive, time consuming and expensive collection of soil related parameters. Typically soils to be characterized exhibit large variations in space and time as well during the cropping cycle, due to biological processes and agricultural management practices: tillage, irrigation, fertilization and harvest. This paper investigates the variability of soil hydraulic properties over a cropping cycle between April and September 2015, within a surface irrigated maize field (6 ha) located in northern Italy.

To this aim, undisturbed and disturbed soil samples were collected from different locations within the study area and at different depths, during three measuring campaigns, at the beginning, in the middle of the cropping season and after the harvest. For each soil sample, several parameters were monitored: organic matter and bulk density together with soil hydraulic parameters. Soil parameters of Soil water retention curve parameters were measured following the evaporation method, while the saturated hydraulic conductivity was determined in the laboratory using the well-known falling head method. Results show that soil properties, mainly the saturated hydraulic conductivity, are subjected to significant variations. The variability of these parameters was taken into consideration when simulating soil moisture using FEST-WB model. An improvement in soil water content si-mulations was observed as compared to field measurements with implications on prediction of water stress conditions that is fundamental for irrigation scheduling.

Keywords: Soil water content, Soil hydraulic properties, Stress index, Irrigation scheduling, Soil temporal variability

1. Introduction

Over the last decades, many advances had been made in terms of development of more sophisticated irrigation techniques. Modern irrigation systems with high efficiency have been suggested (sprinkler, drip, subsurface irrigation) as alternatives to low efficient ones (like surface irrigation). These irrigation techniques allowed increasing the water use efficiency for crop production (Levidow et al., 2014). In spite of this success, still many agricultural lands are irrigated through gravity-fed irrigation systems. According to the Spanish experience, the modernization of irrigation schemes was coupled with infrastructures and energy costs (Rodríguez-Díaz et al., 2011). Thus, the improvement of water management practices is considered as more cost-effective than the modernization of irrigation schemes (Lozano and Mateos, 2008).

Nowadays, "smart agriculture" based on the combination of monitoring and modelling has been widely implemented for producing "more crop per drop". In fact, a better irrigation planning, which allows optimizing water use to maximize crop production, is a precondition to reduce water use in agriculture (Rallo et al., 2011; Mun et al., 2015). Many models exist and they have been mainly developed to better manage water for irrigation such as the Aquacrop model (Steduto et al., 2009).

Implemented as decision support tools, these models should provide accurate information about the timing and amount of irrigation water in order to meet the crop water requirements. This should be reached without developing water stress or surplus conditions. Agro-hydrological models represent a powerful tool to enhance the effectiveness of irrigation scheduling (Rallo et al., 2010). The implementation of these models for irrigation scheduling is constrained by many sources of uncertainties due to: meteorological data, field measurements and the formulation of some processes such as infiltration, and evapotranspiration (Chaubey et al., 1999; Allen et al., 2011; Pereira et al., 2015 Mun et al., 2015). Understanding the controlling factors of water movement within the root zone is essential not only for irrigation scheduling, but also for the design of irrigation and drainage systems

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(Kourgialas and Karatzas, 2015).

The vadose zone, considered as the interface between surface and groundwater, controls key processes such as (infiltration, drainage, evapotranspiration) which determine the water availability (Kourgialas and Karatzas, 2015). In fact, a better characterization of the field conditions, and in particular the soil hydraulic parameters, is important for a better understanding and modeling of water and solute transport in the vadose zone. These later are also required to calculate the water availability for crops.

To be characterized, soils, particularly in the vadose zone, exhibit large variations in space and occasionally in time, due to biological processes and agricultural management practices: tillage, wheel-traffic, irrigation, fertilization and roots development (Cameira et al., 2003; Shirmohammadi and Skaggs, 1984; Iqbal et al., 2005). Therefore, soil properties are subjected to diverse physical and chemical changes that lead to a non-stability in terms of water and solutes movements within the soil as well as to the groundwater. In this context, many researchers have focused their studies on quantifying the effect of tillage on soil properties (Green et al., 2003, Mapa et al., 1986). Others tried to assess the effect of wheel traffic on infiltration (Ankeny et al., 1990; House et al., 2001 Richard et al., 1999 Défossez et al., 2003). While fewer studies were carried out to evaluate the impact of agronomic practices on soil properties and on soil water movement within the vadose zone (Ndiaye et al., 2007).

The temporal variability of soil hydraulic properties was rarely assessed or taken into consideration when modeling soil water movement (Angulo-Jaramillo et al., 1997). Some researchers tried to include within their simulations this temporal variability by measuring soil parameters at different periods of the cropping cycle (Xu and Mermoud, 2003; Schwen et al., 2011). Others tried to assess the effect of irrigation practices on temporal changes of soil properties (Mubarak et al., 2009). To our knowledge, implications of the space and time variation of soil properties on irrigation scheduling were never assessed before. It has been proven that this variability affects the soil moisture simulation results (Schwen et al., 2011). Hence, in a context of precision agriculture and smart farming practices the variability of soil hydraulic properties should be taken into consideration also within decision support tools for irrigation.

This study aimed at: (i) assessing the temporal and spatial variability of soil hydraulic properties over a cropping cycle, (ii) quantifying their effect on the simulations of soil water movement using the FEST-WB model (Rabuffetti et al., 2008) and (iii) evaluating previous irrigation schedule implemented for a maize field in the Po Valley accounting for temporal and spatial variability of soil hydraulic parameters.

In this study, the variability of measured parameters was assessed as the effect of agronomic practices and biological activities on soil properties.

2. Materials and method

2.1. Experimental site

The study site is a maize field (45°13′31.70″ N, 9°36′26.82 E) located in Secugnago, a small town in the Lombardy Region, northern Italy, within the irrigation consortium of the Muzza Bassa Lodigiana (MBL). It is a surface irrigated field that covers an area of 6 ha. Although water resources in northern Italy, and in particular in the Po Valley, are considered abundant, cultivated crops are still subjected to high evaporative demand and water stress conditions during the summer season due to the Mediterranean climate (Ceppi et al., 2014)

To compensate evapotranspiration depletion, irrigation is mandatory during the summer season. However, the irrigation scheduling in northern Italy is constrained by the non-flexibility of water delivery system with a rotation irrigation scheme (typically 14 days); turns, the consortium fixes discharges and durations according to ancient negotiated water rights.

In this paper, we used both meteorological and soil moisture data, monitored from 21st of April until 16th of September 2015. During the monitoring period, the recorded cumulative rainfall for the study site was around 195 mm with a minimum temperature of 8.7 °C and a maximum temperature of 35.4 °C. The maize in this field was sown on 08/04/2015 and 09/04/2015. During the cropping season of 2015, the field was irrigated twice: 30 of June and 14 of July.

The field was equipped with an eddy covariance and meteorological stations. Rainfall was measured by a pluviometer (AGR100 by Campbell Scientific) for the quantification of rain amounts. Within the soil, both the temperature and water content were monitored at different depths. Soil was equipped with two thermocouples (by ELSI) and a heat flux plate (HFP01 by Hukseflux) for the measurement of the specific energy flux leaving the surface layer (G). As well, three TDR probes (Time Domain Reflectometry) (CS616 by Campbell Scientific) for volumetric soil moisture measurement at different depths (10 cm, 30 cm, 65 cm). For the same purpose an FDR (Frequency Domain Reflectometry) (EnviroSMART Sentek probe) was used to measure the soil moisture profile up to a depth of 1 m. Data, stored into an internal logger memory (by Campbell), are daily downloaded with a GPRS connection. For this study, only TDR measurements were considered to compare field measurements with model simulations.

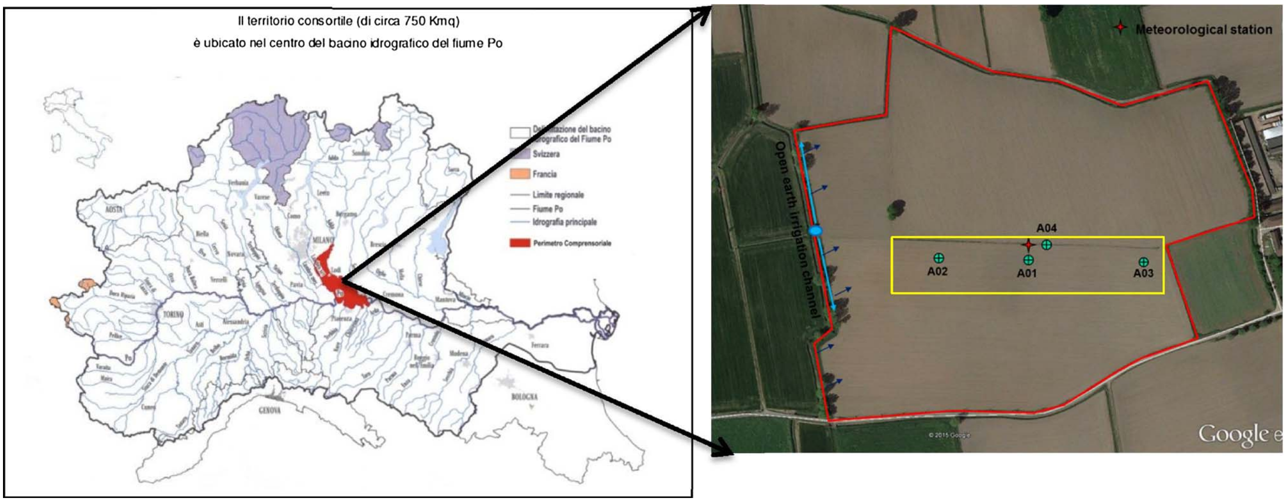

Fig. 1. Study site and sampling point locations.

2.2. Soil sampling

Within the field, we selected a 366 m length and 81 m width plot, highlighted in yellow (Fig. 1), where we carried out our measurements. During several field campaigns, soil samples were collected at different points referred as: A01, A02, A03 and A04, (Fig. 1) at different soil depths (0 cm–20 cm, 20 cm–40 cm and 40 cm–60 cm). The three sampling depths were referred as 0 cm, 20 cm and 40 cm respectively. Considering that the top soil is more susceptible to variability due to agronomic practices and biological activities than deeper layers, we limited our soil parameters monitoring to the upper first 40 cm of the soil. At each sampling point and within each field campaign three replicates were taken using a 250 ml volume steel cylinder with 8 cm inner diameter and 5 cm length. Above ground plant materials were removed before inserting the sampling ring. The selection of sampling points aimed at assessing the spatial variability of soil properties located as presented in (Fig. 1): A01 in the middle of the field, A02 near to the irrigation canal, and A03 at the extremity of the field. The sampling point A04 was selected in an external area of the field that had been left uncultivated for more than 8 years. This point was selected in order to assess the effect of different agronomic practices on soil properties as compared with the rest of the field cultivated with maize for more than 25 years.

Soil sampling was carried out during three field campaigns. The first campaign (C1- 30/04/2015) was carried out two weeks after sowing. Measurements from this campaign aimed at determining the soil characteristics at the beginning of the cropping cycle and to assess the vertical and horizontal variability of soil properties within the field. The second campaign (C2- 08/07/2015) was at a fully developed crop after the first irrigation to assess the possible effect of crop development and irrigation on soil characteristics. Roots were mainly developed near surface (upper first 20 cm of the soil) and their density decreased with depth (up to 40 cm depth). Based on field observations this could be due to some soil properties constraints that will be explained afterwards. For this reason, within the second campaign samples were collected only at surface and 20 cm depth. The last campaign (C3- 25/09/2015) aimed at assessing the variability of soil properties by the end of the cropping season after the harvest and samples were collected only at soil surface.

2.3. Measurements

Collected intact soil samples were used to determine soil hydraulic properties in the laboratory. For each soil sample, we carried out measurements to assess the saturated hydraulic conductivity (Ks), soil water retention curves (SWRC), bulk density, particle size distribution and organic matter content.

Dry bulk density was calculated from the oven-dry weight of the soil and the known volume of the sampling ring. Particle size distribution for each soil sample was determined by sieving and hydrometer experiments. Sand, silt and clay contents were identified according to the USDA (United States Department of Agriculture) system of soil classification. Particle size analysis gave 72% sand, 5.57% clay and 22.43% silt. The soil was classified as sandy loam according to USDA classification. The organic matter content was determined for each sample using loss-on-ignition (LOI) method, which has been considered as inexpensive giving accurate estimation of the organic matter content (Cambardella et al., 2001).The soil total porosity was computed based on the bulk density:

$$\phi = 1 - \frac{\rho_b}{\rho_p} \tag{1}$$

With

$$\rho_b = \frac{\boldsymbol{weight\ \ of\ \ dry\ \ soil}\,(\boldsymbol{g})}{\boldsymbol{volume\ \ of\ \ the\ \ core}\,(\boldsymbol{cm}^3)} \tag{2}$$

where ρ_b is the soil bulk density [g/cm^3] and ρ_p is the soil particle density [g/cm^3]. This later was considered equal to a commonly accepted average value of 2.65 g/cm^3 (Skopp, 2000).

The determination of the saturated hydraulic conductivity, at each sampling point, was carried out following two methods: in situ using the Guelph permeameter (Reynolds and Elrick, 1986) and in the laboratory using KSAT-UMS device (KSAT-UMS Germany, 2012). To carry out Guelph permeameter measurements, at each measuring point a 6 cm-diameter and 16 cm-depth vertical hole was augered. It should be noted that one order of magnitude difference was found between in situ and laboratory measurements of Ks. Considering that this method usually under-estimates the value of the saturated hydraulic conductivity (Mohanty et al., 1994; Jačka et al., 2014), we decided to focus these analysis on laboratory falling head experiments only.

Soil water retention curve parameters (SWRC) were determined based on fitting procedure of evaporation method. Evaporation method is a commonly used method for laboratory determination of soil hydraulic parameters. This experiment was carried out on collected undisturbed soil samples using the HYPROP-UMS device (Hydraulic Property Analyzer; UMS Munich, 2010, Schindler et al., 2010). The accuracy of using the HYPROP device to derive the soil hydraulic parameters was previously confirmed by (Schwen et al., 2014). This method is a simplified method based on pressure head measurements at two different depths measured using two tensiometers installed into the HYPROP base. The soil sample together with the HYPROP base were placed on the top of a balance in order to record the weight (Schindler et al., 2010). Water losses by evaporation from initially saturated soil sample induced changes of the pressure head and the weight. The recorded values of the hydraulic gradient (from pressure head measurements) and soil water content (from weight measurements) allowed drawing the soil water retention curve. Data collected from these experiments were evaluated using the HYPROP-FIT software. This program allows the fitting of collected data to a given parametric soil water retention curve equation using the Levenberg-Marquardt method (Marquardt, 1963). Many studies have focused on the evaluation of temporal variability of soil water retention curve characteristics using the Van Genuchten-Mualem model (1980) given by:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h)^n]^m} \tag{3}$$

$$K(S_e) = K_S S_e{}^{\tau}[1 - (1 - S_e{}^{1/m)m}]^2 \tag{4}$$

where θ, θ_r and θ_s are the actual, residual and saturated water content, respectively [L^3/L^3], K_s is the saturated hydraulic conductivity [L/T], while α, m and n are empirical parameters, τ represents the tortuosity factor and S_e is the effective saturation, calculated as

$$\boldsymbol{S_e} = \frac{(\theta - \boldsymbol{\theta_r})}{(\boldsymbol{\theta_s} - \boldsymbol{\theta_r})} \tag{5}$$

In order to decrease the number of parameters during the fitting procedure, we set the saturated hydraulic conductivity to the measured value from the falling head experiments. The tortuosity factor was fixed at 0.5 as recommended by Mualem (1976).

2.4. Soil moisture simulations

Soil moisture simulations were carried out using the hydrological FEST-WB model, an acronym for “Flash Flood Event-based Spatially-distributed rainfall-runoff Transformations-Water Balance” developed at Politecnico di Milano since 1990 (Ceppi et al., 2014, Ravazzani et al., 2017). This model allows calculating main processes of the hydrological balance: evapotranspiration, infiltration, surface runoff, flow routing, subsurface flow and snow dynamics (Boscarello et al., 2015). Simulations were carried out based on Richards’ equation for 1D water flow solved following the solution proposed by Ross (2003); soil hydraulic parameters for the Van-Genuchten unimodal (1980) were used for these

Table 1
Details of implemented soil hydraulic properties within the performed simulations.

SIMULATION	Details
S1	Soil properties from first campaign with homogeneous soil profile
S2	Soil properties from first campaign with heterogeneous soil profile
S3	Soil properties from second campaign with homogeneous soil profile
S4	Soil properties from second campaign with heterogeneous soil profile
S5	Time variable soil properties with homogeneous soil profile
S6	Time variable soil properties with heterogeneous soil profile

Table 3
The Van Genuchten water retention parameters of all sampling points during all measuring campaign (C1, C2 and C3) for the cultivated and uncultivated parts of the field: bubling pressure (α), van Genuchten shape parameter (n), water content at soil saturation (θ_s), water content at field capacity (FC), water content at wilting point (WP) and available water content (AW).

	Depth (Cm)	α (1/cm)	n	θ_s (%)	FC (%)	WP (%)	AW (%)
Uncultivated							
C1	0	0.11	1.049	40.6	26.90	14.8	12.10
	20	0.04	1.248	30.0	18.60	8.80	9.80
	40	0.05	1.206	27.5	14.40	5.60	8.80
C2	**S**	0.04	1.157	42.0	25.50	10.8	14.70
C3	**S**	0.05	1.123	38.0	23.70	11.00	12.70
Cultivated							
C1	**0**	0.04	1.195	45.0	29.90	14.97	14.93
	20	0.06	1.195	43.0	30.43	16.87	13.57
	40	0.01	1.206	32.0	23.87	9.1	14.77
C2	**0-Inter-rows**	0.07	1.311	43.2	24.97	10.97	14.00
	0-Rows	0.11	1.261	42.6	19.37	6.2	13.17
C3	**0**	0.05	1.235	39.0	19.17	6.6	12.57

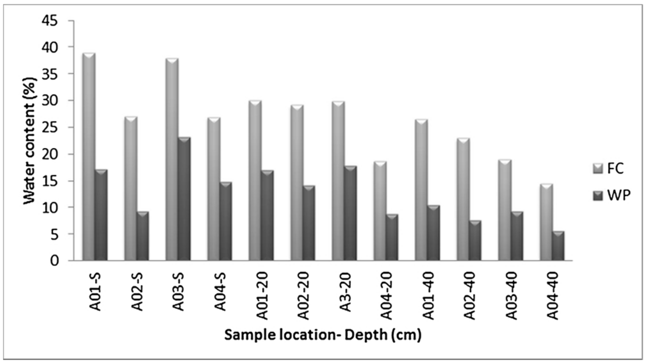

Fig. 2. Vertical and horizontal spatial variability of water content at field capacity (FC) and wilting point (WP).

simulations. Potential evapotranspiration (ETP) was computed based on Hargreaves Samani equation (Hargreaves and Samani, 1985), while crop coefficient K_c was taken from the FAO 56 (Allen et al., 1998). The modeling period started from 30/04/2015 until 17/09/2015. Initial conditions were set in terms of water content. The upper boundary condition was set to atmospheric conditions, while a free drainage was assumed at the bottom of the soil profile. For these simulations, soil profile of 60 cm depth was divided into 6 compartments of 10 cm each. The computational domain was discretized by a mesh of squared cell, of 1 m per side, where water fluxes were calculated at hourly time step.

To evaluate simulations against field measurements, two common statistical indexes were selected: the coefficient of determination R^2 which corresponds to the coefficient of correlation according to Bravais-Pearson and Root Mean Square Error (RMSE).

Model simulations were carried out for two aims: the first was to assess the effect of soil hydraulic parameters on soil moisture simulations of spatial variability and temporal dynamics of these properties during the cropping cycle. Thus, several simulations were performed, as presented in (Table 1), with different sets of soil hydraulic parameters. The second aim was to evaluate the adequacy of the implemented irrigation schedule accounting for the variability of soil hydraulic properties.

At each time step of the simulations, a stress index (SI) was calculated. The evaluation of the stress index was carried out according to a fixed stress threshold and surplus values. The stress threshold was calculated according to the following equation:

$$Stress\quad Threshold = \theta_{FC} - p \times (\theta_{FC} - \theta_{WP}) \tag{6}$$

where p is the management allowed depletion average fraction of the total available water for the plant (TAW) that can be depleted from the root zone before moisture stress and it depends on the crop (Allen et al., 1998). θ_{FC} is the water content at field capacity [L^3/L^3], and θ_{WP} is the water content at the wilting point [L^3/L^3].

Surplus conditions correspond to situations where the water content is higher or equals to the field capacity and this situation is identified by a (*SI*) equals to 1. For water content values between field capacity and stress threshold, (*SI*) is equal to 0 which corresponds to optimum

Table 2
Spatial and temporal variation at different sampling points and at different soil depth of bulk density (BD), organic matter content (OM), total porosity and saturated hydraulic conductivity (Ks).

Sample	1st campaign (C1)					2nd campaign(C2)					3rd campaign (C3)				
	Depth (cm)	BD (g/cm3)	OM (%)	Total POROSITY	Ks (mm/h)	Depth (cm)	BD (g/cm3)	OM (%)	Total POROSITY	Ks (mm/h)	Depth (cm)	BD (g/cm3)	OM (%)	Total POROSITY	Ks (mm/h)
A01	0	1.47	3.76	44.66	0.60	0-Inter-row	1.15	3.09	56.55	132.84	0	1.36	4.04	48.38	392.40
						0-Row	1.06	4.99	59.85	294.48					
	20	1.64	3.05	37.99	0.71										
	40	1.69	2.96	36.3	0.70										
A02	0	1.62	3.67	38.9	13.28	0-Inter-row	1.44	3.64	45.55	1512.00	0	1.4	3.32	46.95	331.20
						0-Row	1.29	4.62	51.41	1659.60					
	20	1.69	3.21	36.4	12.10										
	40	1.7	3.19	35.85	0.46										
A03	0	1.49	3.91	43.61	2.50	0-Inter-row	1.48	4.18	44.26	24.55	0	1.3	3.34	50.62	1486.80
						0-Row	1.25	4.45	52.91	65.88					
	20	1.69	3.48	36.16	2.20										
	40	1.71	2.97	35.4	0.85										
A04	S	1.55	5.26	41.41	219.96	0	1.49	4.35	43.65	191.88	0	1.5	3.77	43.05	651.60
	20	1.70	3.29	35.87	14.58										
	40	1.76	3.00	33.62	0.44										

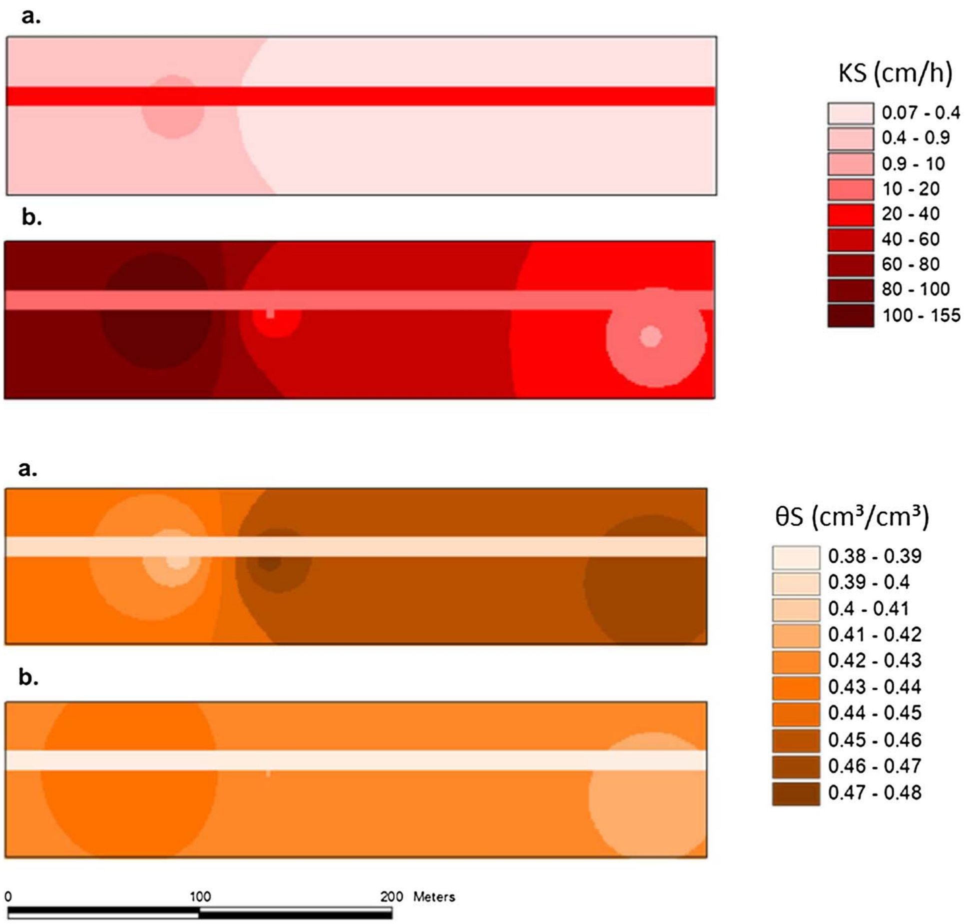

Fig. 3. Spatial distribution and temporal variation of saturated water content and saturated hydraulic conductivity (a. first measuring campaign, b. second measuring campaign).

Table 4
RMSE [cm^3/cm^3] and R^2 indices for soil moisture simulations vs. measured values (In all tests P-value was lower than 0.05).

S1				S2				S3			
Depth	10 cm	30 cm	soil profile	Depth	10 cm	30 cm	soil profile	Depth	10 cm	30 cm	soil profile
RMSE	0.123	0.101	0.118	**RMSE**	0.118	0.112	0.119	**RMSE**	0.122	0.142	0.127
R^2	0.130	0.160	0.168	**R^2**	0.210	0.210	0.268	**R^2**	0.362	0.418	0.459
S4				S5				S6			
Depth	10 cm	30 cm	soil profile	Depth	10 cm	30 cm	soil profile	Depth	10 cm	30 cm	soil profile
RMSE	0.108	0.082	0.085	**RMSE**	0.074	0.095	0.082	**RMSE**	0.062	0.063	0.059
R^2	0.469	0.406	0.480	**R^2**	0.618	0.628	0.646	**R^2**	0.692	0.731	0.772

conditions for roots water extraction. On the contrary, when the soil moisture is lower than the stress threshold; (*SI*) is equal to 2 indicating the occurrence of stress conditions for the crop. In this study, we used the stress index, to evaluate the implemented irrigation schedule within this study area considering the variability of soil hydraulic properties.

3. Results and discussion

3.1. Spatial and temporal variability of soil properties

3.1.1. Bulk density, organic matter total porosity and saturated hydraulic conductivity

The bulk density variation was inversely correlated to the temporal and spatial variations of organic matter content, total porosity and saturated hydraulic conductivity (Table 2). The highest bulk density and the lowest saturated hydraulic conductivity values were recorded within the first field measuring campaign (C1) (Table 2). It should be noted that samples were collected after tillage. Immediately after this operation, the field has received a heavy rainfall of about 42.8 mm/day of which 16 mm in just 30 min. The tillage is supposed to increase the porosity of the soil that yields an increase of hydraulic conductivity while for this case the effect was reversed. The post-tillage rainfall together with the succession of drying and wetting cycles caused a reduction of conductive pores (Messing and Jarvis,1993, Moret and Arrúe, 2007), an increase of the bulk density and as a consequence a decrease of the saturated hydraulic conductivity (Table 2) (Cameira et al., 2003).

Regarding the spatial variability of *Ks*, during the first survey, this parameter did not show a high variation in the cultivated part of the field (A01, A02 and A03) with (0.6, 13.28, and 2.5 mm/h) respectively

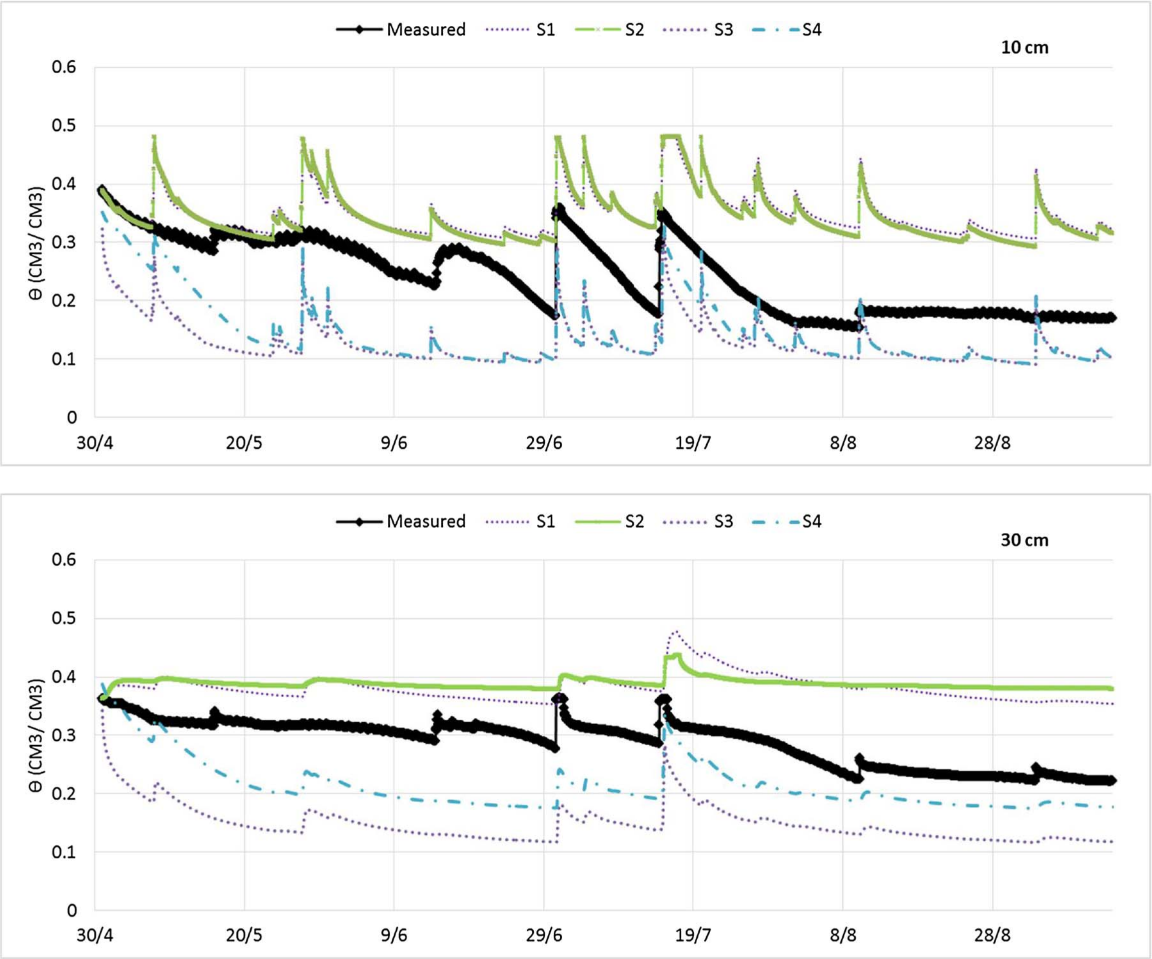

Fig. 4. Soil moisture simulations S1–S4 VS measurements.

for surface samples. For A04 sampling location, the highest organic matter content (5.26%) with a high number of macropores (earthworms channels, grass roots) were observed while none was found within the cultivated part of the field. Altough values of the total porosity of this sampling location were similar to other cultivated part of the field, in particular for (0 cm) samples, this part presented the highest *Ks* value of 220 mm/h. Surface samples collected from A04 gave 97.52% higher Ks values as compared to the cultivated part of the field.

This result is justified by the large influence of macropores on water flow upon micro-meso pores (Messing and Jarvis, 1993, Moret and Arrúe, 2007). These results confirmed the findings of some researchers that conducted studies to quantify the effect of NT (no tillage) and CT (conventional tillage) on soil properties (Comia et al.,1994; Cresswell et al., 1993; Drees et al., 1994). Cropping practices have reduced macropores connectivity, biological activities, thus decreased the saturated hydraulic conductivity. Nevertheless, lower values of *Ks* were recorded at 20 cm and 40 cm depths that was justified by the high bulk density, low organic content values and less macropores.

During the second campaign (C2), under fully developped crop conditions, we focused our measurements on the upper 20 cm of the soil profile and samples were collected in the rows and inter-rows. We observed during this field campaign that rooting depth was limited to the upper first 40 cm of the soil profile, while roots were mainly concentrated in the upper 20 cm of the soil profile. This could be justified by the lower available water and higher bulk density found in the first campaign at deeper soil.

Bulk density for surface samples increased with depth while decreased during the cropping cycle mainly between C1 and C2 with an decrease of 28.36% for row samples and 18.22% for inter-rows samples.

As reported in (Table 2), a sharp increase of the saturated hydraulic conductivity was recorded during the cropping cycle from 0.6 mm/h for A01–0 cm during C1 to 133 mm/h for A01–0 cm-inter-row sample and 294.8 mm/h for A01–0 cm-row sample. Clearly, according to these results *Ks* was a sensitive parameter to temporal variability which is in agreement with the result found by Mubarak et al. (2009). In the middle of the cropping cycle, we observed some earthworms' channels with high number of macropores for samples collected under the plants (row-samples) due to plant roots. These could justify the increase of the total porosity between the first and second campaigns in particular for rows samples. Thus, the *Ks* was amplified with the increase of the macroporosity due biological factors in particular the roots development that inhenced the connectivity of pores. The same result was found by many other researchers such as Cameira et al. (2003) and Rasse et al. (2000).

The temporal variation of measured parameters was more significant between the first and second campaigns. At the end of the cropping season, measured values of *Ks* at different sampling locations were quite homogeneous. The total porosity and organic matter content decreased with 11% and 23% respectively as compared to row samples of the second campaign, while only a little difference was observed for the bulk density.

3.1.2. Soil water retention curve parameters

In favor of comparing the variation in time of the soil hydraulic properties, Table 3 shows the SWRC parameters of the uncultivated part of the field (presented by the samples collected from A04) and averaged

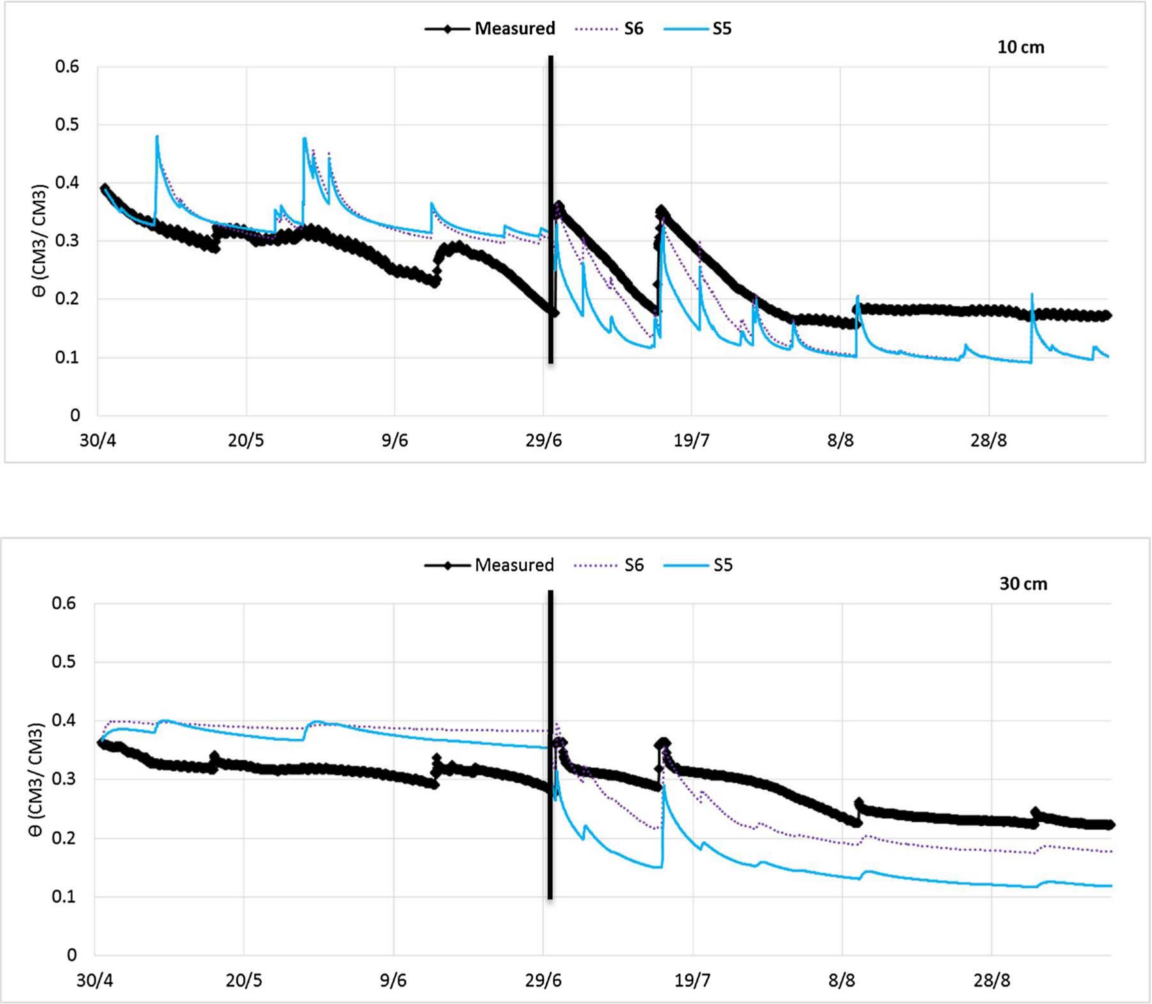

Fig. 5. Soil moisture simulations S5 and S6 VS measurements for the soil profile.

values for the sampling points located within the maize cropped part. The results for the uncultivated part of the field showed that the time variation was not significant, while the cultivated part showed more sensitivity to time variability.

The saturated water content showed time and spatial variability (Table 3, Fig. 3). This parameter tended to decrease with depth for both cultivated and uncultivated soils. Additionally lower values for surface samples were recorded in the second and last measuring campaigns. This decrease was also observed for field capacity and wilting point water contents. As presented in Fig. 2, FC values together with WP decreased with depth. Thus, available water content (AW), calculated as the difference between FC and WP, was lower at deeper soil layers. FC and WP values showed also a decrease throughout the cropping cycle (Table 3). These parameters usually used for soil moisture based irrigation management to fix the stress threshold were subjected to a temporal variation that should be taken into consideration for such an application.

Few studies have adressed the variation in time of soil water retention (Alletto et al., 2015). Results presented in Table 3 showed also the sensitivity of soil water retention curve parameters to the variation in time and space. The van-Genuchten shape parameter n was variable between different measuring campaigns. This variation in time and space does not follow a specific trend, because this parameter depends on soil texture, while the temporal variability is mainly related to changes in the structure (Ndiaye et al., 2007).

The shape parameter α increased between the first and second measurements. The highest values for this parameter were recorded for the surface sample of the uncultivated soil and the surface sample in the second measuring for row samples. The air entry parameter is related to the soil porosity and this variation could indicate its sensitivity to the increasing soil porosity. Further, measurements are required to derive clearer conclusions about the variability of this parameter. Combining these results with the other soil properties, previously mentioned, confirms that the soil is subjected to spatial and temporal variability.

After the harvest, as shown in Table 3, soil hydraulic properties were quite homogeneous between the uncultivated and cultivated parts of the field. While as compared to the measurements of the C2, only a decrease of the saturated water content value was observed from 0.43 $\mathrm{cm}^3/\mathrm{cm}^3$ for the C2 to 0.38 $\mathrm{cm}^3/\mathrm{cm}^3$ for the C3. The bare part of the field did not show the same temporal variability observed within the cropped parts between the C1 and C2, since it was not affected by the cropping practices neither by the crop growth.

3.2. *Soil moisture simulations and assessement of irrigation scheduling*

3.2.1. *Local simulations*

Usually simulations and monitoring activities within agricultural fields are carried out at local scale (one spot). The sampling point A01 was the closest to the meteorological and soil moisture sensors among the other sampling points. We decided to assess the simulation performances at this point locally (Table 4). Note that all simulations were carried out without any calibration, therefore any improvement or degradation of the simulated water content is only due to measured parameters. This makes a perfect fit between the simulations and

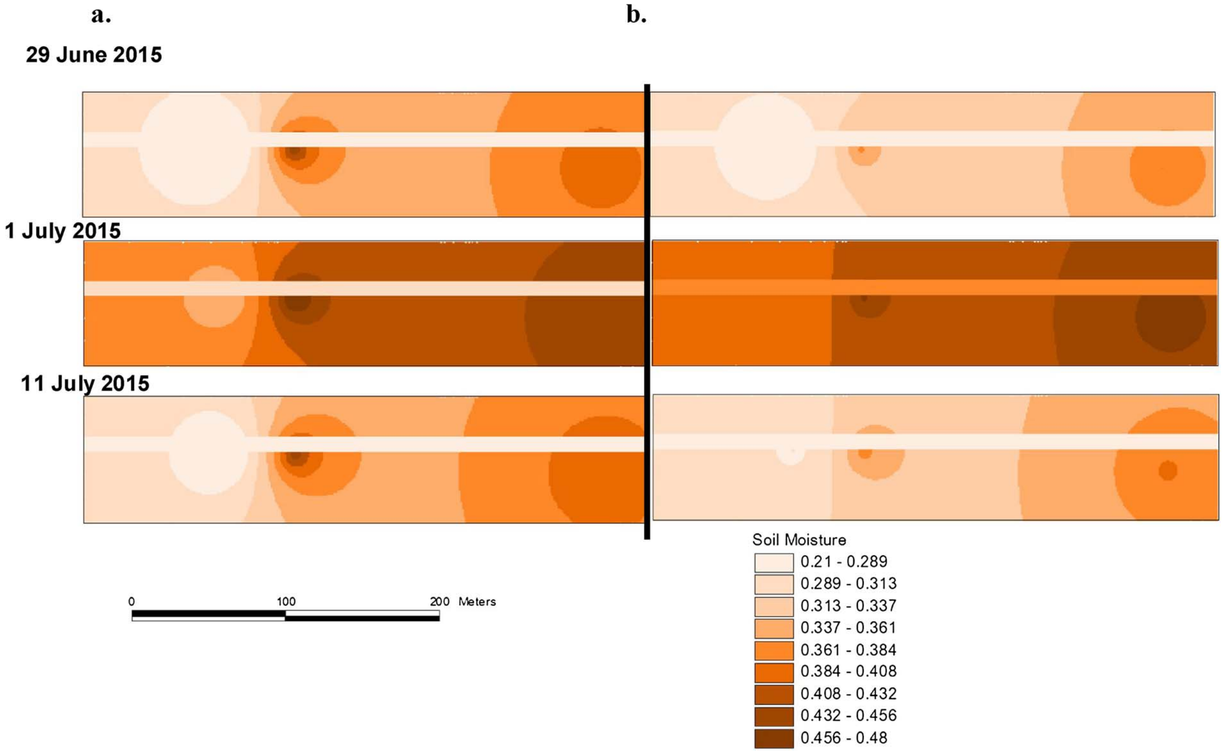

Fig. 6. Spatial distribution and temporal variation of soil water content (cm^3/cm^3): (a. soil data from the first measuring campaign, b. soil data from the second measuring campaign).

measurements impossible. Comparison with field measurements of soil moisture was carried out for 10 cm, 30 cm and averaged soil profile (40 cm).

The effect of the vertical spatial variability of soil water hydraulic parameters on soil moisture simulations was assessed through the comparison between the S1 and S2. For the S1 surface soil samples parameters were considered as representative for the whole soil profile, while for the S2 soil, parameters at (0 cm, 20 cm and 40 cm) were implemented. Very small improvement of simulation results was found between S1 and S2 with value of R^2 from 0.168 to 0.268 for the soil profile. Results of S1 show that taking into consideration time constant set of soil parameters throughout the cropping cycle overestimates soil moisture, in particular under fully developed crop conditions.

By the simulations S3 and S4, we tried to assess the representativeness of soil properties measured during the C2 for the whole cropping cycle. Results show an improvement of soil moisture simulations as compared to simulations performed using soil hydraulic parameters measured at C1. As shown in Fig. 4, both S3 and S4 tend to underestimate soil moisture during the first part of the cropping cycle. The same result was reported by Schwen et al. (2011). Despite the low performance at the beginning of the cropping cycle, the use of this set of parameters measured during C2 improved model results for the whole simulation period (Mubarak et al., 2009). The values of RMSE and R^2 for the soil profile were equal to 0.085 and 0.48, respectively.

In the last simulations (Fig. 5) S5 and S6, time variable soil hydraulic properties were implemented. The soil hydraulic parameters measured during C1 were used as first set of input for the model. The vertical black line represents the time when the second set of soil hydraulic parameters measured in the middle of the cropping cycle (during C2) have been introduced. The comparison between S1 with S5 shows that considering soil properties as constant during the whole simulation period (cropping cycle) gave lower performances then the simulation with time variable parameters. The effect of temporal variability of soil properties was more important than the vertical spatial variability. This effect was shown through the value of RMSE of 0.082 for S5, while this value was 0.119 for S2.

Although there is some small disagreement between simulations and measurements, S6 yielded the best result. This confirms that taking into consideration the temporal variability together with the vertical heterogeneity of soil properties yielded a significant improvement of simulation quality. This simulation gave a value of RMSE and R^2 of 0.059 and 0.772 respectively. This result reflects the significance of accounting for the time variability soil properties on soil water content simulations.

On the other hand, through these simulations, the stress index was assessed considering these parameters as constant and variable in time. At a first step, we considered constant stress threshold depending on the values of wilting point and field capacity measured at A01–0 cm sample during the C1. For taking into consideration the variation in time of this threshold, we selected the results of the sample A01–0 cm-row from the C2, since the irrigation is aiming at satisfying the plant water requirements.

Results of simulations with/without irrigation with constant stress and surplus threshold are presented in Fig. 7a. In order to assess the performances of applied irrigation in this study site and to evaluate its performances, as presented in Fig. 8, we calculated the percentages of occurrence of both stress and surplus conditions at different depths (10 cm, 20 cm and 30 cm).

According to these results, no water stress was observed even without irrigation. At the same time, more surplus conditions were observed in deeper soil at 30 cm than 10 cm and 20 cm layers under irrigation. In this case, the applied irrigation, according to the stress index, has only increased the surplus conditions from 6%, 6% and 7% to 12%, 20% and 25% at 10 cm, 20 cm and 30 cm, respectively. Hence, according to these results, no irrigation was required at all since during the entire cropping season no stress conditions were observed.

On the contrary, when time variable soil properties were considered together with modified stress thresholds in the middle of the cropping cycle, stress conditions were observed. As presented in Fig. 7b, simulations without irrigation show more stress conditions at 10 cm and 20 cm soil depth.

When irrigation was applied, some stress was avoided by the second

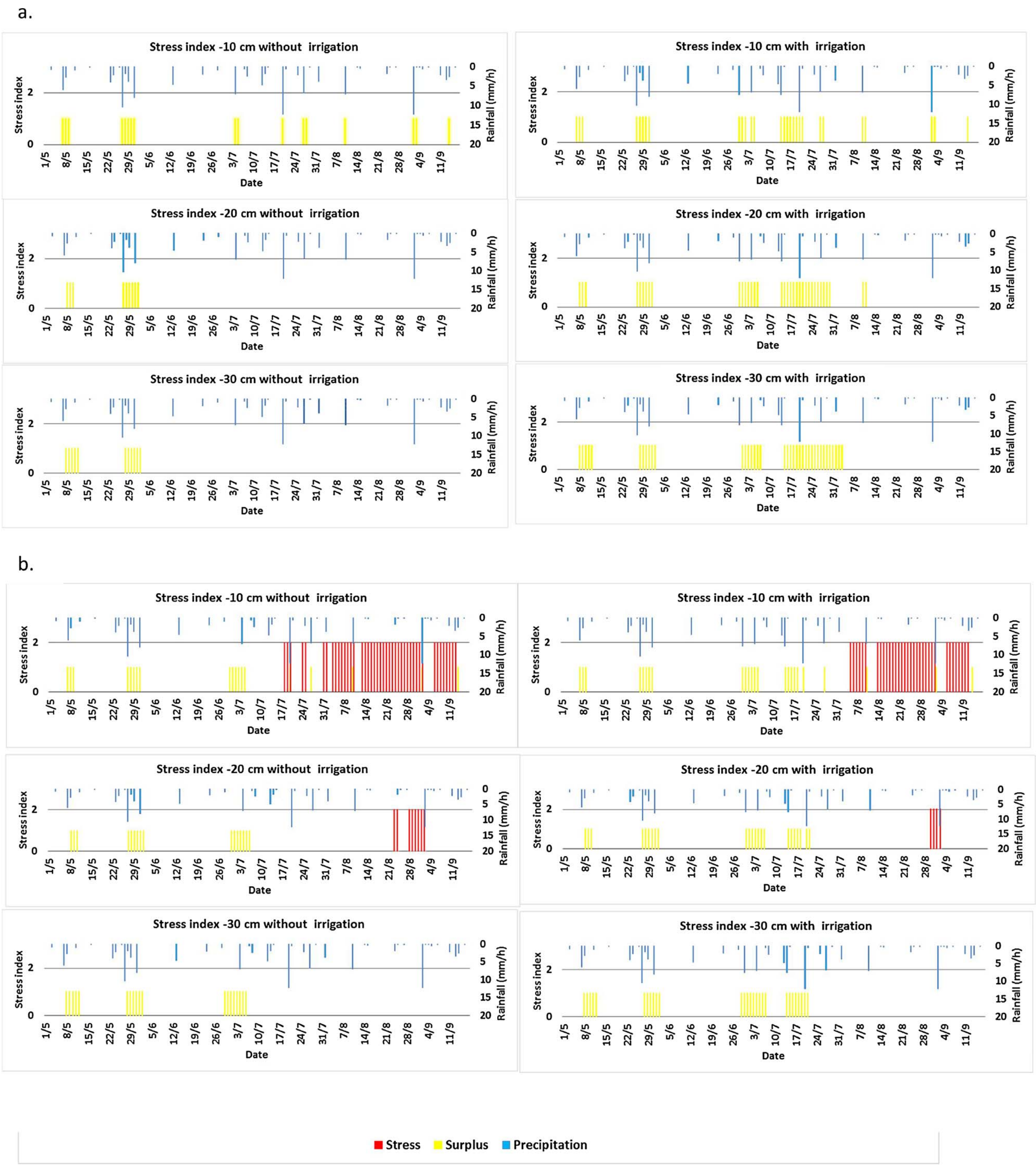

Fig. 7. Stress index variation during the 2015 growing season with and without irrigation A01 sampling point a. without time variable soil hydraulic properties b. with time variable soil hydraulic properties.

irrigation, but the first irrigation has only increased the surplus conditions. The percentage of occurrence of stress conditions without irrigation at 10 cm was equal to 26%, while when the irrigation was applied, was reduced only by 5%.

This result prove a mismatching between the period where the water content reached stress thresholds and the irrigation timing, thus the efficiency in reducing stress conditions was irrelevant; on the contrary, more surplus was developed at different soil depths.

Knowing the stress index at each soil layer, when scheduling the irrigation, is very important. According to these results, considering that roots were mainly concentrated in the upper part of the soil profile, a special interest should be given to the 10 cm and 20 cm depths. Thus, according to these considerations, the irrigation should be shifted later in the cropping season. These results show that considering the stress threshold as fixed during the growing season could lead to erroneous results in terms of irrigation scheduling.

3.2.2. *Spatially distributed simulations*

In order to show the significance of the spatial variability of soil hydraulic properties and their effect on soil moisture simulations were carried out using the data collected at different sampling points of the field. Soil hydraulic parameters from C1 and C2 were mapped using

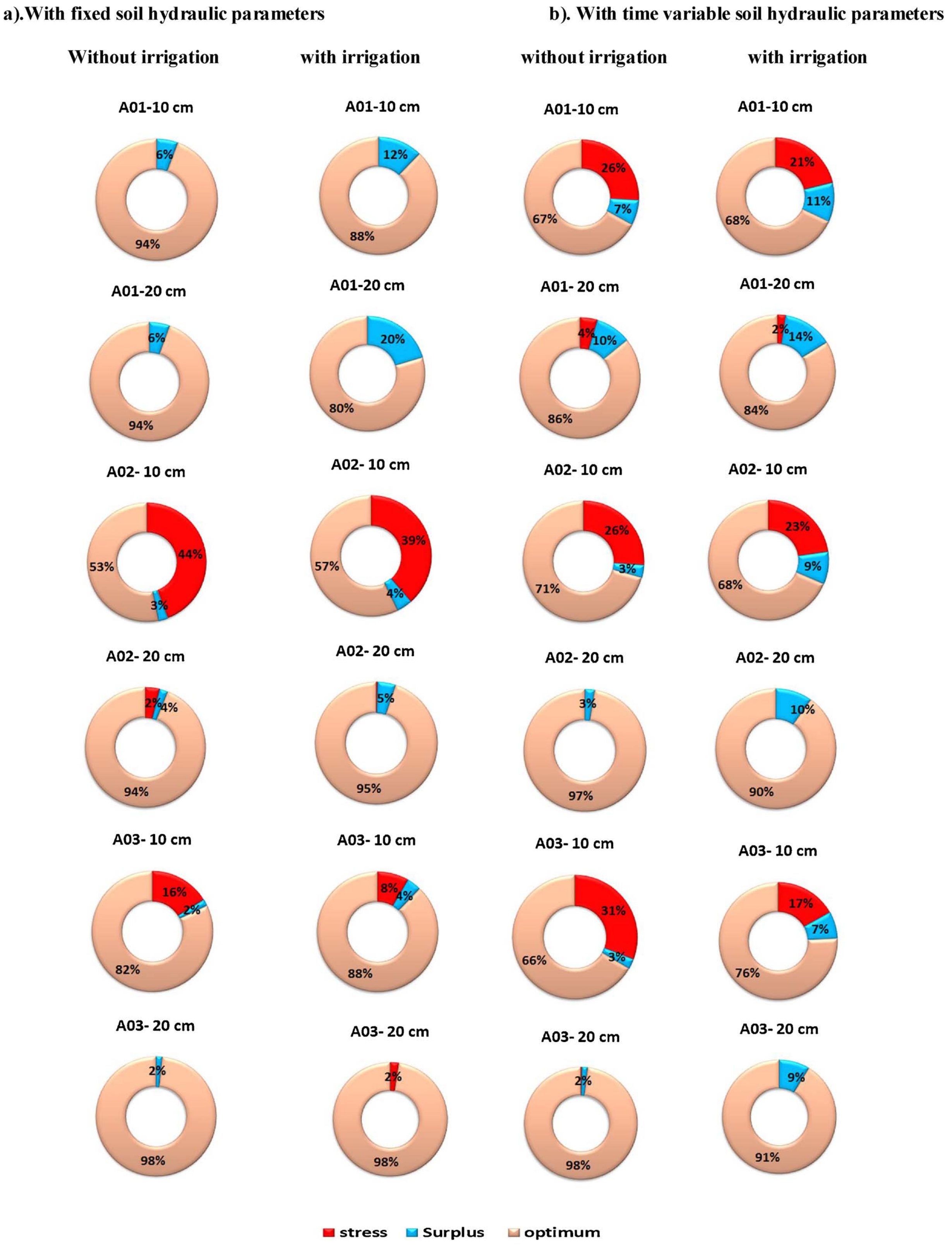

Fig. 8. Percentages of stress, surplus and optimum conditions during the 2015 growing season with and without irrigation at A01, A02 and A03 sampling points: (a) without time variable soil hydraulic properties; (b) with time variable soil hydraulic properties.

inverse distance weighting interpolation. For the uncultivated part of the field we assigned the same soil hydraulic parameters values measured at A04 sampling point. Fig. 3 shows an example of the maps of spatial and time variability of saturated water content and saturated hydraulic conductivity that were used together with the other soil hydraulic properties as inputs for these simulations. Results presented in Fig. 6 show the spatial distribution of soil moisture at three different days during the 2015 cropping season: 29/06/2015 which corresponds to the day before an irrigation event, 01/07/2015 one day after the irrigation and the last date was 10 days later 11/07/2015. The simulation results using soil hydraulic parameters from C1 are presented in Fig. 6a. For the same day and under the same boundary conditions a spatial variation of the soil moisture was observed within the study field. The maps of soil water content at different dates during 2015 cropping season yielded the same distribution patterns of soil moisture.

The results of simulations based on soil hydraulic properties measured during the second field campaign C2 are presented in Fig. 6b. Lower soil moisture values were observed in the field using the second set of soil hydraulic properties as compared to the simulations based on the first set of these parameters. Considering the map of spatial distribution of the *Ks* (Fig. 3) together with the maps of soil moisture (Fig. 4) allow to conclude that zones with high saturated hydraulic conductivity were caracterized by lower soil moisture values as compared with zones with lower *Ks* values. This inverse correlation between the variation of soil moisture and *Ks* confirms the importance of the saturated hydraulic conductivity as an input parameter for soil moisture simulations. Rezaei et al. (2016) found that only *Ks* calibration can allow to reach sufficient simulations accuracy for irrigation management purposes.

The percentages of occurrence of stress, surplus and optimum conditions at the different sampling points of the field were different. Considering or not the temporal variability of soil hydraulic properties, the irrigation did not reduce efficiently the stress while it developed more surplus for both A02 and A03. As observed at A01, more stress was recorded at 10 cm depth. Unlike the A01, the stress appeared at A02 and A03 even when the first set of soil hydraulic properties from C1 were introduced. Nevertheless, when the second set of soil hydraulic parameters was used (Fig. 8b), less stress was observed at A02 while the response of A03 was similar to A01.

These results confirm that the use of local simulations can lead to inadequate evaluation results or decisions if used to schedule future irrigations. This information is of major importance in particular for localized irrigation techniques. Using the FEST-WB model, the spatial distribution stress index can be obtained at hourly time step. This would provide valuable information for farmers to have an idea about the water status distribution within the field.

It should be noted that during the different field campaigns througout the cropping season a spatial hetergeniety in terms of crop developpement was observed. The observed variability of soil properties as well as soil moisture simulations results could justify the restricted developement of the crop at the sampling A02 and the surrouding area.

4. Conclusions

This study allowed highlighting that soil properties, in particular at the surface, are subjected to both spatial and temporal variations during the growing season. Results showed that temporal changes of soil properties were greater and affected mainly the cultivated part of the field. Among the measured soil hydraulic properties, the saturated hydraulic conductivity showed the highest sensitivity to temporal changes. According to the results of the FEST-WB simulations, this temporal variability yielded higher impact on soil moisture simulations. It has been confirmed through this study that a well-parameterized model through measured, time and space variable, soil related input allowed improving the simulations accuracy. A stress index was assessed at hourly time step while simulating the soil moisture. It can be concluded from the analysis of this index, that the decision of the farmer alone was not enough to reach optimal irrigation scheduling. Traditionally, the decision to irrigate is taken according to the farmer's experience that is usually based on local field observations. Neglecting the spatial and time variations of water content and the stress threshold during the cropping season can lead to erroneous decisions. Accounting for spatial distribution of soil water content as well the stress index is crucial for irrigation management purposes. Further researches are required for a better understanding of the dynamic of soil hydraulic properties under different cropping conditions in order to improve irrigation scheduling.

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