Potential of Thermal Images and Simulation Models to Assess Water and Salt Stress: Application to Potato Crop in Central Tunisia

Hiba Ghazouani[a], Fulvio Capodici[b], Giuseppe Ciraolo[b], Antonino Maltese[b], Giovanni Rallo[c], Giuseppe Provenzano*[d]

[a]Département du Génie des Systèmes Horticoles et du Milieu Naturel, Institut Supérieur Agronomique Chott Meriém, Sousse, Tunisie.
[b]Department of Civil, Environmental, Aerospace, Materials Engineering (DICAM), University of Palermo, Viale delle Scienze Bdg. 8, 90128 Palermo, Italy.
[c]Department of Agriculture, Food and Environment (DAFE), University of Pisa, Via del Borghetto 80, 56124 Pisa, Italy.
[d]Department of Agricultural and Forest Sciences (SAF), University of Palermo, Viale delle Scienze, Bdg. 4, 90128 Palermo, Italy.
giuseppe.provenzano@unipa.it

The growing water scarcity is a real concern in Mediterranean countries characterized by semi-arid or arid climate such as Tunisia, where it is crucial to improve water use efficiency without affecting agricultural productivity. The importance of identifying methods and technologies to optimize water use in agriculture has been recognized worldwide, in response to the limited water availability.

Objective of the paper was to verify the potential of the combined use of infrared thermography and simulation models to assess the effects of water and salt stress on potato crop parameters and crop yield, under the environmental conditions of central Tunisia.

The database collected with field experiments allowed the application of Hydrus-2D model to simulate water and salt stress. The achieved results evidenced that water savings are possible in Tunisia if irrigation is scheduled based on the climate and/or plant water status. Experiments showed that the high variability on crop yield within the treatments was mainly associated to possible clogging phenomena, rather than emitters' quality or deficiency in distribution uniformity. When considering the thermal image analysis, it was demonstrated that the crop water stress index (CWSI) is strongly related to soil matric potential, so that handled infrared thermography can be considered a powerful tool for irrigation scheduling of potato crop. Moreover, the rate of maximum evapotranspiration reduction estimated by model simulations, resulted fairly well correlated with the corresponding CWSI obtained by thermal images, thus evidencing the suitability of the model to assess the effects of water and saline stress on crop transpiration and to identify irrigation scheduling parameters aimed to optimize water use efficiency.

1. Introduction

At global scale, water scarcity is considered one of the most dramatic worldwide-problem that, in many countries affected by drought, can be exacerbated by the climate change projections. In arid and semi-arid regions irrigation plays a key-role to intensify agricultural productivity and to fulfil sustainable agricultural development, so that it is compulsory to activate strategies improving water resources management, even involving the stakeholders (Madramootoo and Fyles, 2010).

In Tunisia, irrigated area has been raising from 65,000 ha in 1956 to 408,000 ha in 2010 and, with a percentage of 8% of the potential cultivable lands, provide about 35% of total agricultural productions. Moreover, due to the chronic scarcity of good water quality, Tunisian farmers are quite often obliged to use marginal waters, such as saline waters, whose long term application can cause salt accumulation in the root zone, inhibition of root water uptake and reductions of crop yield. Potato crop represents the second main crop

of the country, with a surface of about 7% of irrigated lands and a production of 360,000 tons per year (Chehaibi et al., 2013).

In order to increase water use efficiency, even for this important crop, from the one hand it is required to design efficient irrigation systems and, from the other, to identify irrigation scheduling strategies aimed to enhance water use efficiency. Subsurface drip irrigation, applying irrigation water below the soil surface, is considered among the most efficient irrigation systems, because it allows to delivery water contents and nutrients in the root zone, to control weeds limiting soil evaporation fluxes and, more in general, to reduce water consumptions. Moreover, even when efficient water distribution systems are used, it is necessary to define the appropriate irrigation timing and doses based on the actual plant needs.

Monitoring soil and plant water status in real time allows to better match irrigation with plant needs, as well as to prevent irreversible damage of plant systems and adverse effects on crop yield. Canopy temperature is considered a suitable indicator of crop water status. In fact, when a plant is subjected to stress conditions, transpiration decreases as consequence of stomatal closure and thus leaf temperature increases. Leaf temperature can be measured in real-time with commercially available thermometers allowing punctual acquisitions; these measurements, however, have a quite high spatial variability and often are not representative of the actual plant water status.

When referring to the whole plant or to a field, infrared thermal imaging represents a rapid, non-invasive and non-destructive sensing technique to map, at a certain time, the distribution of temperature over the canopy or in the field (Cohen et al., 2005). Monitoring plant temperatures allows evaluating spectral indicators related to crop water status, such as the extensively used crop water stress index (CWSI), which was found to be a promising tool to quantify crop water stress (Jackson,1982):

$$CWSI = \frac{(\Delta T_{ca} - \Delta T_l)}{(\Delta T_u - \Delta T_l)} \tag{1}$$

where ΔT_{ca} ($\Delta T_{ca} = T_c - T_a$) is the difference between canopy and air temperature, ΔT_u is the upper limit of canopy minus air temperature obtained on non-transpiring crops, and ΔT_l is the lower limit of canopy minus air temperature of well-watered crops. A value of CWSI=0 indicates the absence of stress, whereas a value equal to 1.0 identifies the maximum stress. This indicator depends on the ambient conditions (relative humidity, wind speed, and air temperature), as well as on the incident radiation on the canopy surface. The upper and lower limits can be determined based on the theoretical approach, according to which crop temperatures have to be combined with meteorological data (maximum and minimum air temperature and relative air humidity). A number of researches have been carried out worldwide to monitor CWSIs of different crop systems, indicating that the upper and lower baselines depends on crop and climate conditions (Idso et al., 1981).

Simulation models of the Soil-Plant-Atmosphere continuum (SPA) are considered a cheap and easy-to-use tool for indirect evaluations of soil and crop water status, because of their ability to estimate the actual crop transpiration and to identify the dynamic of crop water stress (Rallo et al., 2017). Hydrus-2D (Šimůnek et al., 1999) is a numerical tool for simulating bi-dimensional processes of water, solutes and heat transport in unsaturated porous media. The model uses the Galerkin-type linear finite elements to numerically solve the nonlinear Richards' equation for saturated-unsaturated water flow in which, the rate of root water uptake is expressed by a sink term depending on water and salinity stress.

Objective of the research was to verify the potential of the combined use of infrared thermography and Hydrus-2D simulation models to assess the effects of water and salt stress on potato crop parameters and crop yield, under the environmental conditions of central Tunisia.

2. Materials and method

Experiments were carried out on potato crop (*Solanum Tuberosum L., cv. Safran*) during two growth seasons, at the High Agronomic Institute of Chott Meriém, Sousse, Tunisia (longitude 10.5632° W; latitude 35.9191° N, altitude 19.0 m a.s.l.). The site is characterized by semi-arid climate, with hot and dry summer and mild-rainy winter seasons. The experimental plot, 50 m length and 15 m wide, was divided in four subplots (treatments T1, T2, T3 and T4) subjected to similar seasonal management, except for the applied water quality and irrigation regime. In particular, treatments T1 and T2 were irrigated with water characterized by electrical conductivity, EC_w, of about 1.6 dS/m, while treatments T3 and T4 with water having EC_w=4.2 dS/m. On the other hand, treatments T1 and T3 were maintained under full irrigation, by supplying the volumes corresponding to the maximum crop evapotranspiration estimated between consecutive watering, whereas treatments T2 and T4 (deficit irrigation) received approximately the half of volumes provided in the other two treatments. Tuber seeds of the same potatoes cultivar were planted at distance of 0.40 m along the row and 0.80 m between the rows and irrigated with a subsurface drip irrigation system characterized by a single

distribution pipe per plant row, installed at 0.20 m depth. Co-extruded drip emitters, spaced 0.40 m, discharged a flow rate of 3.5 l/h at nominal pressure of 100 kPa.

A weather station located in the field allowed recording the rainfall height and the meteorological variables (air temperature, T, global solar radiation, SR, relative air humidity, RH, wind speed at 2 m height, w_{2m}) used to estimate daily reference evapotranspiration according to the Penman-Monteith equation (Allen et al., 1998).

Preliminarily, the soil water retention curve was determined in laboratory on undisturbed soil samples, 8.0 cm diameter and 5.0 cm height collected in the field at three different depths. The water column technique performed in Buckner funnels (Dane and Hopmans, 2002), equipped with porous plates with air entry point h= -200 hPa was used for matric potentials ranging between 0 hPa (saturation) and about -150 hPa, whereas the pressiometric method using the Richard apparatus (Dane and Hopmans, 2002) was applied for soil matric potential of 330, 1,000, 3,300 and 15,000 hPa. Saturated soil hydraulic conductivity was determined by the constant head permeameter on undisturbed soil samples 8.0 cm diameter and 5.0 cm height.

During the investigated seasons, spatial and temporal variability of soil water content around a single emitter, was monitored with a Trime TDR probe (IMKO Micromodultechnik GmbH) having a precision of ±0.03 cm^3/cm^3 (Douh, 2012). The probe, inserted in plastic access tubes preventively installed, allowed measuring volumetric soil water contents in a soil volume having diameter and height equal to about 15 cm. A total of eight 70 cm long access tubes were installed in each treatment along two sections, perpendicular to the plant row, at distances of 0 cm, 20 cm, 40 cm and 60 cm from the emitter. In each tube, soil water content was regularly measured at 15 cm, 30 cm and 45 cm depths.

Crop agronomic parameters, i.e. main root dimensions and leaf surface area, were also measured on three different plants collected at different crop stages, from randomly chosen locations of each subplot. In particular, after cleaning the roots, the maximum rooting depth and radius, as well as the depth of maximum density were measured with a tape. Then, all the leaves were detached and their surface area measured with the planimetric technique implemented in the Skye Leaf v2 software (Skye Instruments Ltd.). Additionally, in 2015, infrared thermal images were acquired with a thermal camera (HSI3000, Palmer Wahl Instruments Inc., Asheville, NC, USA). The camera spectral response ranges from 8 to 14 microns, which is generally used for objects at field temperature. Imaging system is constituted by a focal plane array (FPA) detector characterized by high resolution (160 x 120 pixels). The camera has a field of view (FOV) of 20° × 15° and an instantaneous field of view (IFOV) of 1.3 mRad, allowing a spatial resolution of 0.4 × 0.4 mm at the minimum distance of 0.3 m. At ambient temperature (23°-25°C), the thermal sensitivity is approximately of 0.15°C and the temperature accuracy ranges between ±2°C and ±2% of the reading in °C.

Seven acquisitions were registered in each treatment, from 15 days after plant emergency to seven days before harvesting. In particular, two measurements were acquired during the crop initiation, three at full development stage and two before harvesting. During clear days, thermal images were acquired at midday in the same plants where soil water status were monitored; the camera was fixed at 1.8 m height, with the main axes along the vertical. In order to remove the disturbance due to soil, images were elaborated by the Wahl Heat Spy HSI3000 dedicated software and then processed with ENVI 1.4 image analysis software, so to obtain the corresponding weighted average temperature. These latter values were finally used to estimate the crop water stress index (CWSI) after determining the upper and lower limits with the procedure proposed by Idso et al. (1981). The database of field and laboratory measurements was finally used to run Hydrus-2D model that, after the preliminary parameterization of soil hydraulic functions, root distribution and water uptake models, permitted the simulation of water and solutes transport in unsaturated soil around the emitters, as well as the evaluation of actual transpiration under the examined climate conditions.

3. Results and discussion

Preliminarily, the van Genuchten (1980) parameters of soil water retention curves (SWRC) at 15.0, 30.0 and 45.0 cm depth, as well as for the whole soil profile (all data) were determined, as indicated in Table 1. For each fitted curve, the coefficient of determination, R^2, is also shown.

During the investigated seasons, T1 and T3 received in 2014 a total of 8 watering with a seasonal volume of 1244 m^3/ha, while in T2 and T4 the seasonal irrigation volumes resulted of 611.0 m^3/ha and 671.0 m^3/ha respectively. In 2015, due to the lower precipitation and the higher evapotranspiration during the season, a total of 14 irrigation events were scheduled and the total volume provided was equal to 1,819.0 m^3/ha in T1, 945.0 m^3/ha in T2, 1,651.0 m^3/ha in T3 and finally 831.0 m^3/ha in T4.

Table 1: Parameters of soil water retention curves according to van Genuchten (1980) model for the three layers and for the whole soil profile

Model	15 cm		30 cm		45 cm		All Data	
	Parameters	R^2	*Parameters*	R^2	*Parameters*	R^2	*Parameters*	R^2
Van Genuchten (1980)	θ_s=0.41 θ_r= 0.08 α=0.01 n=1.83	0.98	θ_s=0.37 θ_r= 0.07 α=0.01 n=1.49	0.99	θ_s=0.40 θ_r= 0.08 α=0.01 n=1.69	1.00	θ_s=0.39 θ_r= 0.08 α= 0.01 n= 1.59	0.96

For both the examined growth seasons and for all the treatments, Table 2 shows the amounts of seasonal precipitation, irrigation, reference and maximum crop evapotranspiration, as well as the mean and standard deviation of crop yield and total water use efficiency. The latter was obtained by dividing crop yield by the sum of seasonal precipitation and irrigation.

Table 2: Values of seasonal precipitation, P, irrigation, I, ET_0 and ET_{max}, mean (μ) and standard deviation (σ) of crop yield and Total water use efficiency obtained in all treatments.

Treatment	P [mm]	I [mm]	ET_0 [-]	ET_{max} [-]	Yield [t/ha]		TWUE [Kg/m^3]	
					μ	σ	μ	σ
2014								
T1	108.6	124.4	198.0	160.2	39.1 a	8.3	16.8 a	3.6
T2	108.6	61.1	198.0	160.2	24.9 b	10.7	14.7 a,b	6.3
T3	108.6	112.2	198.0	160.2	24.1 b	9.4	10.9 a,b	4.3
T4	108.6	67.1	198.0	160.2	19.5 b	13.3	11.1 a,b	7.7
2015								
T1	73.6	181.9	280.0	221.0	39.0 a	8.3	15.3 a,b	3.7
T2	73.6	94.5	280.0	221.0	25.8 b	3.2	15.3 a,b	1.9
T3	73.6	165.1	280.0	221.0	26.3 b	9.4	11.0 a,b	1.7
T4	73.6	83.1	280.0	221.0	16.3 b	2.4	10.4 b	1.5

As it can be observed, crop yield decline was 17.0 t/ha per each 100 mm decrease of applied water, when water was characterized by the better quality and 12.0 t/ha in the other case. An increase of 1.0 dS/m of water electrical conductivity, determined a yield decline rate of about 10%.

Analysis of the temporal dynamic of soil water content evidenced that the greater irrigation doses supplied in treatments T1 and T3, compared to T2 and T4, corresponded to the constantly higher soil water contents in the root zone. The average soil water contents resulted always higher than about 0.20 cm^3/cm^3 (soil matric potential equal to about -770 hPa), except in a very short period in 2015, around the end of crop development stage. During the whole crop cycle then, treatments T1 and T3 were generally not subjected to water deficit. On the contrary, in both seasons soil water contents in treatments T2 and T4 resulted lower than 0.20 cm^3/cm^3 for long time intervals and of about 0.15 cm^3/cm^3 at the end of the full development stage. In the latter two treatments therefore, based on the temporal dynamic of soil water contents, the crop was subjected to a certain level of water stress mainly during the full development stage, with adverse effects on crop yield.

Post-processing of the thermal image sequence allowed estimating the leaf temperature in each treatment during the different growth stages. Figure 1a shows the differences between canopy and air temperature as a function of the vapour pressure deficit, VPD. The theoretical upper and lower baselines, whose equations are indicated in the figure, were computed based on the climate variables, as proposed by Idso et al. (1981). Crop water stress index, showed in Figure 1b for different days after planting, was then estimated on the basis of Eq(1), by assuming the upper and lower theoretical baselines. As can be noticed, the values of CWSI ranged from 0.06 and 0.36 for T1, from 0.2 and 0.56 for T2, from 0.06 and 0.49 for T3 and finally from 0.23 to 0.83 for T4. Even Erdem et al. (2005) observed CWSI values up to 0.85 when irrigation doses was 50% of that provided in fully irrigated plots. As expected, under the examined treatments, the values of CWSI were rather diverse, as result of the different stress levels achieved. In particular, treatment T1 was characterized by the minimum stress level, while treatment T4 evidenced the highest stress level due to the combination of water and saline stress, being T2 and T3 at intermediate levels. According to the achieved results, CWSI might be successful used for irrigation scheduling, after developing specific thresholds, depending on the crop phenological stage.
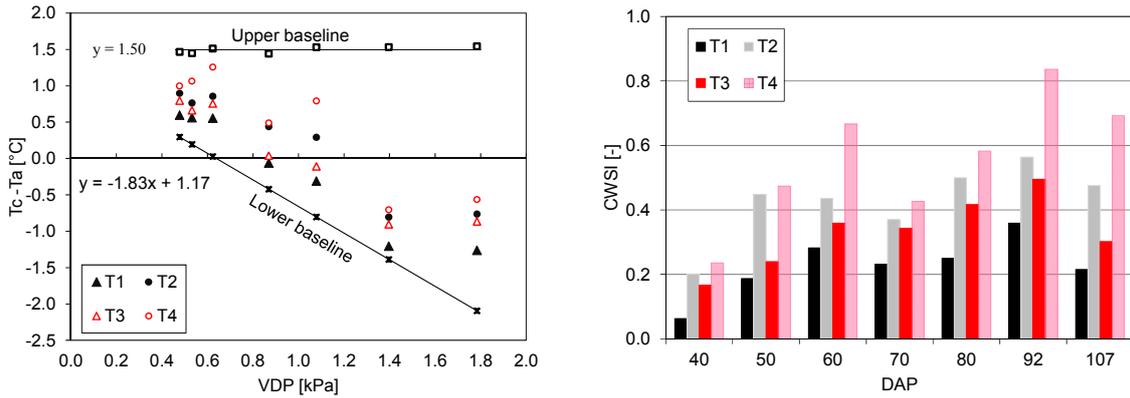
Figure 1a,b: a) Difference between canopy and air temperature, (Ta-Tc), versus the vapour pressure deficit, VDP and b) values of CWSI estimated in treatments T1-T4, at different days after planting

The macroscopic effect of water and salt stress on crop yield can also be observed in Figure 2, in which the total yield obtained in 2015 is represented as a function of the seasonal average crop water stress index, $CWSI_{avg}$. For each treatment, the latter indicator was obtained by considering all the measurements of leaf temperatures acquired with the thermal camera at the different stages of crop cycle.
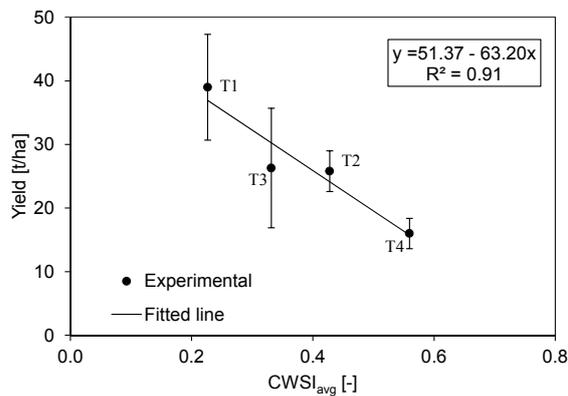

Figure 2: Crop yield in 2015 versus the average crop water stress index, $CWSI_{avg}$, in treatments T1-T4

It is evident that tuber yield is strongly related to the examined indicator (R^2=0.91). The highest tuber yield was obtained in treatment T1, showing the minimum $CWSI_{avg}$, whereas the lowest tuber yield, obtained in treatment T4, due the combined effect of water and salt stress, corresponded to the highest value of the indicator. If considering soil water contents simulated by Hydrus-2D, it was observed that the model is generally able to reproduce the evolution of the soil water contents at different distances and depths from the emitters, as well as the salt content in the root zone. However, local differences between measured and simulated SWC were detected, mostly related to the end of the growth season. This circumstance is probably due to the rising dimensions of tuber that could have occupied the sensing volume, affecting the measurements. To examine the ability of the model to identify water and/or saline stress, the values of simulated stress coefficient, $K_{s,sim}$, were determined as the ratio between actual simulated and maximum transpiration and then compared to the corresponding measured, $K_{s,meas}$, estimated as the complement to one of crop water stress index ($K_{s,meas}$=1-CWSI). Figure 3a,b shows the temporal patterns of simulated and measured K_s, respectively for treatments T1-T2 and T3-T4. As can be detected, despite the limited number of days in which leaf temperatures were measured and the shift between the numerical values, the trend of $K_{s,sim}$ generally follows that of the measured values, demonstrating that the K_s values predicted by the model can be considered suitable to identify crop stress conditions.

The model can be therefore used for an indirect estimation of crop water and/or saline stress, by avoiding tedious and time-consuming field experiments. In addition, once identified the relationship between simulated K_s and crop yield, model simulations can be used to examine the crop response corresponding to different scenarios, in order to identify the best irrigation scheduling strategy aimed to increase water use efficiency.
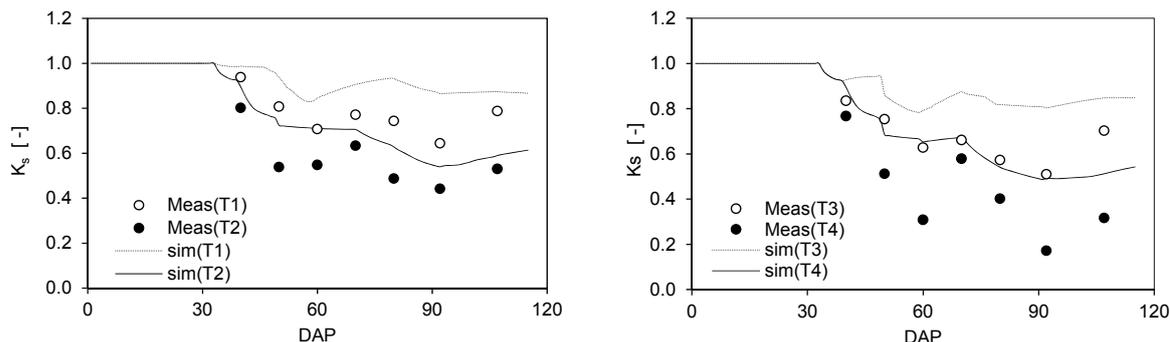
Figure 3: Dynamic of simulated ($K_{s\text{-}sim}$) and measured ($K_{s\text{-}meas}$) stress coefficients, as obtained in 2015

4. Conclusions

The experiments evidenced that Hydrus-2D model, despite some local discrepancies, can be used to predict soil water contents around a buried emitter and to estimate the average soil electrical conductivity in the root volume. Under water and salt stress conditions, the rate of maximum evapotranspiration reduction estimated by model simulations were fairly well correlated with the corresponding CWSI obtained by thermal images, thus evidencing the suitability of Hydrus-2D model to assess the effects of water and saline stress on crop transpiration and to identify irrigation scheduling scenarios aimed to optimize water use efficiency. Further experiments should be aimed to improve the stress response function parameters, as well as the upper and lower baselines used to estimate CWSI. The experimental results, associated to model simulations provided therefore useful guidelines for a more sustainable use of irrigation water in countries characterized by semi-arid environments and limited availability of water resources.

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