Soil Water Status and Water Yield Relationships for Cotton and Maize

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Abstract: In the present study, crop yield of experimental cotton and maize fields, in certain areas of Central Greece, are related to actual evapotranspiration estimates obtained from soil moisture data. Soil moisture measurements are conducted frequently in order to evaluate the soil water status within the various plots of the experimental fields of each crop and to schedule irrigation applications. Various soil water regimes are obtained by the planned non-uniform application of irrigation water, where a moving gun sprinkler is operating in asymmetric angle. Simulation results refer to the soil water profile through the estimates of actual evapotranspiration via the FAO-56 methodology applied under soil water stress conditions. These estimates are also related to the collected yields of the above crops in each experimental plot. Such results could be effectively used, under certain soil and climatic conditions, for the sustainable utilization of the locally available irrigation water resources.
Keywords*:* soil moisture measurements, soil moisture deficit, evapotranspiration modelling

1 Introduction

Water scarcity is widespread in many parts of the Mediterranean region where Greece is situated. Here the soil and climatic conditions favour the development of most crops and high crop yields are achieved when the soil moisture in the crops' root zone is kept at optimum levels. These moisture levels are not sustained by the infrequent rainfalls and supplemental irrigations are required, especially during the summer months, in order to sustain growth and harvest "good" yields.

Thessaly plain is considered one of the most productive agricultural areas in Greece but the frequent droughts and the inadequate water resources during the summer months often lead to high water deficits in the root zone and result to very low crop yields with direct effects on the economic growth of the broader area. Crop yields are closely related to the actual water extracted by the plant roots and they are expressed by mathematical formulae in a substantial body of research works including those of Doorenbos and Kassam (1979), Grimes *et al.* (1969), Hanks (1983), Jensen (1968), Kotsopoulos (1997), Panoras *et al.* (1997), Stewart and Hagan (1973), Stewart *et al.* (1975), Vaux and Pruitt (1983). Since crop yield is closely related to the magnitude of actual evapotranspiration it is therefore of great importance to estimate evapotranspiration under such conditions.

In the frame of the research project "E stimation of crop water requirements of some annual crops" financed by the II European Framework Programme 1994–1995, experimental cotton and maize fields where deficient irrigation is practised have been installed in Thessaly plain (Alexiou *et al.,* 2000, Kalfountzos *et al.,* 2000, Kotsopoulos *et al.,* 1999) where, among other parameters, soil moisture is measured frequently and crop yields are weighted in each plot of every experimental field.

For the estimation of actual evapotranspiration (ET_a) the modified FAO-56 (Allen *et al.,* 1998) methodology under non-standard conditions is selected for its accuracy to predict crop potential evapotranspiration (ET_c) compared to other estimating methods (Jensen *et al.,* 1990, Smith *et al.,* 1996, Alexiou *et al.,* 2000a). Additionally, a linear soil water availability function is employed (Allen *et al.,* 1998, Doorenbos and Kassam, 1979, Kotsopoulos, 1989, 1995) to evaluate actual evapotranspiration from crop potential evapotranspiration estimates. These evapotranspiration rates are alike those obtained from soil moisture measurements. Harvested crop yields have been found closely related to actual evapotranspiration rates and the applied water depths. These results could be utilized efficiently for the irrigation scheduling and the optimal management of the available water resources.

2 Materials and methods

The experiments were conducted in Thessaly plain (Central Greece) during the years 1998 and 1999 in the NAGREF's experimental fields in Larissa and in Palamas where are placed the fields of the Institute for Forage Crops (39° 38′ N, 22° 22.5′ E) and the Experimental Station of Palamas (39° 28′ N, 22° 06′ E) respectively in order to study the effects of deficient irrigation on cotton and maize plantations. The soil texture in the experimental fields is: sandy loam (SL) with average volumetric content 26% at FC and 11% at PWP in Larissa whereas in Palamas the soil texture is clay (L) with average volumetric content 31% and 14% at FC and PWP respectively.

The experimental fields of each crop were divided into a number of plots where different irrigation depths were applied through a moving gun sprinkler operating in asymmetric angle (Louizakis, 1996). In these sites, rain gauges were used to record the irrigation depths. For the monitoring of the soil moisture, special access tubes of up to 2m in length are inserted into the ground after the crop installation. A TRIME-FM device (based on the principle of the TDR method) was utilised to take quick and frequent measurements of the volumetric soil water content at each 17.5cm layer in the soil profile from surface to a depth of up to 175 cm.

Irrigation scheduling was based on the total soil water content in the root zone of the most irrigated plots and the crop's daily potential evapotranspiration rate calculated from climatic and crop data (Doorenbos and Pruitt, 1977, Jensen *et al.,* 1990, Smith *et al.,* 1996, Allen *et al.,* 1998). The various weather data refer to daily recordings of: mean, maximum and minimum air temperatures and relative humidity, wind speed, net solar radiation and rainfall from the nearby automatic weather stations which belong to the Greek Ministry of Agriculture.

The evaluation of crop water requirements (potential evapotranspiration) is based on the reference evapotranspiration (Doorenbos and Pruitt, 1977, Jensen *et al.,* 1990, Smith *et al.,* 1996, Allen *et al.,* 1998) and the crop coefficient approach (Doorenbos and Pruitt, 1977, Jensen *et al.,* 1990, Allen *et al.,* 1998). Additionally, and in order to estimate the actual water consumption by crops (actual evapotranspiration) the water stress coefficient is taken into account (Doorenbos and Kassam, 1979, Allen *et al.,* 1998, Kotsopoulos, 1989, Shaozhong *et al.,* 2000).

The measured (observed) cumulative actual evapotranspiration rates, ΣET_{a_obser}, are estimated from the following equation:

$$\Sigma ET_{a\_obser} = \pm \Delta S + P - RO + Irr - DP + UF \qquad (1)$$

where ΔS the change in soil water storage over the root zone (mm) measured by TRIME-FM, P the precipitation depth (mm), RO the runoff (mm), Irr the irrigation depth (mm), DP and UF the deep percolation below the maximum rooting depth and upward flux into it respectively (mm). Under the prevailing soil and weather conditions no runoff occurred while DP and UF where not significant ($DP, UF \approx 0$).

Additionally, the evaluation of the cumulative actual evapotranspiration, ΣET_{a_calc}, is based on the above assumptions and, for periods between rainfalls or irrigations, it is calculated from the estimated available soil water depths in the root zone as:

$$\Sigma ET_{a\_calc} = x_1 - x \qquad (2)$$

where x_1 and x are the calculated initial and final available soil moisture (mm) in the root zone based on the FAO-56 Penman-Monteith methodology under non-standard conditions (Allen *et al.,* 1998, Doorenbos and Pruitt ,1977, Kotsopoulos, 1989, 1995).

Apart from the data mentioned above, the calculation of actual evapotranspiration requires: (a) the values of the crop coefficients during the various growth stages which are taken from FAO-56 (Allen *et al*., 1998), (b) the duration of the growth stages. These are evaluated from leaf area index (LAI) measurements through a Sun Scan Analysis System in order to incorporate into calculations the local conditions (Alexiou, 2000), while (c) the root depths for both crops are considered constant at stages {1}, {3}—{4} and to increase linearly during stage {2} (Allen *et al*., 1998).

3 Results

The adequacy of the aforementioned methodology is based on comparative measures between observed (measured) and calculated (predicted) soil moisture values. In the present study the selected measures are (Babajimopoulos *et al.,* 2000, Loague and Green, 1991) the mean error (E), the root mean square error ($RMSE$), the maximum absolute relative error ($MARE$), the coefficient of residual mass (CRM) and the coefficient of determination (R^2):

$$E = \sum_{i=1}^{n} (O_i - P_i)/n \tag{3}$$

$$RMSE = \left(\sum_{i=1}^{n} (O_i - P_i)^2/n \right)^{1/2} \times \frac{100}{\bar{O}} \tag{4}$$

$$MARE = \frac{|O_i - P_i|}{O_i} \times 100 \tag{5}$$

$$CRM = \left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i \right) \Big/ \sum_{i=1}^{n} O_i \tag{6}$$

where O_i and P_i are the observed (measured) and calculated (predicted) values respectively.

Measurements refer to the periods from April to September during the years 1998 and 1999 and the calculations are performed on a daily basis. Soil moisture was measured into various depths (up to 1.75m) very frequently (even daily) depending on the soil water status and the prevailing weather conditions.

From the soil water balance equation in the root zone, Eq. (1), (2), and the daily evapotranspiration (potential and actual) values, the soil water depths in the soil profile throughout the growing period are estimated. Figures 1 and 2 give representative soil water depths in the root zone (0.0m—1.2m) from both experimental sites during the growing period. These figures reveal that the estimated values fit very well the measured (observed) ones. The statistical indices of a greater number of applications of the presented model shown on Table 1 and the comparison results, presented on Table 2, of measured (observed) and calculated cumulative evapotranspiration during specific periods, prove the adequacy of the proposed methodology.

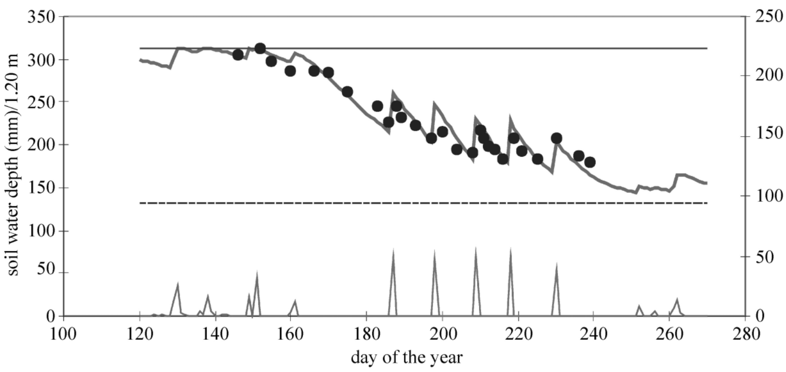

Fig.1 Observed and calculated soil moisture depths for cotton during 1998 in Larissa

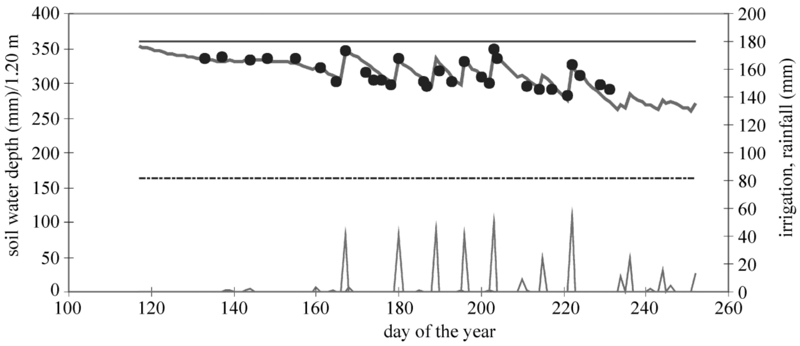

Fig.2 Observed and calculated soil moisture depths for maize during 1999 in Palamas

Table 1 Indices used for the comparison of observed and calculated soil moisture depths in the soil profile for cotton and maize during the years 1998 and 1999 in Central Greece

Area	Year	Crop	*E* (mm)	*RMSE* (%)	*MARE* (%)	*CRM*	Slope a	R^2
Larissa	1998	cotton	–2.00	4.15	8.28	–0.0087	1.0106	0.9546
	1999	cotton	–1.66	3.07	6.81	–0.0072	1.0061	0.9678
	1998	maize	1.28	4.22	9.05	0.0045	1.0094	0.8600
	1999	maize	–0.93	3.67	8.14	–0.0043	1.0053	0.8965
Palamas	1998	cotton	0.09	3.54	8.12	0.0046	1.0011	0.9450
	1999	cotton	–1.80	2.62	5.48	–0.0067	1.0560	0.9703
	1998	maize	0.30	3.39	7.62	0.0011	0.9982	0.9525
	1999	maize	–1.00	2.35	4.94	–0.0031	1.0028	0.8659

Table 2 Comparison of observed (ΣET_{a_obser}) and calculated (ΣET_{a_calc}) cumulative values of actual evapotranspiration for cotton and maize during specific periods in Central Greece

Area	Period	Crop	Cumulative evapotranspiration values ΣET_c	ΣET_{a_obser}	ΣET_{a_calc}	Difference %
Larissa	26-5/27-8-98	cotton	502.1	403.4	410.7	–1.81
	2-6/26-8-99	cotton	434.2	403.4	411.5	–2.01
	22-5/25-8/98	maize	565.4	515.9	530.2	–2.77
	2-6/26-8-99	maize	453.8	376.2	396.6	–5.42
Palamas	10-6/27-8-98	cotton	402.9	292.4	305.7	–4.55
	10-6/27-8-99	cotton	326.1	303.7	302.4	0.43
	28-5/24-8-98	maize	520.6	426.5	444.3	–4.17
	13-5/19-8-99	maize	421.3	378.1	392.8	–3.89

Crop yields are selected manually from the various experimental plots and are related to relative evapotranspiration values over the growing period ($\Sigma ET_{a\_g} / \Sigma ET_{c\_g}$). The results are presented in Figures 3 and 4 for cotton and maize respectively. The linear relationships in the same figures fit very well the experimental data and could be easily utilized to predict crop yields under similar pedoclimatic conditions.

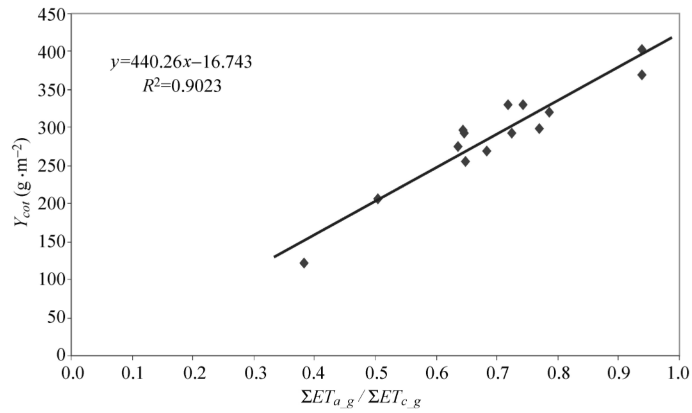

Fig.3 Seed cotton yield, Y_{cot}, vs. cum. rel. evapotranspiration over the growing period, $\Sigma ET_{a\_g}/\Sigma ET_{c\_g}$

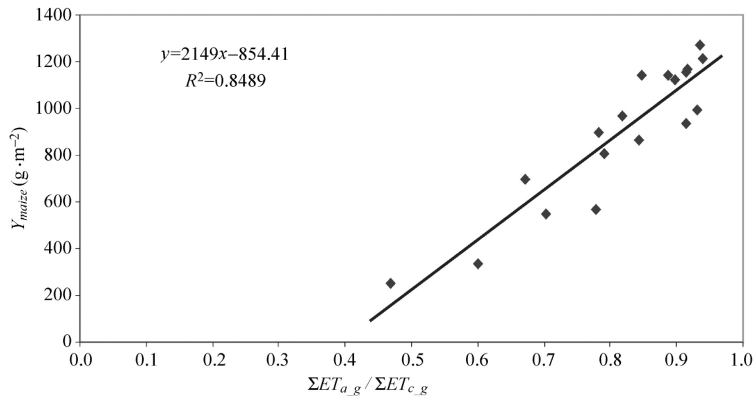

Fig.4 Maize yield, Y_{maize}, vs. cum. relat. evapotranspiration over the growing period, $\Sigma ET_{a\_g}/\Sigma ET_{c\_g}$

4 Conclusions

From the above results it may be concluded that:

The utilization of the FAO-56 Penman-Monteith methodology under non-standard conditions is estimating efficiently the soil moisture regime and the actual crop evapotranspiration in the irrigated fields under the semiarid environment of Central Greece and should be preferred for irrigation scheduling.

Crop yields are linearly related to relative evapotranspiration rates and such relationships could be easily utilized for the sustainable management of the available water resources.

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