Evaluation of irrigation practices for maize and cotton crops using the FAO AquaCrop model

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Abstract. The scope of this study is the comparative evaluation of irrigation practices for maize and cotton crops in Thessaly, Greece with the use of FAO AquaCrop model and it is a contribution to the "HUBIS" research project. The comparison is made between two irrigation practices for the two crops (maize and cotton): 1) the first one is the common irrigation practice that farmers apply based on their experience and 2) the second one is a water-saving irrigation practice based on the use of precision agriculture tools. These tools are the application of the FAO Aquacrop model for the simulation of the yield response of crops to water, the installation of low-cost soil water sensors and hydrometers for irrigation scheduling, and the use of the Weather Research and Forecasting (WRF) atmospheric model to produce high-resolution weather forecasts. For this comparison to be carried out, two fields have been selected as experimental fields for the two crops: 1) the "Farmer" field for the application of the common irrigation practice and 2) the "Hubis" field for the application of the water-saving irrigation practice. The study is still in progress as it refers to the cultivation period of the two annual crops in 2022 and the first results so far are presented. The results indicate that the water-saving percentage for cotton and maize reaches 11.1% and 27.2%, respectively.

1 Introduction

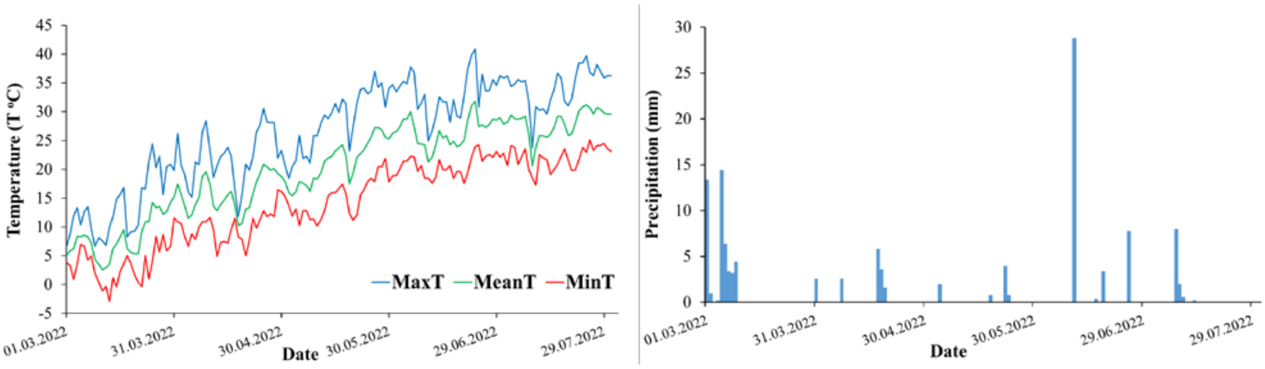
In Greece, the cultivation period of maize and cotton starts in spring and lasts till the first two months of fall (Georgopoulou et al., 2017). This means that the major part of these two annual crops' cultivation period occurs during the Mediterranean summer, which is characterized by high temperatures and evapotranspiration, and lack of precipitation. Farmers must apply irrigation, based on their experience. Due to this fact, in most cases, irrigation is not appropriate both in terms of scheduling and water volume applied. Specifically, farmers apply greater volumes of water than necessary in their attempt to maximize crop-yield. But this leads to waste of water while water resources in the Mediterranean are limited (Allam et al., 2020). To save water, precision agriculture tools should be applied combined with a variety of field data such as climatic, soil, and crop ones. The core of this save-water process is the application of a crop simulation model which can use a water-driven strategy. For this reason, AquaCrop (Steduto et al., 2009) is selected as it links crop yield and crop water use under different management and biophysical conditions (Raes et al., 2009). More specifically, it assumes a linear relationship between biomass production and crop transpiration (Steduto et al., 2007) for predicting water requirement, crop productivity, and water use efficiency under water stress and unstressed conditions. In comparison to other crop models, AquaCrop requires a small number of explicit and mainly straightforward parameters to be established, and it has been tested and applied effectively for numerous crop types in a variety of environmental and agronomic conditions (Vanuytrecht et a., 2014). The calibration of AquaCrop against observed field data is crucial for successful prediction and sustainable management. To achieve this, appropriate equipment must be established at the farm level, and weather forecast tool must be applied (Lalić et al., 2018).

This paper presents an evaluation of irrigation practices for maize and cotton crops in Thessaly, Greece, based on the use of precision agriculture tools. These tools are the application of the FAO AquaCrop model for the simulation of the yield response of crops to water and the soil moisture evolution, the installation of low-cost soil water sensors and hydrometers for irrigation scheduling, and the use of the Weather Research and Forecasting (WRF) atmospheric model to produce high-resolution weather forecasts. Two irrigation practices for the two crops are compared: 1) the first one is the common irrigation practice that farmers apply based on their experience and 2) the second one is a water-saving irrigation practice based on the use of precision agriculture tools. The study is still in progress as it refers to the cultivation periods 2021 (calibration) and 2022 (validation) of the two annual crops (maize and cotton).

2 Materials and Methods

2.1 Field Experiments and Data

The field experiments took place on farms of cotton and maize near the village of Falani (Larisa, central Greece) at the altitude of 60 m. above MSL. For the comparison of the two irrigation practices, two fields have been selected as experimental fields for each crop: 1) the “Farmer” field for the application of the common irrigation practice and 2) the “Hubis” field for the application of the water-saving irrigation practice. The area of each experimental field for cotton is 2.5 hectares, while for maize 2 hectares. The climate is the temperate Mediterranean characterized by cold humid winters and hot and dry summers (Bsk—Csa according to Köppen’s climatic classification) (Köppen, 1936). Based on historical data, the average precipitation is about 560 mm/year, the mean annual temperature is around 14 °C, and the average relative humidity 67%. From March to July of 2022, the temperature varied from -2.9 °C (min of March) to 40.9 °C (max of June) (Figure 1a) and the total rainfall was 121.4 mm (Figure 1b).



(a) (b)

Figure 1. Daily values of (a) maximum, mean, and minimum temperature and (b) precipitation for 2022 (1-3-2022 to 31-07-2022).

Soil samplings were performed at the center of each experimental plot (Farmer and Hubis). Soil samples (0–20 cm, 20–30 cm, 30-60 cm, and 60-90 cm depth, n = 4) were collected from the side of trench excavated in the center of every plot of cotton field. Soil samples (0–30 cm, 30-60 cm, and 60-90 cm depth, n = 3) were collected similarly from the plots of maize field. The soil samples were analyzed in the laboratory for soil texture as determined by physical fractionation (Bouyoukos, 1951), and for soil organic matter as determined by the Walkley–Black method of wet oxidation (Nelson and Sommers, 1982). For cotton, the Hubis field is characterized as clay to clay-loam and the Farmer one as clay-loam. For maize, the Hubis field is characterized as loam to sandy clay-loam and the Farmer one as clay-loam (Table 1).

Table 1. Soil properties

Crop Type	**Cotton**								**Maize**					
Field Type	**Hubis**				**Farmer**				**Hubis**			**Farmer**		
Depth (cm)	0-20	20-30	30-60	60-90	0-20	20-30	30-60	60-90	0-30	30-60	60-90	0-30	30-60	60-90
Sand (%)	29	32	26	34	30	24	28	36	43.4	46.7	54.4	31.7	31.2	41
Clay (%)	39	35	53	41	33	37	33	31	27.9	25.3	26.4	32.7	36.2	29.3
Loam (%)	32	33	31	25	37	39	39	33	28.7	28	19.2	35.6	32.6	29.7
Soil Type	CL	CL	C	C	CL	CL	CL	CL	CL	L	SCL	CL	CL	CL
pH	8	8.1	8.2	8.6	8.1	8	8.5	8.6	8	8.2	8.3	8.2	8.3	8.3
El. Conductivity (μS/cm)	396	377	498	487	423	417	340	347	512	380	432	395	437	432
$CaCo_3$ (%)	2.5	3	3.5	4.1	3.5	5.5	4.4	3.8	4	19	15.4	12.9	15.4	14
Organic matter (%)	-	-	-	-	-	-	-	-	0.9	0.7	0.8	0.6	0.3	0.3

From a side of the trenches samples were also taken for texture, gravimetric soil moisture, and bulk density allowing for the estimation of initial conditions. Multi-sensor systems were installed (TEROS 10) in the center of each field and at 15, 30, 60, and 90 depths to monitor the soil moisture. A data logger is installed next to the sensors recording the soil moisture on an hourly basis.

The grown cotton cultivar was ST318 of Pioneer, an early variety. It was selected because it has new genetic material, excellent quality, fiber performance (>38%), and high production. The plant density was 210,000 plants per hectare. The seeds of cotton were sawn at 3 cm depth on 22 April 2021. The grown maize cultivar was DKC 6897 of Dekalb, a French variety of FAO 700 class which is popular among Greek farmers. It was selected as it combines a new genetic material, excellent germination, excellent agronomic characteristics, and adaptation to high sowing density in good and fertile fields leading steadily to increased yields. The seed density was high and equal to 95,000 plants per hectare. The seeds of maize were sawn at 3.5 cm depth on 27 March 2022.

2.2 Weather Research and Forecasting Model

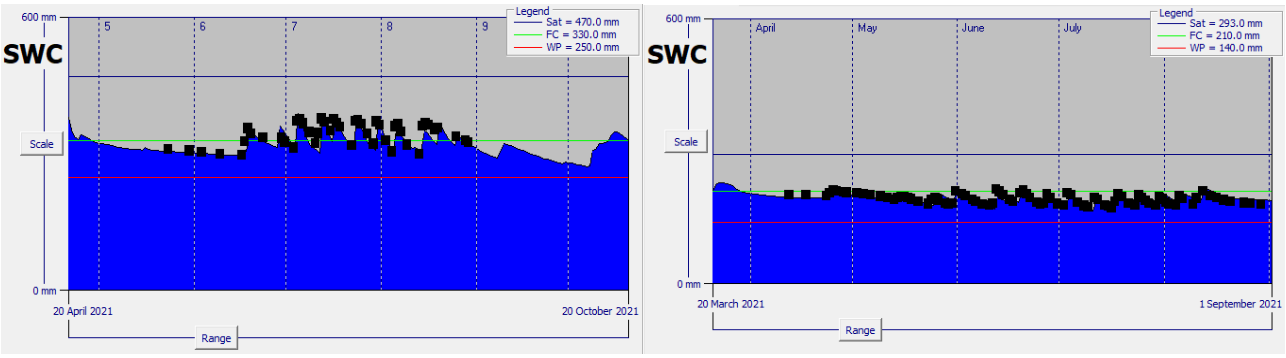
For weather forecasting, the Weather Research and Forecasting Model (WRF) was used. It is a state-of-the-art next-generation mesoscale Numerical Weather Prediction system designed to serve both operational forecasting and atmospheric research needs. It features multiple dynamical cores, a 3-dimensional variational (3DVAR) data assimilation system, and a software architecture allowing for computational parallelism and system extensibility. WRF is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. WRF produces a principal 5-day weather forecast for the study area. To ensure reliability and maintain a standard of more than 97% accuracy automated mechanisms are developed that monitor and review the quality of the forecast daily.

2.3 Aquacrop development and calibration

Aquacrop was developed and calibrated for the growing season of 2021 (Sidiropoulos et al., 2022). The reference evapotranspiration was calculated by the model using as input the minimum, mean, and maximum daily temperature according to FAO 56 protocol (Allen et al., 1998). The cotton was simulated with the use of Default Cotton, GDD (Cordoba, 15Apr86) crop file, and the maize was simulated with the use of Default Maize, GDD (Davis, 1Jun96) crop file. For both crops, adjustments were made to specific days during the phenological period, plant density according to field measurements, and Reference Harvest Index (HI_o) according to crop yields. Specifically, for cotton, the duration of the initial stage, canopy development, mid-season stage, and the late-season stage were 45, 35, 56, and 48 respectively, while for the maize the days were 46, 36, 62, and 18 respectively. The HI for cotton was 35% and for maize 55%. The irrigation method for all the fields was drip irrigation with a 40% percentage of soil surface wetted by irrigation. There was not any specific field management and no shallow groundwater table was observed. The physical soil characteristics of all the plots were processed with Soil Water Hydraulic Properties Calculator (USDA, 2007) to calculate the hydraulic parameters required by AquaCrop. These included volumetric soil water content at field capacity (FC), permanent wilting point (PWP), saturation (SAT), and saturated hydraulic conductivity (K_{sat}). The final values of the parameters were determined by the calibration procedure of Aquacrop through the trial-and-error method till the simulated soil moisture values matched the observed ones. Table 2 presents the hydraulic parameters values and the calibration statistics of the “Hubis” fields for the two crops. Figure 2 presents the observed (black line) and simulated (blue area) soil water content of the 1 m profile for 2021. The initial soil water profile was determined by the soil samples’ laboratory analyses. For cotton the soil water content (vol %) was 45 % for the 1 m profile, while for maize 20.87% for 0-35 cm, 21.66% for 35-47 cm, and 17.68% for 47-100 cm depth. Soil salinity was equal to 0.45 dS/m for both crops’ fields.

Table 2. Hydraulic parameters values and calibration statistics of the “Hubis” fields for the two crops

	Hydraulic parameters				**Calibration Statitics**				
	Sat (mm)	**FC (mm)**	**WP (mm)**	**Ksat (mm/d)**	**Pearson Correlation Coefficient (r)**	**Root Mean Square Error - RMSE (mm)**	**Normalized Root Mean Square Error - CV(RMSE) (%)**	**Nash-Sutcliffe Model Efficiency Coefficient (EF)**	**Willmott's Index of Agreement (d)**
Cotton	470	330	250	200	0.86	14.8	4.3	0.63	0.91
Maize	293	210	140	45	0.76	7.4	3.8	0.51	0.87



(a) (b)

Figure 2. Observed (black line) and simulated (blue area) soil water content of the 1 m profile: a) cotton, b) maize.

3 Results

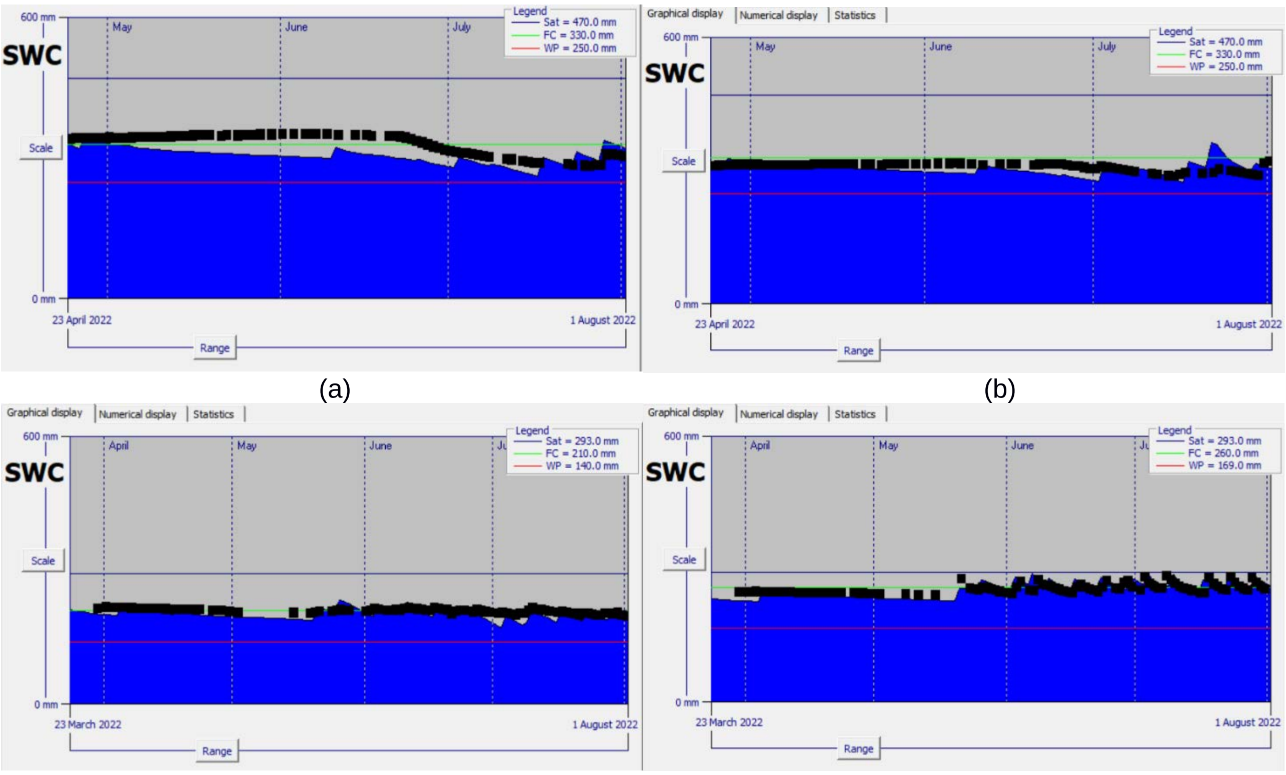
AquaCrop was performed on the one hand to validate the simulated results of soil moisture according to the historical observed values from the sensors and on the other hand to schedule the date and the water volume of the forthcoming irrigation event. For both crops, a lower threshold value of soil moisture was set so as not to be violated. This threshold was the 50% of the Available water (Available water=Field Capacity-Wilting point). When the soil moisture reaches this threshold, the farmer must apply the next irrigation event. Table 3 presents the supplementary irrigation for "Farmer" and "Hubis" fields.

Table 3. Irrigations events

Irr. Event	Cotton			Maize		
	Date	**Farmer (mm)**	**Hubis (mm)**	**Date**	**Farmer (mm)**	**Hubis (mm)**
1	28.04.2022	26	26	04.04.2022	26	26
2	02.07.2022	46.7	24.6	21.05.2022	48.9	48.9
3	17.07.2022	50.9	43.7	26.05.2022	50.7	55.6
4	23.07.2022	82	39.2	04.06.2022	45.4	35.6
5	28.07.2022		49.3	07.06.2022	48.4	24.6
6				17.06.2022	26.9	38.1
7				22.06.2022	49.9	22.5
8				29.06.2022	45	0
9				02.07.2022	43	29.8
10				08.07.2022	49.6	35.5
11				16.07.2022	54.4	25.6
12				21.07.2022	51.7	37
13				28.07.2022	54.4	53.4
	Sum	**205.6**	**182.8**	**Sum**	**594.3**	**432.6**

A reduction in water volume of 11.1% was achieved for cotton "Hubis" plot and of 27.2% for maize "Hubis" plot. Since the area of the cotton field is 2.5 ha (Hubis plot), the reduction of the total water volume amounts to 570 m^3. Since the area of the maize field is 2 ha (Hubis plot), the reduction of the total water volume amounts to 3,234 m^3. The results of simulated soil moisture for all fields, calculated by AquaCrop, are presented in Figure 3. Since the growing period of the two plants extends beyond 31 July 2022, no prediction for the crop yield can be carried out.

In Figure 3 a and b the soil moisture measured and estimated by the model for cotton field is presented. The convergence between measured and estimated values, in comparison to the 2021 calibration period (Figure 2a), is smaller, mainly in the case of Hubis plot (Figure 3a). In the case of maize (Figure 3, c and d) the convergence of measured and estimated soil moisture values is better but not as good as the one observed in the 2021 period (Figure 2b)



(c) (d)

Figure 3. Graphs of simulated soil water content of the 1 m profile for: a) “Hubis” cotton field, b) “Farmer” cotton field, c) “Hubis” maize field, and d) “Farmer” maize field.

It is well known that the behavior of soil moisture capacitance sensors is related to the contact of the sensors with the soil. Probably, the accuracy of the sensors is affected by the settling (natural phenomenon) and the compaction caused by the tractor.

It is necessary to mention that the sensors were left in the field from spring 2021 up to now.

In Figure 4 it is shown that the compacted soil has pushed down the sensors, which have lost the initial contact with the soil. Therefore, the sensitivity and the accuracy of the soil moisture was reduced.

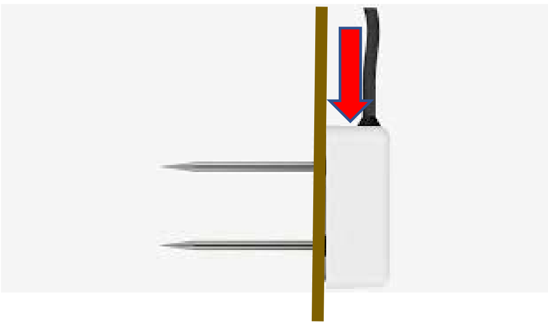


Figure 4. Force that pushes down the sensors due to soil compaction

Previous experience from similar soil moisture installations proves this hypothesis. In order to avoid this kind of problems, during the next cultivation period the sensors will be installed vertically as presented in Figure 5.

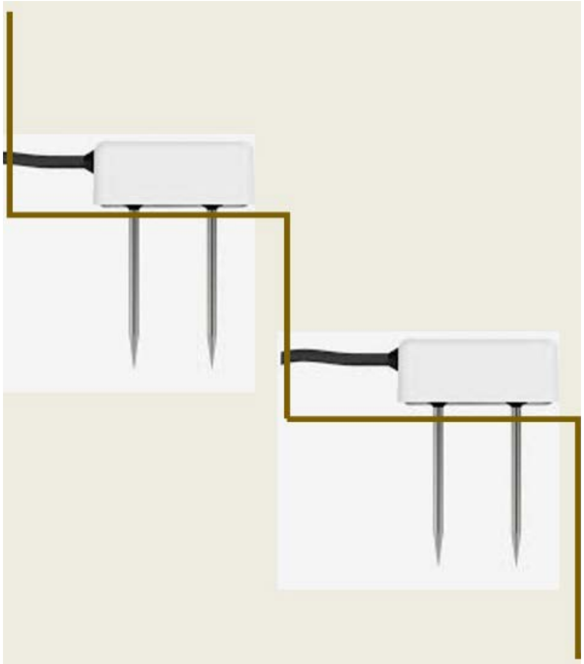


Figure 5. Proposed installation in order to avoid the compaction effect.

4 Summary

In this study, a comparative evaluation of irrigation practices for maize and cotton crops in Thessaly, Greece is presented with the use of precision agriculture tools. These tools are the application of the FAO Aquacrop model for the simulation of the yield response of crops to water, the installation of low-cost soil water sensors and hydrometers for irrigation scheduling, and the use of the Weather Research and Forecasting (WRF). The results indicate that for the cotton the water-saving percentage is 11.1% and for the maize, the percentage reaches 27.2%.
This experiment allows us to understand the problem that may arise when the sensors stay in the field throughout the year and are subject to soil compaction, especially due to tractor impact. A solution to this problem has been presented.

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