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Rainfed and Supplemental Irrigation Modelling 2D GIS Moisture Rootzone Mapping on Yield and Seed Oil of Cotton (*Gossypium hirsutum*) Using Precision Agriculture and Remote Sensing †

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Abstract: The effects of two irrigation (IR1: rainfed; IR2: rainfed + supplemental drip irrigation), and two fertilization (Ft1, Ft2) treatments were studied on cotton yield and seed oil by applying a number of new agro-technologies such as: TDR sensors; soil moisture (SM); precision agriculture; remote-sensing NDVI (Sentinel-2 satellite sensor); soil-hydraulic analyses; geostatistical models; SM-rootzone, and modelling 2D GIS mapping. A daily soil-water-crop-atmosphere (SWCA) balance model was developed. The two-way ANOVA statistical analysis results revealed that irrigation (IR2 = best) and fertilization treatments (Ft1 = best) significantly affected yield and oil content. Supplemental irrigation, if applied during critical growth stages, could result in substantial improvement on yield (+234.12%) and oil content (+126.44%).

Keywords: geostatistical modelling; cotton yield; 2D TDR-GIS soil moisture mapping; precision agriculture; GIS and NDVI; rainfed and supplemental irrigation; soil-hydraulic analyses

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1. Introduction

Cotton plant grows as a perennial crop but is cultivated annually and considered the world's largest non-food crop [1]. Global cottonseed production has ranged between 35 and 59 million tonnes in the last three decades [2]. Regarding water, on a global scale, the agricultural sector accounts for 70% of global freshwater withdrawals [1,3,4]. In Europe, it accounts for around 59% of total water use, and approximately 284,000 million m^3 of water is abstracted annually to meet the demands of the European economy [5]. At present, many countries worldwide are experiencing a scarcity of fresh water [1,3,4] for potable and irrigation use. Global water demand is projected to increase by 55% between 2000 and 2050, from 3500 to 5425 km^3. Evidence has shown that climate change will have an adverse impact on world water resources and food production, with a high degree of regional variability and scarcity [6]. The irrigation water amount has always been the main factor limiting crop production in much of the world, where rainfall is insufficient to meet crop water requirements [1,4,7]. With the ever-increasing competition for finite water resources worldwide, and the steadily rising demand for agricultural commodities, the call to improve the efficiency and productivity of water use for crop production, to ensure future food and crop products security and address the uncertainties associated with climate change, has never been more urgent [8]. The global challenge for the coming decades will be increasing crop production with less water. Precision agriculture (PA) is a management strategy that helps farmers to improve crop production, efficiency and productivity of water use. The aim of this study was to determine the effects of rainfed (IR1) and rainfed plus supplemental irrigation (IR2) and fertilization (Ft1, Ft2) treatments on cotton yield and seed oil content, by applying new agro-technologies.

2. Materials and Methods

2.1. Experimental Plot Design, Soil Sampling and Laboratory Soil and Hydraulic Analysis

The 2.15 ha field had a factorial split plot design with the main factor being the 2 irrigation treatments: (a) IR1: rainfed; (b) IR2: rainfed + supplemental drip irrigation. The sub factor was 2 fertilization treatments: Ft1: N-P-K = 91.00-19.62-37.35 $Kg \cdot ha^{-1}$, and Ft2: N-P-K = 71.40-13.08-24.90 $Kg \cdot ha^{-1}$. A GPS receiver was used to identify the locations of soil samples that were collected at a depth of 0–30 cm, and then analyzed at the laboratory. The soil's pH was measured in a 1:2 soil/water extract, with a glass electrode and a pH meter. Soil organic matter was analyzed by chemical oxidation with 1 $mol \cdot L^{-1}$ $K_2Cr_2O_7$ and titration of the remaining reagent with 0.5 $mol \cdot L^{-1}$ $FeSO_4$ [9]. The cation-exchange capacity (CEC) was analyzed by (i) saturation of cation exchange sites with Na by "equilibration" of the soil with pH 8.2, 60% ethanol solution of 0.4N NaOAc-0.1N NaCI; and (ii) extraction with 0.5N $MgNO_3$. The total Na and CI were determined in the extracted solution [9]. The soil's nitrate and ammonium nitrogen were extracted with 0.5 mol L^{-1} $CaCl_2$, and estimated by distillation in the presence of MgO and Devarda's alloy, respectively. Available phosphorus P (Olsen method) was extracted with 0.5 mol L^{-1} $NaHCO_3$, and measured by spectroscopy [9]. The potassium exchangeable K forms were extracted with 1 mol L^{-1} CH_3COONH_4, and measured with a flame photometer. Field capacity (FC) and wilting point (WP) were measured with the porous ceramic plate method, with 1/3 Atm for FC and 15 Atm for WP [1]. Cotton (*Gossypium hirsutum*, var. *Armonia*) was seeded at the end of April, and harvested on 10th (1st harvest) and 25th of October (2nd harvest).

2.2. Soil Moisture Measurements, Digital 2D GIS Moisture Maps Utilizing GIS, Precision Agriculture and Geostatistics

The TDR (time domain reflectometry) method was used to measure the soil moisture, because it gives accurate results within an error limit of ±1% [1,7,10,11]. A TDR instrument and probes with 5 sensors each were used [1,7,12], placed at 0–15, 15–30, 30–45, 45–60 and 60–75 cm depths for measuring volumetric water content ($\theta vi, \ldots, \theta vn$) ($i = 1, 2, \ldots, n$ and $n = 5$) of the root zone. Data were imported daily in a GIS geodatabase, utilizing precision agriculture and geostatistics [1,7,12] in order to model and produce soil moisture 2D maps of the cotton's root zone profile.

2.3. Remote Sensing Crop's NDVI, Evapotranspiration and Net Irrigation Requirements

Climatic data were obtained from a nearby meteorological station. The effective rainfall was calculated according to USDA-SCS (1970) [13]. The NDVI (Normalized Difference Vegetation Index) [1] was calculated every week using remote-sensing (RS) data (Sentinel-2 satellite sensor) for studying spatial crop development and coefficients. The reference evapotranspiration was computed based on the F.A.O. Penman–Monteith method [1,7,8]. The crop evapotranspiration (ETc) and actual evapotranspiration (ETa) were computed using crop coefficients obtained from remote-sensing NDVI vegetation index [1,7,8]. The net irrigation requirement (NIR) was calculated using a soil-water-crop-atmosphere balance model (Equation (1)) [1,7]:

$$\boldsymbol{NIR = ETc - Pe - GW - \Delta\theta v_{(TDR)}} \quad (1)$$

where: $\boldsymbol{NIR}$ = net irrigation requirement (mm); $\boldsymbol{ETc}$ = evapotranspiration (mm); $\boldsymbol{Pe}$ = effective rainfall (mm); $\boldsymbol{GW}$ = groundwater contribution from water table (mm); $\boldsymbol{\Delta\theta v_{(TDR)}}$ = change in TDR sensors measuring soil–water content $\theta v_{(TDR)}$ (mm).

3. Results and Discussion

3.1. Study Area, Soil-Hydraulic Analysis and 2D Moisture Maps Utilizing GIS, Precision Agriculture and Geostatistics

The experiment was conducted in a farm field located at Livadia, in Central Greece. The study area was characterized by a typical Mediterranean climate [1,4,7] with a cold winter, hot summer, and low precipitation in spring and summer (Figure 1a). The results found from TDR sensors and analyses were used as input variables to delineate the digital soil moisture profile on a 2D GIS map of the cotton's root zone (Figure 1b). SM is the major factor for crops' enhanced growth and production [1,7]. The spatial analysis revealed an excellent moisture distribution.

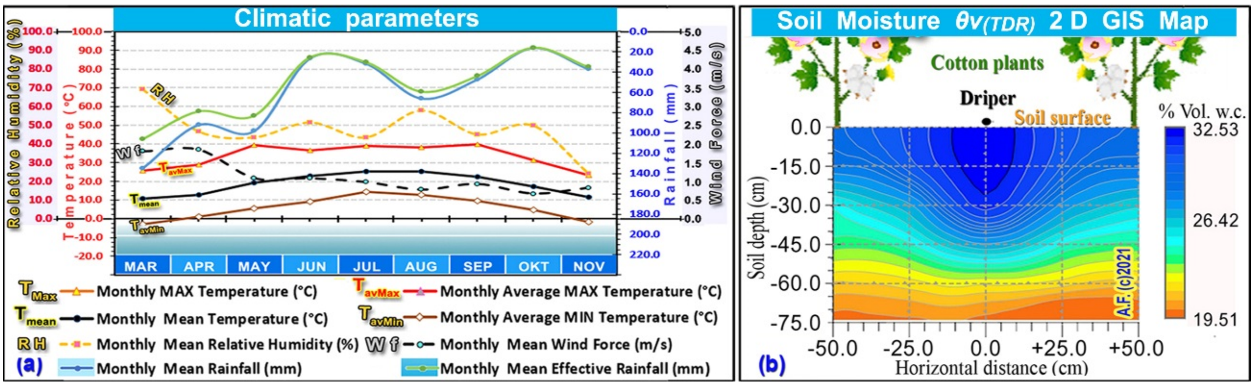

Figure 1. (**a**) Climatic parameters' time variation; (**b**) a soil moisture 2D GIS map of cotton's root zone soil profile.

The results of the laboratory soil and hydraulic analysis revealed that the field's soil was suitable for cotton growth [1,8,9,13], and was characterized as sandy clay loam (SCL) [1,9,13]. Soil organic matter was 1.62% (±0.15), the bulk specific gravity of the soil was 1.42g cm^{-3} (±0.02), plant available water was 0.130 cm cm^{-1} (±0.02), the pH at (1:2) soil/water extract was 8.06 (±0.21), and the cation-exchange capacity of the soil was 19.72 cmol kg^{-1} (±1.05) [a sufficient level]. The N-NO_3 was found at 9.05 mg kg^{-1} (±2.23) [a marginal level] and the N-NH_4 was found at 3.07 mg kg^{-1} (±1.02) [a low level]. The phosphorus P-Olsen was found at 17.60 mg kg^{-1} (±2.15) [a sufficient level], and the potassium K-exchangeable was found at high concentration levels (520 mg kg^{-1} (±21.15)).

3.2. Daily Soil-Water-Crop-Atmosphere (SWCA) Balance Model and NDVI Vegetation Index

The NDVI vegetation index [1] was calculated using RS data (the Sentinel-2 satellite sensor) for monitoring spatial crop development and coefficients for the SWCA model (Figure 2a,b). The daily TDR moisture measurements, 2D GIS SM mapping, the accurate estimations of ETc, the monitoring of the system inflows and estimated surface outflows, and NDVI vegetation index mapping, resulted in a reliable daily soil-water-crop-atmosphere model [1,7] for the four crop-growth stages of cotton.

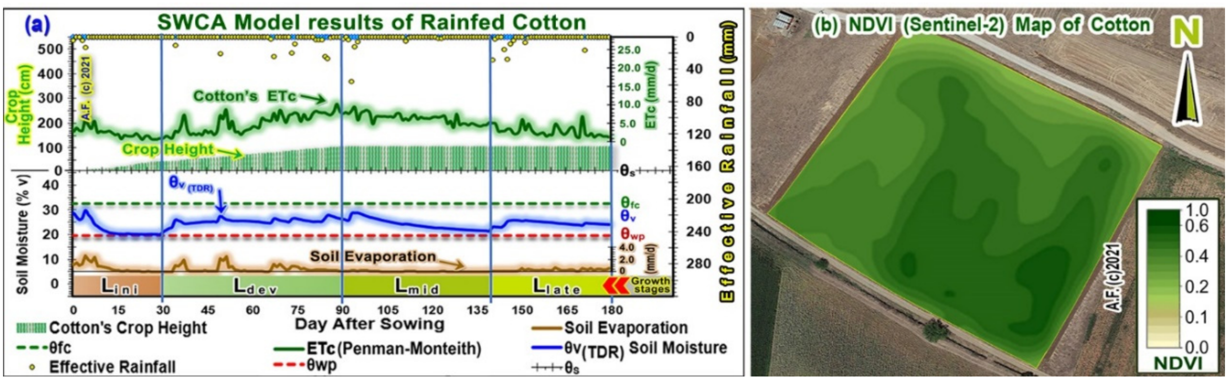

Figure 2. (**a**) Treatment IR1 results of the daily soil-water-crop-atmosphere model for the four cotton growth stages; (**b**) cotton's field NDVI vegetation map (using Sentinel-2 satellite sensor data) in early July, after the blossom of the first flowers of the crop.

3.3. Statistical Analysis, Cotton's Yield and Seed Oil Content Results

The two-way ANOVA statistical analysis (p = 0.05) using IBM-SPSS (v.26) [1,7,14,15] revealed that the irrigation treatments (IR2: rainfed + supplemental irrigation [best]) and the fertilization treatments (Ft1: [best]) significantly affected the cotton yield and seed oil content. Whenever a prolonged shortage of soil moisture occurred during the most sensitive growth stages (flowering (L_{mid} stage) and grain filling (L_{late} stage)) (see Figure 2a), the rainfed crop growth was poor, and yield was consequently low [1,7,8]. Supplemental irrigation, if applied during the cotton's critical growth stages, could result in substantial improvements in yield (+234.12%) and seed oil content (+126.44%).

4. Conclusions

The prolonged shortage of soil moisture in dry rainfed areas often occurs during the most sensitive growth stages (flowering (L_{mid} stage) and grain filling (L_{late} stage)) of many crops. As a result, rainfed crop growth is poor and yield is consequently low. Supplemental irrigation, if applied properly by the use of new agro-technologies during the critical crop growth stages (L_{mid} and L_{late}), may constitute a method that can result in substantial improvement in yield (+234.12%) and seed oil content (+126.44%), in addition to water use efficiency, and the sustainable management of environment and water resources.

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