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Greenhouse Soil Moisture Deficit under Saline Irrigation and Climate Change

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Abstract

The sustainability of protected horticultural crops in the Mediterranean region, typically under deficit irrigation and intensive cultivation practices, is facing increasing risks due to soil salinization. Climate change may augment this threat to ecosystem services. In this study, the SALTMED leaching requirements model was calibrated using soil moisture measurements from time domain reflectometry (TDR) sensors. Measurements are performed on a small-scale Solanum lycopersicum (tomato) greenhouse experiment that simulates semi-arid conditions in the RECARE Project Case Study in Greece (Timpaki basin in Crete). The use of local planting soil with initial Electrical Conductivity (EC_e) 1.8 dS m^{-1} and local cultivation practices aim to replicate prevailing conditions at the Case Study. Plants are drip irrigated with two NaCl treatments: slightly (S) saline (EC_w= 1.1 dS m^{-1}) and moderately (M) saline water (EC_w = 3.5 dS m^{-1}), resulting to very high and excessively high EC_e, respectively. Based on these approaches, the calibrated SALTMED model was used for simulating groundwater degradation by seawater intrusion. In order to estimate crop yield in a warmer future, climate model data obtained from 9 GCMs for the "worst case" Representative Concentration Pathway of 8.5 W m^{-2} of the 5th phase of the Coupled Model Intercomparison Project are corrected for bias against historical observations with the Multisegment Statistical Bias Correction method. Preliminary results predict that to sustain greenhouse productivity at current levels in the future, a substantial increase of water demand will be required.

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1. Introduction

Global population, currently 6.5 billion approximately, is expected to reach 9 billion by 2050 [1]. A result of this profound global growth is a significant increase in food and water demand [2]. At the same time, natural resources are under significant threats due to non-optimal management, but also climate change. However, soil and water resources of high quantity and quality are needed to sustain these rates of growth, as well as the current welfare. Soil salinization, defined as an excessive accumulation of salts in soil at levels that hinder crop production [3], is one of the most ominous soil degradation threats [4]. The main cause of human induced (or secondary) soil salinisation is poor quality or mismanaged irrigation [5]. Between 34 and 45 Mha [5] or over 10% of irrigated land [6] all over the world are characterized as salt-affected.

In coastal agricultural regions, and especially in arid and semiarid areas such as those of the Mediterranean basin, soil resources and crop production are highly compromised due to irrigation with saline water. In Greece, water demand is largely covered by groundwater resources; yet, the overexploitation promotes seawater intrusion thus undermining groundwater quality (Fig. 1). Soil salinization due to seawater intrusion poses a threat to the local water security, plaguing about 9% of the approximately 1.4 Mha of irrigated land [7]. Due to a more arid climate, the coasts of southern Greece face a relatively greater risk of seawater intrusion progressing at a great distance inland [8]. With intensive agriculture constituting the main factor that strongly impacts water resources availability, the island of Crete (Fig. 1) is no exception to this rule. Under the threat of climate change, the sustainability of the current agricultural system of these regions is highly uncertain. Motivated by these challenges, we investigate the projected changes in water resources requirements under the combined stress of soil salinisation and climate change. The approach involves the use of State of the Art climate datasets and the SALTMED model [9] under the typically optimised greenhouse cropping conditions at the RECARE Project Case Study in Greece, Crete.

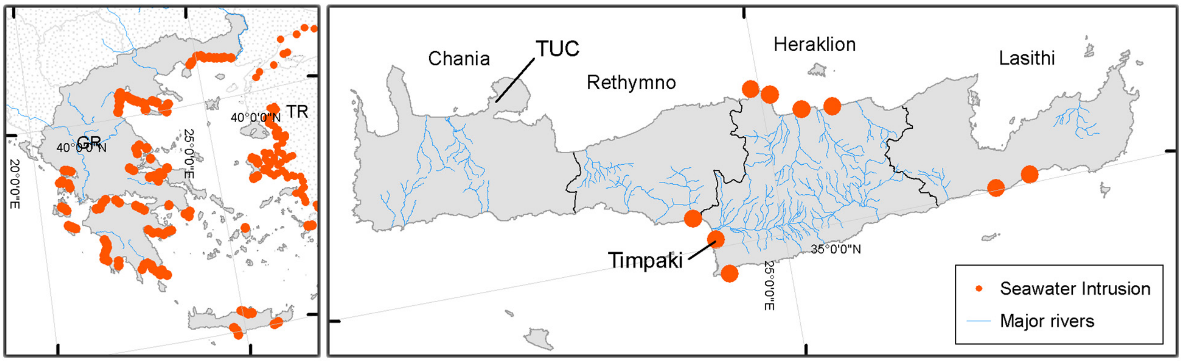

Fig. 1. Areas of seawater intrusion in Greece (left) and specifically in Crete (right).

2. Methodology

Salt-affected soils can be classified into three categories; saline, saline-sodic and sodic soils [10], with the latter being the most problematic [4]. Saline soils are those for which a solution extracted from a water-saturated soil paste (EC_e) values greater than 4 dS m^{-1}, and at the same time exhibit Sodium Adsorption Ratio (SAR) values less than 13. On the other hand, sodic soils have SAR values greater than 13 and EC_e values less than 4 dS m^{-1} [4]. The SALTMED model [9] is based on mathematical equations that depict nutrient and irrigation water uptake by the plant roots under specified soil, irrigation quantity and quality, nutrient concentration, and climate conditions. Based on those, SALTMED can estimate soil profile Electrical Conductivity (EC) and crop yield through time. SALTMED estimates the additional amount of water required under saline irrigation to avoid yield loss or Leaching Requirements (LR) as:

$$LR = \frac{D_d}{D_i} = \frac{EC_i}{EC_d} \tag{1}$$

where EC_i is the electrical conductivity [dS m^{-1}] of the amount of total irrigation water D_i [L] and EC_d is the salt concentration of the amount of drained water D_d.below root depth when no yield loss occurs. SALTMED has been applied successfully in a range of greenhouse experiments [11].

The SALTMED model requires daily values of maximum and minimum temperature $T_{in}(t)$ [°C], relative humidity RH_{in} [%] (where the "in" subscript signifies variables inside the greenhouse) and optionally total or net radiation or both. In order to calibrate SALTMED for the current conditions, daily indoors temperature and relative humidity measurements were recorded 3 HOBO Pro V2® sensors equipped with a solar radiation shields which have an accuracy of ±0.21 °C from 0 to 50 °C and ±2.5% from 10% to 90% RH. In order to calibrate SALTMED for future conditions where only ambient climatic variables are available, the effect of greenhouse insulation has to be modelled. Inside temperature T_{in} [°C] can be estimated from ambient (subscript "out") temperature T_{out} [12] using:

$$T_{in}(t) = T_{out}(t) + \frac{bs(t)+h(t)}{U+q} \tag{2}$$

where $s(t)$ [W m^{-2}] is the solar radiation, b [%] is the constant solar heating efficiency, $h(t)$ [W m^{-2}] is the heating control variable, U [W m^{-2} °K^{-1}] the heat transfer coefficient from within the greenhouse towards the ambient environment (assumed positive) and q [W m^{-2} °K^{-1}] is the heat transfer coefficient due to ventilation. For the calibration of the indoors temperature model in the pilot greenhouse a U of 5.65 W m^{-2} °K^{-1} is used [11]. Greenhouse conditions in the region are typically accomplished by almost strictly passive means, therefore we consider a high solar heating efficiency b and zero additional heating $h(t)$. Optimal b and q are estimated at 78.9% and 23.05 W m^{-2} °K^{-1} respectively, yielding R^2=0.893 and RMSE=1.49 °K between measured $T_{in}(t)$ and $T_{out}(t)$ values (Fig. 2, left). Indoors relative humidity RH_{in} [%] is estimated using a simple 4-10-1 feedforward artificial neural network trained and tested using indoors temperature $T_{in}(t)$, outdoors temperature $T_{out}(t)$, outdoors relative humidity RH_{out} and solar radiation R [W m^{-2}] as input. For the entire dataset, the network scores R^2=0.803 and RMSE=3.15% (Fig. 2, right) thus providing confidence in terms of modelling future greenhouse indoors relative humidity. For this process, as well as subsequent modelling, we assume that greenhouse materials do not affect incoming solar radiation.

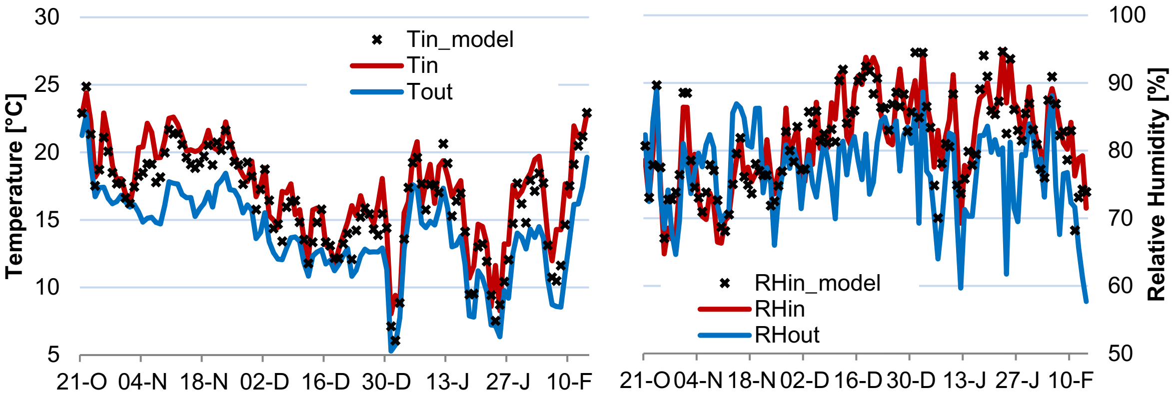

Fig. 2. Measured (Tin, Tout, RHin, RHout) and estimated (Tin_model, RHin_model) values of mean daily indoors and outdoors temperature (left) and relative humidity (right).

In the majority of cases, GCMs fail to reproduce the local scale climate due to their coarse resolution (~3 degrees) and their limitation in the representation of physical processes. Therefore, their use is limited to reproducing the global circulation patterns under changing forcings [13]. At higher resolution, it is common to downscale GCM projections using the more detailed physics of Regional Climate Models (RCMs) to depict local climate [14]. Remaining biases can be adjusted using sophisticated statistical methods. Here we employ a modification of the Multisegment Statistical

Bias Correction (MSBC) method [15] which provides improved skill in removing the bias in the mean, the standard deviation, as well as in higher moments of the climate variables' distributions [11].

Different techniques for soil moisture (SM) measurements have been developed over the last decades [16]. Most commonly, electromagnetic sensors are used to establish continuous in situ soil moisture networks. These sensors make use of the high permittivity of water to estimate the volumetric water content (VWC [m^3 m^{-3}]) in the soil [17] based either on time domain reflectometry (TDR), frequency domain reflectometry (FDR), or capacitance techniques. Recent developments and improvements of ECH_2O soil moisture sensors allow for detailed monitoring of soil water content at the relatively low cost of FDR methods that measure capacitance of the soil, which is related to the permittivity of the surrounding medium and then to the VWC of the soil. The characteristics and performance of the EC-5 ECH_2O sensors used in this study have been examined under various conditions [18] and are suitable for our application [19]. Here, SM is monitored at two depths (5 and 20 cm bellow soil surface) with the EC-5 sensors being embedded at the side of each pot in a radial arrangement. Given the EC-5 sensor dimensions the recorded SM value represents the value at a distance of approximately 12 cm from the irrigation source.

In order to estimate expected crop yield and irrigation use, the following assumptions were made. Based on the obtained data from the first two harvests (February 2016), the mean weight of harvested tomato fruits $\bar{W}_T$ is calculated. At this stage, the number of fruits per treatment (LS or HS) averaged per plant per treatment (n=5) regardless of maturity stage $\bar{N}_T$ is counted and plants are pruned to stop new fruit formation. The expected total yield per treatment $\bar{Y}_T$ [g] can be estimated as:

$$\bar{Y}_T = \bar{W}_T \times \bar{N}_T \tag{3}$$

assuming that all unharvested fruits will develop proportionally to the harvested. Assuming a number of 30,000 plants per hectare and considering the number of plants per treatment (n=5), the total yield per hectare Y_T [t ha^{-1}] can be estimated. Similarly, relative yield $\hat{Y}_T$ [%] from a baseline yield Y_B can be estimated as:

$$\hat{Y}_T = (Y_T - Y_B)/Y_B \tag{4}$$

Furthermore, after SALTMED model calibration and validation, the amount of water $W_{LS}^{80\%}$ [L] required to achieve $Y_{LS}^{80\%}$ or 80% of the total yield estimated for the unstressed LS treatment (Table 2) is determined and used as a baseline for subsequent calculations. Therefore, starting from $W_T^{80\%}$, irrigation quantity is adjusted for all treatments and climatic scenarios in order to achieve $Y_{LS}^{80\%}$ within SALTMED.

3. Case Study

The Timpaki coastal basin (Fig. 1), located at the central-south Crete, encompasses an area of 50 km2. The basin has a mean elevation of 200 m with mostly flat topography ranging from sea level in the west to stepper slopes at the northeast. To the east, Timpaki basin is linked to the Messara catchment through the Phaistos constriction. The region's economy is mainly based on agriculture and especially on greenhouse cultivation due to the favourable climatic conditions year round. The biannual harvest of horticultural crops is mostly drip-irrigated with Solanum lycopersicum (tomato) being the prevailing cultivation [11]. Groundwater is the main irrigation source as well as the limiting asset for the economic development of the region due to the few surface water flows outside the winter period [8]. Water resources and ecosystem services in the Messara plain and downstream have been significantly disturbed by unsustainable agricultural growth and the resulting groundwater overexploitation. The emergent seawater intrusion in the coastal aquifer of Timpaki adversely affects local water resources and soil health [8,11].

In order to restrict side effects on crop yield due to farms' mismanagement at the Timpaki basin, a small-scale greenhouse experiment was conducted at Technical University of Crete, Chania (Fig. 1), from October 2015 to February 2016. Tomato seedlings (Elpida F1 commercial hybrid) were transplanted into plastic 35 L pots, containing sandy clay loam soil (24% sand, 45% silt, 31% clay) obtained from Timpaki. Pots were lined with gravel to permit good drainage. Since this soil is rather poor in nutrients (pH 7.6, Total Organic Carbon 12.5 mg g^{-1}, Total Nitrogen 1.2 mg g^{-1}, Total Phosphorus 1.9 mg g^{-1}, initial ECe 23.5 dS m^{-1}), organic amendment was used to increase soil organic matter to values slightly greater than 1.0%, from the initial 0.8%, a practice common at Timpaki greenhouses.

Tomato plants were subjected to two drip-irrigation treatments with respect to water quality: Low Salinity (LS, n=5 replicates) and High Salinity (HS, n=5 replicates) with EC_w of 1.1 and 3.5 dS m^{-1}, respectively. A fertigation scheme with KNO_3, $Ca(NO_3)_2$, KH_2PO_4 and $Mg(NO_3)_2$, applied in different concentrations depending on growth stage was followed.

SALTMED was calibrated with data obtained from the LS treatment (Fig. 3, left) in accordance with soil hydraulic properties, based on soil moisture data. Given the type of soil used, soil hydraulic parameters, such as saturated hydraulic conductivity, lambda pore size distribution index and bubbling pressure, were tuned based on bibliographic ranges. Afterwards, the model was validated against the soil moisture data obtained from the HS treatment (Fig. 3, right) and the RMSE value was found to be 0.020 and 0.012 m^3 m^{-3} for LS and HS irrigation treatment respectively at 5 cm from top, as well as 0.015 and 0.029 m^3 m^{-3} for LS and HS irrigation treatment respectively at 20 cm from top. The effect of salinity on crops yield was calibrated for the HS treatment by tuning the π_{50} values, which stands for the osmotic pressure at which the roots' maximum capacity for water uptake is reduced by 50%. The yield of LS treatment (Table 2) was assumed to be the maximum unstressed yield. Table 2 shows the mean weight per fruit $\overline{W}_T$ [g], the mean number of fruits $\overline{N}_T$ and the expected yield Y_T [t ha^{-1}] for the two treatments. Based on these calculations, $Y_{LS}^{80\%}$ reaches almost 8 kg $plant^{-1}$ (250 t ha^{-1}). The estimate is rather optimistic [11] since it assumes yield weight and successful ripening will be constant for all harvest, nevertheless it serves well the purpose of this work.

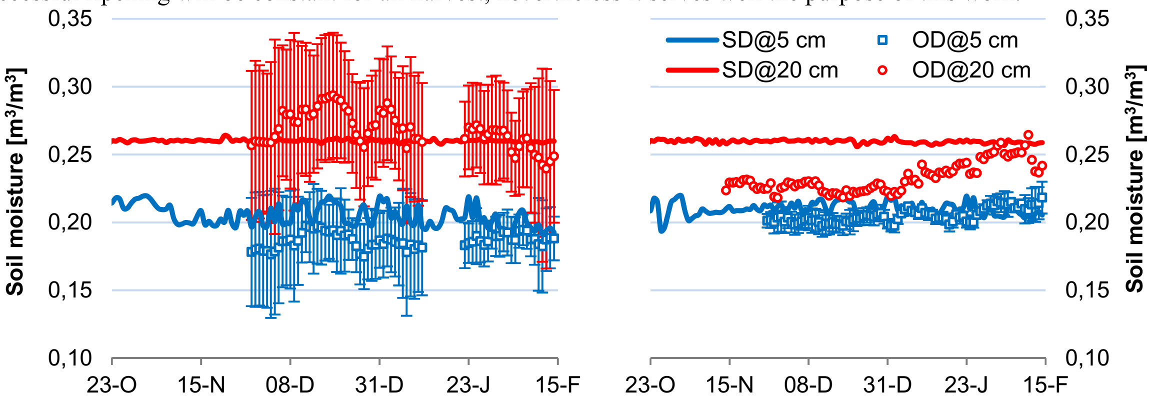

Fig. 3. Soil moisture observed (OD) and simulated (SD) data for the LS (left) and HS (right) irrigation treatment at 5 and 20 cm from top. Error bars (when shown) accounts for standard error from 3 replicates.

Table 2. Mean weight per fruit $\overline{W}_T$ [g], Mean number of fruits $\overline{N}_T$ and expected Yield [t ha^{-1}] for the treatments LS and HS. The standard error is calculated from the five replicates of each treatment

Yield parameter	LS	HS
Mean weight per fruit $\overline{W}_T$ [g]	201.5±28.8	210.5±21.7
Mean number of fruits $\overline{N}_T$	50.5±3.1	46.6±3.8
Yield Y_T [t ha^{-1}]	305.2±2.7	294.2±2.5

Two Euro-CORDEX (Coordinated Downscaling Experiment over Europe) climate simulations of from the 4th iteration of Sweden's Meteorological and Hydrological Institute-the Rossby Centre Regional Atmospheric Climate Model (SMHI-RCA) provide the climate data for the period 1951 to 2100. The RCM simulations are driven by two well established global climate models simulations of the Couple Model Intercomparison Project Phase 5 (CMIP5), SMHI-RCA4 and KNMI-RACMO22E. More information about the performance of the Euro-CORDEX experiment and the SMHI-RCA4 model can be found in the literature [20]. The Representative Concertation Pathway (RCP) 4.5 and 8.5 scenarios that until 2100 project average increases in radiative forcing of 4.5 and 8.5 W m^{-2} or roughly average global warming of 1.8 °C and 3.7 °C globally, were chosen for the analysis.

The RCM temperature data were adjusted for biases against the E-OBS dataset [21] using MSBC [15]. Instead of modeling yield results for the entire dataset, 4 years that had proportionally warm cropping seasons (November-

January) to the current (2015-2016) were selected. The selection process is described in detail in the literature [11]. Temperature and radiation data were considered for the historical period of 1951 – 2010 and an equal projection period of 2041 – 2100. Fig. 4 (left) shows the projected change of the quartile range of daily temperature for Chania according to the 2 models used in this study. After locating the current observed average temperature (13.52 °C) in the quartile range of each model for the present (green box plots in Fig. 4, left), a year with average temperature falling in the respective quartile of the future set was selected. Ambient temperature for the current and future conditions is converted to indoors greenhouse climate conditions and considering the typical specification of a local greenhouse (Fig. 4, right). Fig. 4 (right) shows ambient and greenhouse temperatures for the current (2015-2016) and respective future conditions during the cropping season. Future conditions in Fig. 4 (right) are presented as the range of daily temperature enveloped by the two models and 2 RCPs.

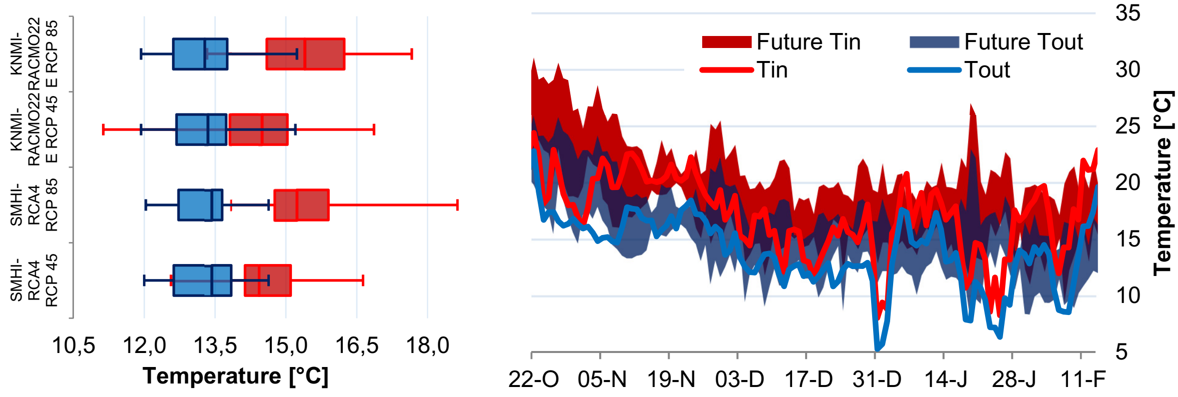

Fig. 4. Distribution of the average cropping season (NDJ) temperature [°C] in Chania, for the current (1951-2010 in blue) and future (2041-2100 in red) climate, according to the climate models presented in this study (left). Observed average temperature is 13.52 °C. Current and estimated future daily temperatures [°C] outside and inside the greenhouse (right). Overlapping area of future Tin and Tout appears in purple.

4. Results

Based on the initial SALTMED calibration using the pilot greenhouse measurements, it was estimated that yield equal to $Y_{LS}^{80\%}$ could be achieved using just 47 L of water per plant for the entire cropping season (Table 3). Under current climatic conditions, the HS treatment requires more than three times (243%) the amount of water in order to sustain the same yield ($Y_{LS}^{80\%}$). If the quantity of water is not increased to this level, the final yield of the HS treatment produces a relative yield of less than 20%, thus becoming practically unproductive (Fig. 5). As shown in Fig. 5, under irrigation with $W_{LS}^{80\%}$, relative potential yield for the HS treatment starts to decline early in the season as the effects of saline irrigation become apparent. By the middle of the season the crop has probably reached an irreversible stage of degradation.

Table 3. Estimated irrigation and for Yield equal to 8 kg plant^{-1} ($Y_{LS}^{80\%}$) for the LS and HS irrigation quality under irrigation with $W_{80\%}$ for current and future climate conditions.

Climate scenario	LS treatment		HS treatment	
	Irrigation [L]	Excess irrigation [%]	Irrigation [L]	Excess irrigation [%]
Current conditions	47	-	157	243
KNMI 45 2065	50	10	156	242
KNMI 85 2048	51	11	157	244
SMHI 45 2047	54	18	158	246
SMHI 85 2060	57	25	163	256

Regarding future scenarios, irrigation practices represented by $W_{LS}^{80\%}$ become less sustainable even for the LS treatment as relative yield drops from 80% to the area of 67-77% (Fig. 5). The relative increase of water required to maintain production is in the range of 10-25% depending on climatic conditions. As shown in the previous paragraph, $W_{LS}^{80\%}$ is not enough to sustain production under the HS treatment. The estimated increase in water requirements is projected to augment in the future in the range of 242-256%, or about 5% more current conditions requirements (243%).

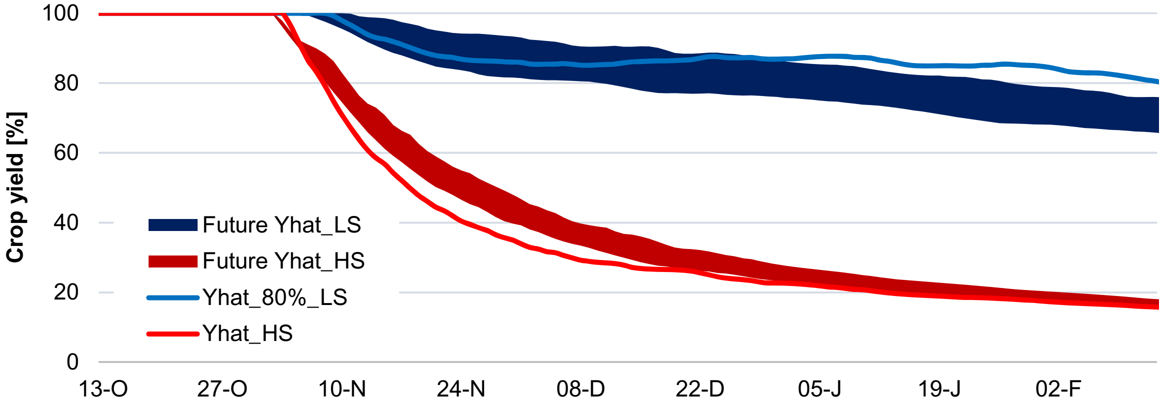

Fig. 5. Relative crop yield $Y_{LS}^{80\%}$(blue line) and $\hat{Y}_{HS}$ achieved for the irrigation quantity $W_{LS}^{80\%}$ (red line) for current conditions. Blue and red surfaces depict the range of future $\hat{Y}_{LS}$ and $\hat{Y}_{HS}$ for the same amount of irrigation ($W_{LS}^{80\%}$).

5. Conclusions

This research includes several assumptions that introduce limitations to its results. For example we consider that climate conditions in Chania and Timpaki are similar. In reality Timpaki is somewhat warmer (and is projected to be even warmer). Thus an underestimation of highlighted problems is to be expected, nevertheless authors preferred to present a solidly validated SALTMED simulation were data was more readily available and results are more conservative. Furthermore, we consider that water quality is stable for each treatment, whereas groundwater quality in Timpaki fluctuates seasonally. Furthermore, limitations related to the scale of the greenhouse experiment and the use of pots instead of the typical ground planting, apply. Finally, here we assume that the future water availability will be similar to the current, a rather optimistic scenario when accounting for current abstraction and land degradation rates.

Besides limitation, SALTMED was successfully calibrated to simulate greenhouse conditions in Crete. We consider that soil conditions, irrigation and climate conditions are directly comparable. Results demonstrate that future conditions will not worsen the situation for greenhouses that already face a high salinity problem. Therefore, over-consumption is not projected to increase more than the already 250% excess. On the other hand, greenhouses that use relatively better quality water will be forced to increase their water consumption by as much as 25%. Based on estimates from State of the Art climate models policy makers can assess greenhouse future water requirements with respect to water quality.

It is worth noting that regardless of the selected climatic model or the selected RCP, future water demand is expected to increase for all users. This constitutes a robust outlook towards an unfavourable future for the local agricultural industry that strives to intensify production and expand irrigated land [22]. Similar problems are expected to arise in other Mediterranean regions that face the same water management issues and are projected to reach a warmer future during the current century. In view of these results, it is evident that action needs to be taken towards a more sustainable water resources management by securing new distributed source of adequate quality water and ensuring its efficient consumption by users.

Acknowledgements

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