Application of the SWAP model to predict impact of climate change on soil water balance in a Sicilian vineyard

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Abstract

In Sicily, the increasing scarcity of quality water is leading to irrigation with saline water in soils having a considerable susceptibility to salinization and degradation. In this paper, water flow and solute transport in a Sicilian irrigated soil was simulated by using the SWAP model, and the simulated results compared to measured values of soil moisture and salinity. The investigation was carried out in a vineyard located in Sicily (Mazara del Vallo, Trapani) within the framework of the Project *Evolution of cropping systems as affected by climate change* (CLIMESCO). The soil hydraulic parameters were obtained by inverse method based on multi-step outflow experiments. The results obtained using field measurements from two soil profiles showed that SWAP provided reliable predictions of water content, θ, and of electrical conductivity of saturated extract, EC_{sat}. The effect of climate change on soil water balance was predicted by application of SWAP under the soil-crop and irrigation management conditions currently practiced in the vineyard. Simulations were carried out with climatic data generated by the statistical downscaling process based on the global CGM HADCM3 for two IPCC scenarios (A2 and B1) and for the 2070-2100 time interval. The two mentioned IPCC scenarios (A2 and B1) were then compared to a third reference scenario (BASELINE) obtained by using the climatic data recorded from 1951 to 2004. The results indicated that the only significant effect of climate change was to shorten and to advance the crop cycle length, which decreased of 16 and 27 days respectively in B1 and A2 compared to values obtained for the BASELINE scenario. Further application of SWAP carried out simulating an advance in the irrigation starting time according to the advance in the crop cycle indicated that this could be considered a kind of adaptation strategy to be applied in the future in the vineyard to counterbalance the impact of climate change. This means that in the future farmers might be likely to anticipate the irrigation season in order to avoid any significant reduction in the crop productivity.

Introduction

Application of physically-based models simulating water and solute transport, and predicting soil salinity (expressed by measurement of electrical conductivity or by concentration of the pore solution), represents an essential tool for the development of management scenarios suitable to prevent salinization. By these models different options can be analysed and compared, and strategies for sustainable irrigation in the short and in the long term can be delineated (Crescimanno and Garofalo, 2006). Van Dam *et al.* (1997) developed a model for fine-textured clay soils containing shrinkage cracks. This model, named SWAP93, takes into account shrinking and swelling as a function of the water content, and uses statistical properties of cracks as parameter input. SWAP93 provides as output the water content (and matric potential), as well as the concentration of the soil solution, C, from which the electrical conductivity of the saturated extract (EC_{sat}) can be also calculated (Rhoades, 1996). With reference to solute transport, SWAP93 predicts solute concentration (C) by using the advection-dispersion (ADE) equation, assuming a constant dispersivity and neglecting the process of cationic exchange. Due to these simplifying assumptions, accuracy of the predicted C or EC_{sat} in clay soil needs to be checked by comparison with measured EC_{sat} values.

Climate change is already happening and represents one of the greatest environmental, social and economic threats facing the planet. The warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global mean sea level. Global climate change may have serious impacts on water resources and agriculture in the future. Based on a range of several current climate models, the mean annual global surface temperature is projected to increase by 1.4 to 5.8°C over the period of 1990 to 2100 (IPCC, 2007), with changes in the spatial and temporal patterns of precipitation (Southworth *et al.*, 2000). Semi-arid areas already suffering from limited water availability are likely to be most sensitive to climate

change due to an increase in water demand for irrigation projected under a warmer climate. It is therefore necessary to develop adaptation strategies aimed at counterbalancing the adverse impact of climate change. This paper reports results of a field investigation carried out in a vineyard located in Sicily (Mazara del Vallo, Trapani Province) within the framework of the project *Evolution of cropping systems as affected by climate change* (CLIMESCO), funded by three Italian Ministries (University, Agriculture, and Environment). Investigation was carried out at the Foraci Farm (http://www.cantineforaci.com/), a vineyard located in the Mazaro basin region of Sicily, where two different irrigation treatments were established (L and R) to monitor soil response to irrigation water salinity (Crescimanno and Marcum, 2009). The first objective of this investigation was to evaluate the ability of SWAP to accurately predict both θ and EC_{sat} in two soil profiles located in the L and R plots respectively. The second objective was to evaluate the impact of climate change on soil water balance, crop water stress and irrigation strategies in the Foraci vineyard.

Materials and methods

Data collection was carried out in a vineyard located in the Mazaro basin region of western Sicily (Foraci Farm, Trapani), (37° 40' 55" N; 12° 38' 50" E). Soil was uniform across the research area, classified as Typic Calcicxerept (Soil Survey Staff, 1999) with soil texture a clay according to USDA classification). The research area was divided into two large (2300 m^2) irrigation sections (Figure 1), each receiving a different irrigation water source. Irrigation treatment *L* used irrigation water from a lake having EC=1.6 dS m^{-1}, irrigation treatment *R* used water from a well having EC=0.6 dS m^{-1}. Two soil profiles were selected in the *L* and *R* treatments respectively, named Foraci_G (L treatment) and Foraci_F (R treatment).

Table 1 reports the soil physical characteristics, together with the soil classification (Soil Survey Staff, 1999) for the two considered soil profiles. Undisturbed soil cores (diameter d=8.5 cm, height H=11.5 cm) were sampled to measure the soil shrinkage curve, which was determined by measuring vertical and horizontal shrinkage (Crescimanno and Provenzano, 1999). Replicated soil cores (d=8.5 cm, H=5 cm) were sampled to determine soil hydraulic parameters/functions by inverse method based on multi-step (MSTEP) outflow experiments. The MSTEP experiments were performed in pressure cells by applying three successive steps with pneumatic pressures ranging from 10 to 40 cm, from 40 to 70 cm, and from 70 to 800 cm (Crescimanno and Garofalo, 2005). After the MSTEP experiments, the cores were put in a pressure plate apparatus in order to measure the water content at h=-15300 cm, i.e. wilting point, θ_{wp}. Independent measurement of θ_s and θ_{wp} was necessary because only the pressure range from 10 to about 1000 cm can be explored in the pressure cells used for the MSTEP. Parameter estimation was carried out according to Crescimanno and Garofalo (2005), representing the soil hydraulic functions by:

the equation proposed by Brutsaert (B) (1966), for the water retention curve:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \Theta = \left[1 + \left|\alpha'h\right|^{n'}\right]^{-1} \quad (1)$$

coupled with the model proposed by Gardner (G) (Gardner, 1958) for the hydraulic conductivity function $k(h)$:

$$k(h) = \frac{k_{sat}}{1 + \left|\beta h\right|^{\lambda}} \qquad (2)$$

Parameter estimation was performed by fixing both the saturated water content and the saturated hydraulic conductivity, K_s, at the measured values. Optimized parameters of the B-G model were therefore θ_r, α', λ' and n' (eqs. 1 and 2).

Irrigation scheduling was established according to a water balance model taking into account climatic data, the amount of soil water available for crops (AW$_{max}$), and crop parameters. Table 2 reports the irrigation scheduling applied from 7 June 2007 to 30 July 2009. Irrigation in R and L row plots was performed on subsequent days.

Simulations were carried out with SWAP using March 1st 2007 as starting date for the vegetative growth and September 15th as the max-

Figure 1. Foraci Farm (Mazaro basin, Sicily, Italy): location of the two treatments (L and R).

Table 1. Physical characteristics and soil classification (Soil Survey Staff, 1999) of the two soil profiles.

Soil	Classification	Horizon	Depth (cm)	Clay (%)	Silt (%)	Sand (%)
Foraci_F	Typic Calcixerepts	Akp1	0-30	47	42	11
Foraci_F	Typic Calcixerepts	Akp2	30-60	54	36	10
Foraci_G	Typic Calcixerepts	Akp1	0-20	53	37	9
Foraci_G	Typic Calcixerepts	Akp2	20-60	52	37	11

Table 2. Irrigation scheduling and measurement dates from 2007 to 2009.

L treatment		R treatment	
Irrigation	Measurements	Irrigation	Measurements
7 June 2007	-	7 June 2007	-
17 July 2007	18 July 2007	18 July 2007	19 July 2007
25 July 2007	26 July 2007	26 July 2007	27 July 2007
25 June 2008	26 June 2008	24 June 2008	25 June 2008
1st July 2008	2 July 2008	30 June 2008	1st July 2008
8 July 2008	9 July 2008	7 July 2008	8 July 2008
16 July 2008	17 July 2008	15 July 2008	16 July 2008
29 July 2008	30 July 2008	28 July 2008	29 July 2008
8 July 2009	9 July 2009	7 July 2009	8 July 2009
22 July 2009	23 July 2009	21 July 2009	22 July 2009
30 July 2009	31 July 2009	29 July 2009	30 July 2009

imum harvest date. According to the on-going irrigation practices aimed at improving wine quality in the Foraci vineyard irrigation scheduling was simulated in a limited time interval, ranging from July 1st to July 31st. This is the current irrigation practice adopted by the farmers to achieve a controlled crop water stress from the end of July until harvesting.

Irrigation (Ir) was scheduled by SWAP after adopting a fraction equal to 0.9 for the allowable depletion of the totally available water (TAW). Irrigation depth was calculated by using a fraction of the TAW equal to 0.45. Crop phenology was simulated by adopting a variable crop cycle based on the sum of temperatures recorded from the vegetative growth to anthesis, and then from anthesis to maturity (920 and 2500°C, respectively). A soil cover fraction of 0.5 was used to partition the reference evapotranspiration (ETo) into potential evaporation and transpiration. A root depth of 1 m was assumed, with a linearly decreasing root density distribution from top to bottom. Crop water uptake was calculated adopting the values of -1000 cm and of -16,000 cm for HLIM3 and for HLIM4 parameters (van Dam et al., 1992). Gravimetric water content (U) was determined on undisturbed soil cores sampled at 15, 30 and 60 cm in the two profiles on several dates from 21 June 2007 to 19 October 2008. Bulk density (ρ_b) was determined from the measured shrinkage curve; U and $\rho_b(U)$ were used to calculate volumetric water content, θ. Soil saturated extracts were prepared using the soil collected in the field. Soil electrical conductivity, EC_{sat}, was determined on these extracts by a conductivimeter (Micro CM 2002, Crison Strumenti, Carpi, MO, Italy).

To check accuracy of predicted θ, the root mean squared residual ($RMSR_\theta$) between measured and predicted θ values was calculated as:

$$RMSR_\theta = \sqrt{\frac{\sum_{i=1}^{N}\left(\theta_{meas} - \theta_{pred}\right)^2}{N}} \qquad (3)$$

where θ_{pred} is the predicted value, θ_{meas} is the measured value, and N is the number of measurements. To check systematic errors between measured and predicted θ, predicted values were regressed against the measured values, and hypotheses that the slope (b) of the regression line was not significantly different from 1, and that the intercept (a) of the regression line was not significantly different from 0, were checked. The Durbin-Watson (DW) test was used to check whether the random errors in the regression line exhibited autocorrelation (Crescimanno and Garofalo, 2005).

The d-index (d) (Willmott, 1981) was also calculated (Ali et al., 2000):

$$d = 1 - \frac{\sum_{i=1}^{n}\left(P_i - O_i\right)^2}{\sum_{i=1}^{n}\left(\left|P_i'\right| - \left|O_i'\right|\right)^2} \qquad (4)$$

where P_i and O_i are the predicted and observed concentrations (at a particular depth and time), respectively, and O_m is the average of all observed values. The denominator quantities are computed as $P_i'=P_i-O_m$ and $O_i'=O_i-O_m$ respectively. According to Willmott (eq. 4), a d value equal to 1 indicates perfect agreement between predicted and observed values, and a d value of 0 indicates perfect non-agreement. Between these two extremes, there are no statistically derived thresholds of acceptable agreement. The dimensionless d is a measure of model efficiency because i) it takes into account additive differences or differences in proportionality which are not taken into account by the correlation coefficient (R); and ii) it is sensitive to differences between

observed and estimated means (Willmott, 1981). For our system we assumed a d value of 0.6 as the threshold value discriminating an acceptable prediction from an unsatisfactory result. For the two soils, d values were calculated with reference to single depths (d values at 15, 30, 60 and 80 cm) to check reliability of predicted θ and EC_{sat}.

After checking accuracy of the predicted θ and EC_{sat}, the effect of climate change simulated by Pizzigalli et al. (2012) on soil water balance was predicted by application of SWAP under the soil-crop and irrigation management conditions currently practiced in the Foraci vineyard. Specifically, SWAP was applied using climatic data generated by the statistical downscaling process based on the global CGM HADCM3 for two IPCC scenarios (A2 and B1) and for the 2070-2100 time interval. The two mentioned IPCC scenarios (A2 and B1) were then compared to a third reference Baseline scenario (BASELINE) obtained by using the climatic data recorded from 1951 to 2004. The climatic parameters used were: daily minimum temperature, maximum temperature, global radiation, and rainfall. The Priestly-Taylor equation (Priestly-Taylor, 1972) was used to estimate the reference evapotranspiration (ETo).

The crop water stress index (CWSI), the irrigation efficiency (IE) and the ratio (Er) between actual evaporation (Ea) and actual evapotranspiration (Eta) were calculated by the following equations:

$$CWSI = 1 - \frac{T_a}{T_p} \qquad (5)$$

$$IE = \frac{E_a}{Ir} \qquad (6)$$

$$Er = \frac{E_a}{ET_a} \qquad (7)$$

CWSI is considered an index related to crop productivity especially in arid areas (Doorenbos and Kassam (1979).

Results and discussion

Figure 2 shows the temporal evolution of the most important climatic parameters at the monthly scale, i.e.: minimum and maximum temperatures, rainfall and reference evapotranspiration (ETo) calculated by the Priestly-Taylor equation.

For both the two future IPCC scenarios, the GCM HADCM3 showed a significant increase in the minimum and in the maximum temperature from April to December compared to the values obtained for the BASELINE. The increase was more evident for the A2 scenario, for which the average monthly maximum temperature values exceeded 35°C from June to September, being 6°C higher than those found in the BASELINE. The minimum temperatures approximately showed the same increase. The highest increase in the minimum and maximum temperatures was found from May to September. As expected, the increase in the minimum and maximum temperature was less significant in the B1 scenario than in A2: the average monthly maximum temperatures values of B1 exceeded the value of 30°C. The thermal variations compared to the BASELINE were significantly lower in the winter period than during the spring and the summer seasons.

With reference to rainfall, the A2 and B1 scenarios showed almost the same annual rainfall of about 545 mm. This value was not significantly different from that of the BASELINE (534 mm). Considering the

rainfall at the monthly scale, the same temporal pattern of the BASE-LINE was obtained for the A2 and B1 scenarios, with the rainfall concentrated in the winter and in autumn and with an arid period with almost no rainfall characterizing the summer season. The differences between the A2 and B1 scenarios and the BASELINE mainly occurred in autumn, and showed an increase. Figure 1 also reports the daily Eto averaged at monthly scale. The A2 and B1 scenarios showed the same temporal evolution of the BASELINE, except for the two first winter months. A significant increase in Eto was found for the A2 and B1 scenarios compared to the BASELINE from April to December, with a monthly increase ranging from 5% to 19% in B1 and from 8 to and 33% in A2. The soil hydraulic parameters determined for the two soils are reportd in Table 3, while Table 4 reports some information related to the simulations performed using the SWAP model. Table 5 reports values of the parameters determined to check accuracy of the predicted θ, which values were in close agreement with those measured for the two soil profiles. The *a* and *b* parameters of the equation found by regressing the predicted θ against those measured were not significantly different from 0 and 1 respectively at the 0.01 probability level except for two of the considered cases. This indicated a satisfactory match between measured and predicted θ. The d values were all higher than 0.65, with values ranging between 0.68 (one case only) and 0.88. These results confirmed that the *B-G* parameters/functions accurately represented the hydraulic behavior of the considered soil. Since no calibration was performed to adjust the estimated hydraulic properties, the good match between the measured and the simulated θ, obtained using the *B-G* soil hydraulic properties, also confirmed previous results (Crescimanno and Garofalo, 2005).

Figure 3 illustrates the agreement between the measured and the simulated θ for the two soil profiles at the depth of 30 and 60 cm. Table 6 reports values of the parameters determined to check accuracy of the predicted EC_{sat}. Prediction of EC_{sat} was less accurate than prediction of water content, θ, with RMSRECsat ranging from a minimum of 0.312 to a maximum of 0.624 dS m^{-1}. However, the *a* and *b* parameters of the equation found by regressing the predicted values against those measured were not significantly different from 0 and 1 respectively at the 0.01 probability level except for three of the considered cases. The *d* values ranged from a minimum of 0.65 to a maximum of 0.93, indicating reliable prediction. Accuracy of the predicted EC_{sat} was therefore considered acceptable and comparable with the predictive accuracy of SWAP previously investigated with reference to other Sicilian soil profiles (Crescimanno and Garofalo, 2005; 2006).

Figure 4 illustrates the simulated and the measured EC_{sat} for the two profiles at the depths of 30 and 60 cm. With reference to the impact of
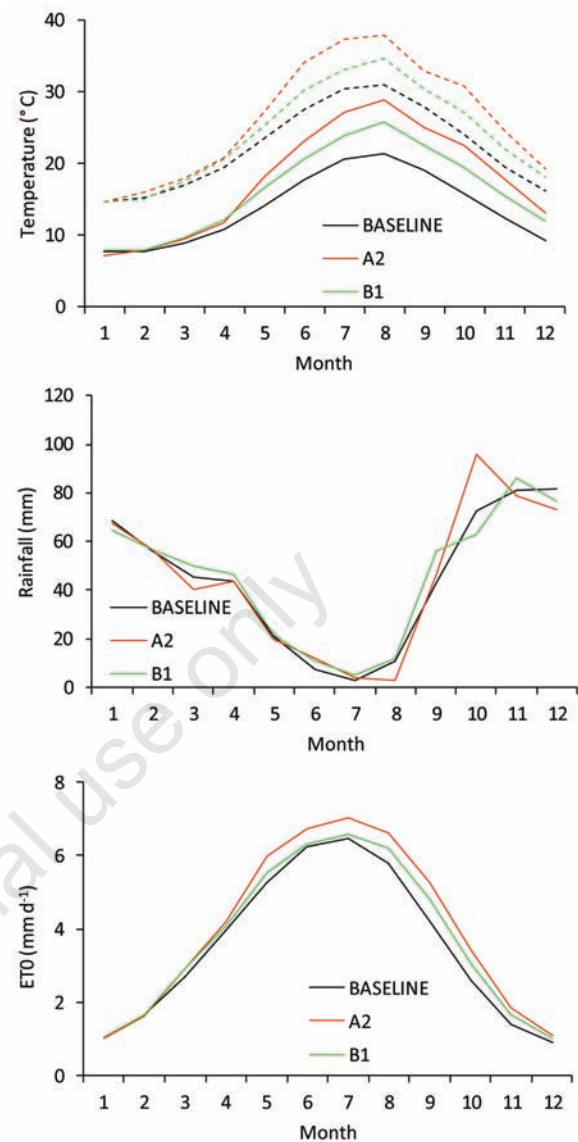

Figure 2. Effect of climate change on monthly temperature (continuous and dashed lines for minimum and maximum temperature, respectively), rainfall and reference evapotranspiration (ETo).

Table 3. Soil hydraulic parameters (B-G model).

Soil	Depth cm	K_s cm h^{-1}	θs cm^3 cm^{-3}	θr cm^{-1}	α° -	n° -	β° -	λ° -
Foraci_F	0-30	3.62	0.45	0.26	0.005	0.379	2.184	1.725
Foraci_F	30-60	0.36	0.45	0.26	0.005	0.557	1.929	1.393
Foraci_G	0-20	1.94	0.45	0.25	0.005	0.533	1.337	2.472
Foraci_G	20-60	1.44	0.45	0.25	0.001	0.363	1.169	2.554

K_s, saturated hydraulic conductivity of the soil matrix (measured value); $θ_s$ saturated volumetric water content at saturation (measured value); $θ_r$, residual water content (optimized value); °parameters of B-G model.

Table 4. Data related to the simulations performed using SWAP.

Soil	Simulation period	Lenght of simulation (days)	Total rainfall (mm)	Number of irrigations -	Total irrigation (mm)	EC (dS m^{-1})	SAR -
Foraci_F	28/06/2007 - 01/09/2009	796	1517	13	486	0.60	3.20
Foraci_G	28/06/2007 - 01/09/2009	796	1517	13	486	1.60	6.07

EC, electrical conductivity of water used to irrigate the two profiles; SAR, sodium adsorption ratio of water used to irrigate the two profiles.

Table 5. Values of the parameters determined to check accuracy of the predicted θ.

	Foraci F				Foraci G			
Depth (cm)	15	30	60	80	15	30	60	80
N	46	46	46	46	46	46	46	46
RMSE$_\theta$, (m^3 m^{-3})	0.042	0.037	0.043	0.035	0.051	0.034	0.037	0.053
b	0.72*	0.69	0.69*	0.99*	0.57	0.72*	0.66*	0.
a	0.12	0.12	0.12	0*	0.17	0.1*	0.13*	0.07*
R	0.63	0.80	0.71	0.78	0.68	0.73	0.65	0.50
m$_\theta$ (m^3 m^{-3})	0.35	0.35	0.35	0.33	0.37	0.36	0.36	0.36
d-index	0.78	0.88	0.80	0.88	0.80	0.85	0.80	0.68
DW test	1.49*	1.38*	0.71*	1.26*	1.35*	1.43*	1.03*	1.31*

N, number of measurements; RMSE$_\theta$, root mean squared residual; a, intercept of linear regression equation; b, slope of linear regression equation; R, correlation coefficient; m, average of measurements θ; d-index, index of agreement of Willmott (Willmott, 1981); DW, Durbin-Watson test. *Significance at the 0.01 probability level.

Table 6. Values of the parameters determined to assess accuracy of the predicted EC_{sat}.

	Foraci F				Foraci G			
Depth (cm)	15	30	60	80	15	30	60	80
N	46	46	46	46	46	46	46	46
RMSE$_{ECsat}$, (dS m^{-1})	0.312	0.325	0.383	0.544	0.624	0.573	0.601	0.314
b	0.87*	0.78*	1.14*	2.22	0.39	0.63	0.84*	0.96*
a	0.35	0.45*	-0.36*	-2.72	0.95	0.82	0.56*	0.08*
R2	0.94	0.85	0.78	0.89	0.68	0.84	0.71	0.87
m$_{ECsat}$ (dS m^{-1})	1.39	1.50	1.73	1.95	1.37	1.63	1.76	1.67
d-index	0.93	0.83	0.68	0.68	0.65	0.78	0.68	0.88
DW test	0.78*	1.04*	1.07*	0.81*	0.51*	0.24*	0.25*	0.74*

N, number of measurements; RMSE$_{ECsat}$, root mean squared residual; a, intercept of linear regression equation; b, slope of linear regression equation; R, correlation coefficient; m_{ECsat}, average of measurements EC_{sat}; d-index, index of agreement of Willmott (Willmott, 1981); DW, Durbin-Watson test. *Significance at the 0.01 probability level.

Table 7. Values of parameters obtained by simulating impact of climate change (climate change scenarios BASELINE, B1 and A2) using SWAP; values of the same parameters obtained by simulating impact of climate change advancing the irrigation season according to the shortening and advancing of the crop cycle length (scenarios B1-Ad and A2-AD).

Scenario	CL (d)	R	Ir	Tp	Ta (mm)	Ep	Ea	Qb	CWSI	IE -	Er
Baseline											
Mean	187.63	135.90	149.63	521.03	345.89	521.03	142.74	97.24	0.31	2.31	0.29
SD	8.19	55.01	1.70	21.26	42.74	21.26	25.15	81.43	0.17	0.29	0.03
VC	4.37	40.48	1.13	4.08	12.36	4.08	17.62	83.75	54.83	12.73	8.83
B1											
Mean	171.27	138.77	149.74	491.90	388.86	491.90	151.19	65.29	0.21	2.60	0.28
S. dev	0.98	35.27	1.55	3.90	32.73	3.90	17.01	46.73	0.07	0.23	0.02
VC	0.57	25.41	1.04	0.79	8.42	0.79	11.25	71.58	31.41	8.74	7.17
A2											
Mean	161.00	120.16	150.34	481.29	383.09	481.29	142.69	78.07	0.19	2.55	0.27
SD	1.02	35.24	2.29	5.13	44.27	5.13	19.01	45.14	0.12	0.31	0.02
VC	0.63	29.33	1.53	1.07	11.56	1.07	13.32	57.82	65.25	12.04	9.04
B1-AD											
Mean	171.27	138.77	145.15	491.90	387.70	491.90	150.31	65.04	0.21	2.69	0.28
SD	0.98	35.27	10.06	3.90	32.56	3.90	16.88	46.64	0.07	0.38	0.02
VC	0.57	25.41	6.93	0.79	8.40	0.79	11.23	71.70	30.83	14.07	7.24
A2-AD											
Mean	161.00	120.16	144.89	481.28	378.88	481.28	140.08	75.38	0.21	2.64	0.27
S. dev	1.02	35.24	9.32	5.13	44.04	5.13	19.57	44.36	0.09	0.47	0.03
VC	0.63	29.33	6.43	1.07	11.62	1.07	13.97	58.85	42.72	17.76	9.57

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climate change on soil water balance, crop stress and irrigation requirement, Table 7 reports the main results obtained by the simulations. Figure 5 illustrates the temporal evolution of the CWSI for three representative years (2004 for the BASELINE, 2080 for B1 and A2) selected for each of the simulated scenarios (BASELINE, B1 and A2). As it can be seen in Figure 5, the CWSI values obtained for the BASELINE scenario tend to increase from 0 to 1 starting from the beginning of

March until the end of June, showing some variability due to rainfall events. CWSI suddenly decreases at the beginning of July in concomitance with starting of irrigation, ranges between 0.2 and 0.4 during July and then rapidly increases in August until reaching a constant value of about 1 after August 20. The CWSI values obtained by the B1 scenario show that water stress in grapes is higher and starts before compared to results provided by the BASELINE scenario. This effect can be attrib-
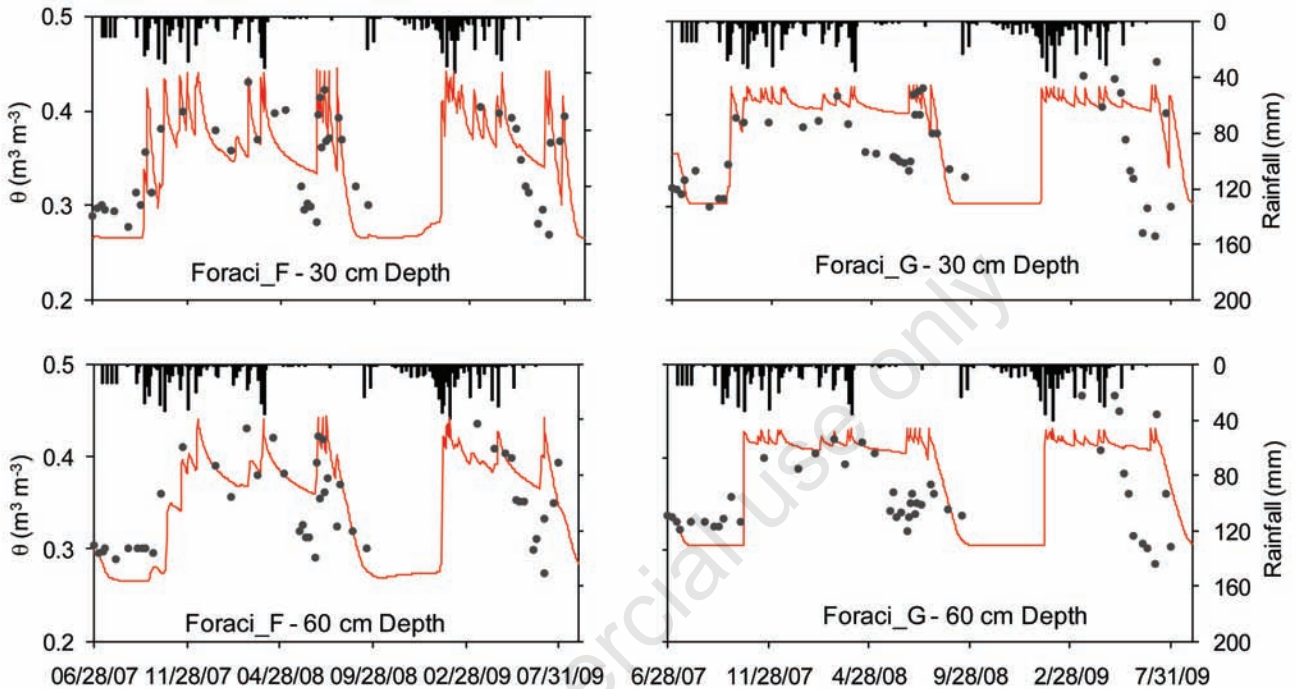
Figure 3. Water content measured and simulated by SWAP at 30 and at 60 cm in the two soil profiles.
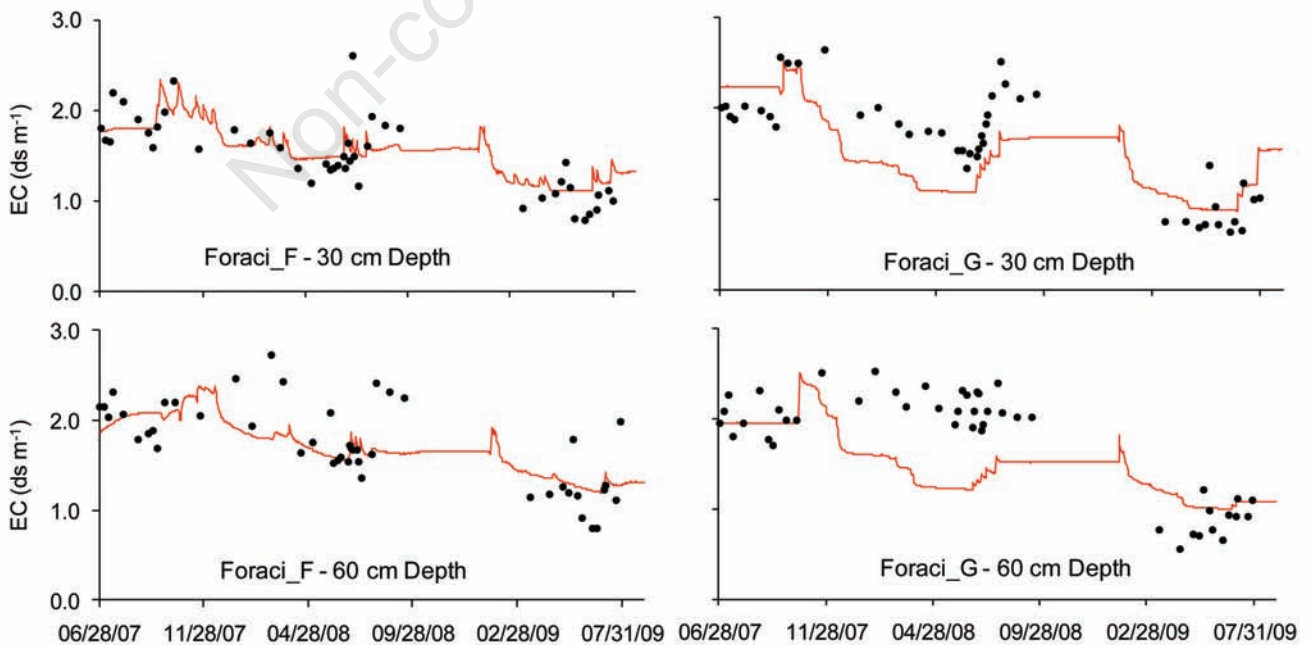
Figure 4. Agreement between simulated and measured EC_{sat} for the two profiles at the depths of 30 and 60 cm.
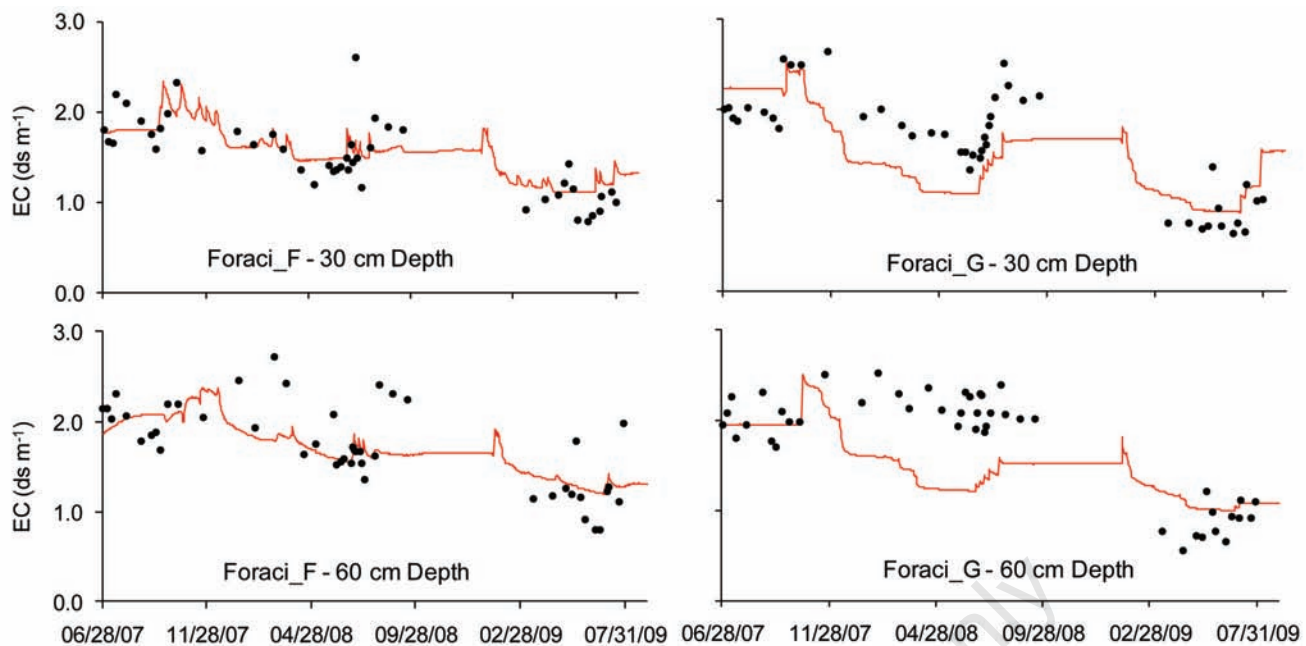
Figure 5. Temporal evolution of the crop water stress index (CWSI) for three representative years (2004 for the BASELINE, 2080 for B1 and A2) selected for each of the simulated scenarios (BASELINE, B1 and A2).

uted to the higher temperature observed in B1 compared to BASELINE. The trend observed in B1 can be observed again in A2, but in this case higher differences can be observed compared to BASELINE. The Figure also shows that three irrigation events (of about 50 mm each) were simulated by SWAP for all the three scenarios.

As it can be seen in Table 7, the crop cycle length (Cl) decreased of 16 and 27 days respectively in B1 and A2 compared to values obtained for the BASELINE scenario. As a consequence, compared to BASELINE, Tp showed a reduction of 6% in B1 and of 8% in A2. The same reductions can be observed for Ep. No significant differences were found in the Rainfall (R) considered by SWAP in B1 during the crop cycle. Instead, a reduction of 11% in R was found for A2. No significant differences were found in the irrigation amount (Ir) for B1 and A2, with an average value of about 150 mm. An increase of about 11% was found in Ta for both B1 and A2. No significant differences were found in the actual soil evaporation (Ea) for both B1 and A2. The bottom flux (Bf) showed a significant reduction for B1 and A2 (33% and 20% ,respectively). The CWSI showed a reduction of 32% and of 39% in B1 and A2, respectively, demonstrating a significant improvement in the crop water status. This significant improvement was confirmed by the increase of about 11% in the irrigation efficiency (IE) for both B1 and A2. Instead, the Er ratio remained constant and equal to about 0.28 for all the three scenarios. Considering that the main effect of the climatic scenarios B1 and A2 was to shorten the crop cycle, also advancing the phenological phases, SWAP was again applied to simulate an advance in the irrigation season of the same magnitude as the advance in the crop cycle (15 and 20 d for B1 and A2 respectively). The results obtained by these further simulations can be considered to provide a sort of adaptation strategy for the vineyard in terms of irrigation management that could be adopted by the farmers to deal with the impact of climate change on agriculture in the future.

The results, also reported in Table 7 and named B1-AD and A2-AD, indicated that advancing the irrigation season did not determine significant changes in Ta, Ea, Fb, CWSI, IE and Er (comparison between between B1 and B1-AD, and between A2 and A2-Ad). This means that in the future farmers might modify the irrigation starting time(s) in order to avoid significant reduction in the crop productivity.

Conclusions

The SWAP model applied to two Sicilian profiles provided a satisfactory prediction of water content, θ, as well as of electrical conductivity of soil saturated extract, EC_{sat}. These results confirmed that accurate simulation of water and solute transport can be obtained by the SWAP model if the soil hydraulic parameters have been accurately determined and represented. SWAP can be considered a reliable tool to be used to simulate management strategies and options. The main impact of climate change, as simulated by application of SWAP, was to shorten and advance the crop cycle. Since this effect counterbalanced the increase in the evaporative demand of the atmosphere predicted for the future by the climate change models, the irrigation requirement simulated by the model did not increase, remaining almost constant.

The simulations also showed that CWSI values tended to decrease in the future as an effect of climate change. This was the consequence of an increase in Ta and of a decrease in Tp due to crop cycle shortening. Should these simulated results reflect the reality for the future, farmers would probably advance the irrigation season of about 15-20 days as an adaptation strategy to climate change.

According to our results, application of this practice should make it possible not to determine negative effects on productivity. This information might be relevant not only for farmers but only for decision makers and irrigation networks.

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