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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

Olive yield and future climate forcings

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Abstract

The rainfall reduction and the temperature increase forecasted for Mediterranean regions would likely increase the vegetation water stress and decrease productivity in rainfed agriculture. Olive trees, which have traditionally been grown under rainfed conditions, are one of the most characteristic tree crops from the Mediterranean not only for economical importance but also for minimizing erosion and desertification and for improving the carbon balance of these areas.

In order to simulate how climatic change could alter soil moisture dynamics, biomass growth and fruit productivity, a water driven crop model is used in this study.

The model quantitatively links olive yield to climate and soil moisture dynamics using an ecohydrological model, which simulates soil moisture, evapotranspiration and assimilation dynamics of olive orchards. The model is able to explicitly reproduce two different hydrological and climatic phases in Mediterranean areas: the well-watered conditions and the actual conditions, where the limitations induced by soil moisture availability are taken into account. Annual olive yield is obtained by integrating the carbon assimilation during the growing season, including the effects of vegetation water stress on biomass allocation. The numerical model, previously calibrated on an olive orchard located in Sicily (Italy) with a satisfactory reproduction of historical olive yield data, has been forced with future climate scenarios generated using a stochastic weather generator which allows for the downscaling of an ensemble of climate model outputs. The stochastic downscaling is carried out using simulations of some General Circulation Models adopted in the IPCC 4AR for future scenarios. In particular, 2010, 2050, 2090 and 2130 scenarios have been analyzed.

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Keywords: Olive yield; climate change; crop model;

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1. Introduction

The production of olive tree crops is dependent on water availability given by the winter rainfall, which replenishes soil moisture, by the rare summer events or by the irrigation. This is particularly true in the Mediterranean area where the climate is typically characterized by high potential evaporation and low rainfall during the summer. Olive is a xerophytic plant which is considered one of the best adapted species to the semiarid environment [1], although, under these conditions, it usually shows a decrease in photosynthesis that limits growth and yield. Viola et al [2] and Pumo et al [3] showed how the rainfall reduction and the temperature increase forecasted for Mediterranean regions will likely increase the vegetation water stress.

Given these premises, this work aims to investigate how climate change could affect olive yield using a crop model that has been recently proposed for simulating the olive biomass and yield in response to the soil water availability dynamics in both rainfed and irrigated conditions [4]. The model is structured to deal with external climatic forcing and provide as results soil moisture and biomass dynamics, making it suitable for the simulation of the behavior of olive orchards in future climatic scenarios.

The model distinguishes between two different levels: the so-called “well watered conditions” and the “water-stressed conditions”. First, potential evapotranspiration and assimilation are evaluated without water availability limits and then the constraints of soil moisture dynamics are taken into account in case of water stress. Daily evapotranspiration under well-watered conditions is calculated with the Penman-Monteith equation [5], in which the canopy stomatal conductance is calculated through the Jarvis' empirical formulation [6] using a multiplicative relationship; this relationship takes into account solar radiation, atmospheric temperature, potential saturation deficit, and CO_2 concentration. The coupled Farquar model [7] allows calculating the assimilation in well-watered conditions. Evapotranspiration and carbon assimilation are represented by a strong nonlinear function of soil moisture [8; 9]. Using a daily stepwise function which relates soil moisture condition to actual evapotranspiration, and assuming that the same relation is also valid for the assimilation process, the actual evapotranspiration and the assimilation as a function of climate and soil moisture conditions can be then evaluated. Assimilation is then integrated over the entire growing season obtaining the total biomass. The knowledge of the soil moisture dynamics throughout the growing season allows the model to evaluate the vegetation water stress which, in turn, affects the amount of biomass allocated in fruits, namely olive yield, by the harvesting index. Full details about model components and parameters values are reported in Viola et al [4].

In order to assess future productivity, a preliminary evaluation of the future climate scenarios is necessary. Precipitation and temperature data have been downscaled from an ensemble of climate model outputs, using the AWE-GEN weather generator [10]. The stochastic downscaling methodology allows one to derive the distributions of factors of change that are calculated as ratios (for the precipitation) or ‘‘delta’’ differences (for the temperature) of climate statistics for historical and future periods. More specifically, a set of factors of change is computed at the station level to reflect changes in the mean monthly air temperature and several statistics of precipitation (e.g., mean, variance, skewness, frequency of no-precipitation) at different aggregation periods, as a result of comparing historical and predicted climate. The factors of change derived from a general circulation model (GCM) realization have been subsequently applied to a set of statistics of an observed climate in order to obtain statistics representative of future climate. Using these statistical properties, an updated set of AWE-GEN parameters is estimated. Each set of AWE-GEN parameters is calculated assuming climate stationarity for any considered period. The re-parameterized weather generator has been used to simulate hourly time series of hydro-climatic variables that are considered to be representative of the predicted climate. In this study, realizations from twelve GCMs, for future scenarios 2046-2065 and 2081-2100, are used in all of the analyses. These models represent a subset of GCMs used in the fourth assessment report (4AR) of the IPCC [11]. The realizations correspond to the A1B emission scenario (IPCC, 2000).

2. Case study

The case study is the same of the one presented in Viola et al [4] which is a 19 ha olive orchard located in Trapani in the southern Italy (37°55’N, 12°30’E), where the model has been calibrated on olive yield data collected for a long period from the farm owner. The considered area is almost flat, according to the assumption of the absence of lateral redistribution of soil moisture and the soil is clayish with porosity equal to 0.5 measured in the field. The rooting-deep has been set equal to 100 cm, as was observed in a trench, that is a common value for olive trees. The cultivars are “Nocellara del Belice” and “Cerasuola”. The orchard is cultivated in rainfed conditions and composed by mature plants, spaced 6 x 6 m, resulting in a vegetation cover of 40%.

Climatic data necessary for the model implementation have been registered from SIAS (Servizio Informativo Agrometeorologico Siciliano) from January 2002 to December 2012 in the Trapani Fulgatore station (37.9475N°, 12.6614E°, 180 m a.s.l.). Climatic data have been used for the characterization of the baseline and for the downscaling of the GCM model.

Four climate scenarios have been investigated, namely 2010, 2050, 2090 and 2130. For each of the considered scenario, 50 years of rainfall, solar radiation, temperature, relative humidity and wind speed have been generated using the AWE-GEN model at hourly time scale. Changes of solar radiation, relative humidity and wind speed are not a direct consequence of the calculated factors of change, but are only due to statistical and casual relationships assumed by the weather generator. No variation in CO_2 concentration has been considered. Since the crop model works at daily time scale, data have been aggregated, allowing model runs. In Table 1 mean values for the considered scenarios are reported. The main facts characterizing climate scenarios are the rainfall reduction (30% less in 120 years) and the temperature increase (3°C in 120 years).

Table 1. Mean values for climatic scenarios generated by the AWE-GEN model.

	2010	2050	2090	2130
Rain [mm/y]	649	570	526	448
Solar radiation [W/m^2 d]	207	209	212	213
Mean Temperature [C°]	18.7	19.7	20.9	21.8
Relative umidity [%]	65	62	60	58.1
Wind speed [m/s]	1.51	1.52	1.53	1.55

Also olive productivity records for the Trapani province are available from ISTAT (Italian Institute for STATistics) in the period 1999 to 2012. These data have been analyzed in order to obtain the productivity baseline for a wider area, which consists of almost 25.000ha of olive orchards. The current mean olive yield is about 26 ql/ha with a minimum of 16, a maximum of 40 ql/ha and a standard deviation of 7 ql/ha.

3. Results

Soil moisture dynamics are evaluated for each scenario using the soil characteristics and daily climatic forcing as given by the AWE-GEN model. Each scenario consists of 50 years and therefore can be considered as a stationary scenario englobing only the interannual variability. In order to simulate the soil moisture evolution it has been assumed that the initial value is close to the field capacity and, since the simulation starts at the beginning of January, this assumption can be considered realistic. Moreover, it is worth emphasizing that the choice of initial value does not significantly influence the final results.

Actual evapotranspiration and assimilation have been calculated at daily time scale as a function of soil moisture, as shown in Figure 1 for the 2090 scenario where a limitation induced by water stress especially during summer periods is evident. In particular, it is possible to observe that at the beginning of the growing season, when soil moisture is still high because of the winter recharge, the evapotranspiration and the assimilation are almost at their maximum level. Proceeding toward the summer, the initial soil moisture is depleted and the evapotranspirative demand continues to grow, causing an increasing gap between the potential and actual evapotranspiration and assimilation. Olive trees reduce their activity under such conditions, namely in August [12]. Usually at the beginning of September, the first autumn rainfall events occur increasing the soil moisture content; in this way trees can finalize the process of fruit development without water limitations. This alternation of dormancy and activation as a function of solar radiation and soil moisture availability made, as mentioned above, the olive tree one of the best adapted species in Mediterranean ecosystems.

It is interesting to calculate the mean annual values of potential evapotranspiration and assimilation and compare them with the actual values limited by water availability. As climate forcings change, also potential evapotranspiration and assimilation vary. In the four considered scenarios, because of the temperature increase and relative humidity decrease, the atmospheric water demand increases, thus increasing the value of potential evapotranspiration, up to the 5% in 120 years, as showed in Table 2. At the same time also potential assimilation increases, up to 12% in 120 years, being intimately linked to transpiration. The influence of CO_2 concentration increase has not been included in this study, although it is recognized to be an important factor in reducing potential evapotranspiration [13].

The reduced rainfall input is reflected in soil moisture dynamics and, in turn, it affects actual evapotranspiration and assimilation rates. Because of the water availability reduction, also actual evapotranspiration and assimilation are reduced, moving from the current scenario to the 2130. Actual evapotranspiration shows a reduction from about 500 mm to 350 mm, while assimilation is reduced by 15% in 120 years.

Integrating actual assimilation over the vegetative growth period, which lasts for 5 months from June to November [12], it is possible to evaluate olive yield for each year within the considered scenario. Figure 2 shows the model outputs in the four considered scenarios. Because of the stochastic inputs, also the model outputs result as stochastic series with pronounced interannual variability. From the observation of the olive yield time series is already visible a clear reduction from the 2010 to the 2130 scenario.

Average values of olive yield obtained in the four considered scenarios are reported in Table 2. Simulated olive yield amounts to 27 ql/ha in the 2010 scenario (baseline) and progressively decreases to 19 ql/ha in the 2130 scenario. The 30% reduction in 120 years reflects the rainfall reduction (30%) by the soil moisture limitation to transpiration (actual evapotranspiration is reduced of 28%) and assimilation over the growing season (27%).

The model has been calibrated over historical olive yield measures and consequently is representative of a specific orchard, with a specific soil, vegetation cover, etc. Notwithstanding that, it provides for the 2010 scenario an average productivity very close to the one provided from the statistical analysis carried out on the ISTAT data relative to the Trapani province making the obtained results representative of the northwestern part of Sicily.

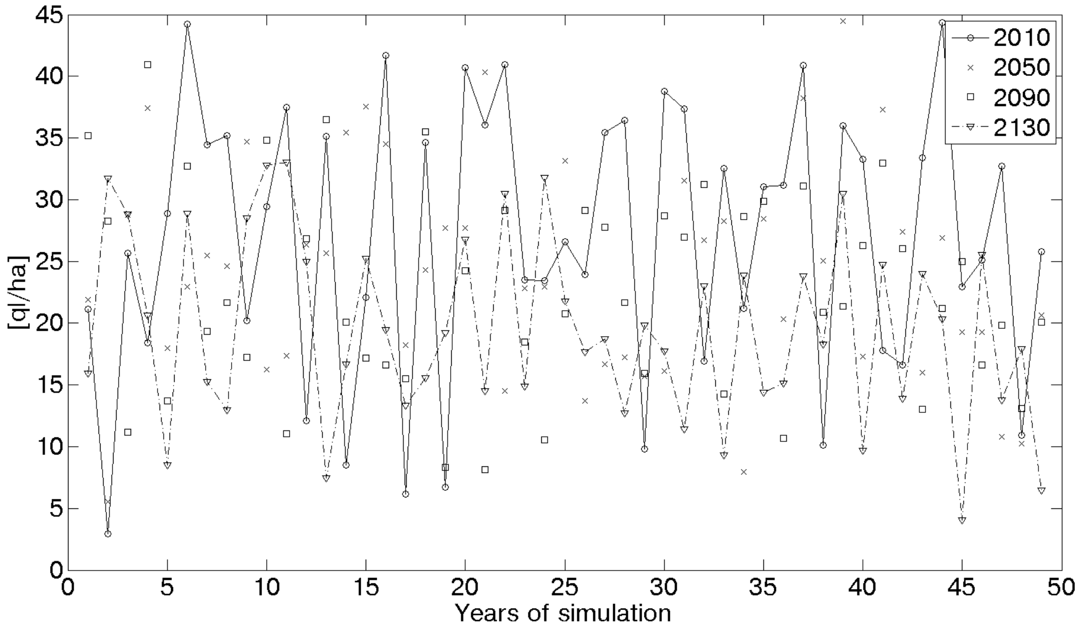

Fig. 2. 50 years of modeled olive yield in the four considered scenarios.

The model results indicate a likely reduction in productivities. A simple market analysis made assuming currtent price for the olive and based on these model results shows a reduction of about 65M€ in the gross income for the Trapani province in the next 120 years. Such information could give the opportunity to economically evaluate the feasibility of stress-avoidance irrigation systems making the proposed model a valuable tool for farmers and managers to assess the value of rainfed versus irrigated cultivation.

Table 2. Modeled mean annual values in the four considered scenarios

	2010	2050	2090	2130
Potential ET [mm/y]	1135.15	1149.75	1171.65	1186.25
Actual ET [mm/y]	492.75	452.60	423.40	350.40
Potential Assimilation [mol/m2]	0.80	0.84	0.88	0.90
Actual Assimilation [mol/m2]	0.35	0.34	0.33	0.30
Olive yield [ql/ha]	26.96	24.08	22.57	19.51

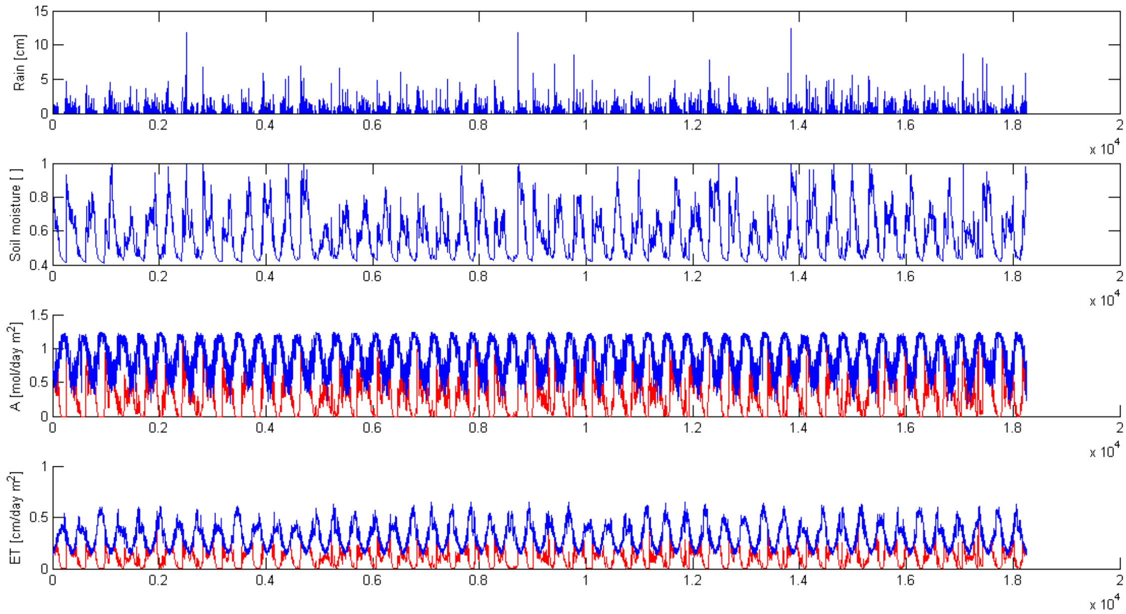

Fig. 1. 50 years of stochastic rainfall and soil moisture series in the 2090 scenario. The two bottom rows show the comparison between potential (blue lines) and water limited (red lines) assimilation and evapotranspiration.

4. Conclusions

The interrelations between olive yield and future climate scenarios have been investigated in this study. The ecohydrological model used here emphasizes the fundamental processes involved in crop productivity and the dependencies on water deficits, both from a physiological and an agronomic perspective. Evapotranspiration and assimilation have been assessed as a stepwise function of soil moisture at daily time scale. Integrating assimilation rates over the olive growth period, olive yield has been obtained in four future scenarios. Climate data have been downscaled from an ensemble of climate model outputs, using the AWE-GEN weather generator.

Results show significant reductions in olive yield for the considered scenarios as a consequence of rainfall reduction and temperature increase. The diminished water input affects soil moisture dynamics, which, in turn, limit evapotranspiration and assimilation, notwithstanding the latter have an higher potential rate because of the temperature and the vapor water demand increase. The loss, in productivity terms, may be considered representative for a wide area located in the North-West of the island. In the next 120 years the model predicts an olive yield reduction of 8 (27-19) ql/ha, which could result in a 30% gross income loss for farmers in the considered area.

Further analyses are necessary in order to include the effects of CO_2 concentration increase in plant evapotranspirative and assimilation processes. These are expected to reduce the water stress induced by water availability, thus the preliminary results discussed here may represent the extreme condition or a condition in which olive trees do not operate physiological adaptation to changing environmental conditions.

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