Published in:

European Journal of Agronomy (2021) 129: 126319

https://doi.org/10.1016/j.eja.2021.126319

Sustainability of olive growing in the Mediterranean area under future climate scenarios: exploring the effects of intensification and deficit irrigation

Hanene Mairech[a,b,*], Álvaro López-Bernal[c], Marco Moriondo[d], Camilla Dibari[d,e], Luca Regni[b], Primo Proietti[b], Francisco J. Villalobos[a,c], Luca Testi[a]

[a] Department of Agronomy, Institute for Sustainable Agriculture, Spanish National Research Council (ISA-CSIC), Avenida Menéndez Pidal s/n, Campus Alameda del Obispo, 14004 Cordoba, Spain

[b] Department of Agricultural, Food and Environmental Sciences (DSA3), University of Perugia, Via Borgo XX Giugno 74, 06121 Perugia, Italy

[c] Department of Agronomy, Plant Production Area, ETSIAM, University of Cordoba, Campus Rabanales, 14071 Cordoba, Spain

[d] Institute of BioEconomy, Italian National Research Council (IBE-CNR), Via Caproni 8, 50145 Florence, Italy

[e] Department of Agricultural, food, environmental, forestry sciences (DAGRI), University of Florence, Piazzale delle Cascine 18, 50144 Florence, Italy

* Corresponding author: mairech.hanene@gmail.com

ABSTRACT

Olive orchards represent a key agricultural system with high economic and environmental prominence. Expected future climate tendencies over the Mediterranean could threaten the sustainability of such strategic tree crop. This study evaluates the productive and environmental performance of olive orchards under different climate change scenarios and management strategies across the main olive-farming regions over southern Europe using the process-based model OliveCan. Simulations were performed for low density LD (100 trees ha^{-1}), high density HD (400 trees ha^{-1}) and super high density SHD (1650 trees ha^{-1}) olive orchards over baseline period (1980-2010) and future scenarios (2041-2070 and 2071-2100 for RCP4.5 and RCP8.5). Results showed that the future increase in CO_2 concentration may compensate the negative effects of higher evaporative demand and diminished water supply resulting in an enhancement of water use efficiency and carbon capture potential in olive orchards. Irrigation requirement for the maximum productivity are expected to increase by 5-27%. Moreover, rainfed low density orchards will be the most vulnerable to expected climate changes, in particular in the driest areas. In fact, a decrease in yield up to 28% with an increase in its interannual variability of 20% is expected over the Iberian Peninsula while yield increased up to 26% over the centre of the Mediterranean. Deficit irrigation and intensification will improve olive orchard productivity and carbon sequestration capacity. Besides, the decrease in winter chilling is not expected to be enough to produce significant flowering anomalies or failures over the study area. Even though findings of this research showed that olive orchards may benefit from future conditions, assessment of management alternatives at local scale will be a must for a better adaptability of olive orchards.

Keywords:

Olea europaea; Climate change; Agricultural management; Productivity; Carbon sequestration; Sustainability

1. Introduction

The Mediterranean, renowned as a climate change hotspot, is one of the most responsive areas to global warming (Giorgi 2006; IPCC 2013). Long-term climate projections provided by the fifth report of the Intergovernmental Panel on Climate Change (IPCC) foresee a global warming increase of 1.5-2 °C within the 21st century (IPCC 2013). Several changes in climate with high regional variability are expected. Over the Mediterranean, most climate change scenarios predict an increase in temperature and a decrease in rainfall (Giorgi and Lionello 2008; Gualdi et al. 2013; Stocker et al. 2014) with a higher frequency of extreme events (Hertig et al. 2013). These predicted climate changes imply potential consequences on natural resources and on agricultural performance.

Olive (*Olea europea* L.) orchards are the most extended perennial agroecosystem in the Mediterranean basin. Over 10.8 Mha are cultivated worldwide, 95% of which are in the Mediterranean region (FAOSTAT, 2017). Olive cultivation plays an important economic and environmental role for the area (Tous and Ferguson 1996; Moriondo et al., 2013; Ponti et al., 2014; Montanaro et al., 2017). The ability of olive plantation to sequestrate carbon has been a subject of consensus (Proietti et al., 2014; Proietti et al., 2016; Proietti et al., 2017; Brilli et al., 2016; Regni et al. 2017; Massaccesi, et al. 2018; Mairech et al. 2020) reflecting their potential to mitigate carbon emission

Even though olive is assumed to be resistant to drought (Connor and Fereres, 2010), climate changes may increase the frequency and severity of such events (Tanasijevic et al., 2014). Some studies have projected higher net irrigation requirements, yield decrease and shifting of phenological phases for olive in the Mediterranean region at the end of the 21st century due to the increased heat and water stress (Koubouris et al., 2009; Rodríguez Díaz et al., 2007). Potential changes in rainfall and evapotranspiration may reduce olive yield (Moriana et al. 2003; Iniesta et al., 2009). Spring and summer rainfall and both maximum and minimum temperatures in summer and autumn could affect final fruit production (Galán, 2008; Rossi et al., 2020). The expected increase in temperature could influence the developmental cycle of olive trees (De Melo-Abreu et al., 2014) and could result in an advance in olive flowering date (Gabaldón-Leal et al. 2017) or even lead to sterile years for olive due to the lack of vernalization (Morales et al., 2016). Tanasijevic et al., (2014) and Moriondo et al., (2013) predicted a gradual northward shift of olive cultivation areas in the coming decades. In the context of global warming, these implications of climate changes pose considerable challenges to maintain olive cultivation sustainability and improve their productivity and environmental performances.

Olive productivity is not influenced by climate factors only but by management too. During the last decades, olive growing has known substantial changes in the structure and management aiming at improving productivity and profitability. New planting systems along with irrigation and mechanization are pervading the traditional rainfed olive groves (Proietti, et al. 2012). The diversity of olive orchards management types in the main growing areas has thus increased. In recent years, intensification techniques have been extensively adopted. Nowadays, olive orchards structure varies from traditional orchards with widely spaced trees (usually 50 to 160 trees ha^{-1}) to hedgerow orchards with densities of 1200-2500 trees ha^{-1} (Caruso et al. 2014). This new structure of olive plantation differs from predominant traditional ones in term of performance and adopted techniques (irrigation, fertilization, mechanical harvesting and pruning). The requirements and quick adoption of these intensive management types casts doubts about their sustainability in the future. The same happens with the conversion of already-existent rainfed orchards to irrigation. Assessing the implications of climate change on these various cultivation systems in the future is crucial for the sustainability of olive sector.

Investigating olive grove responses to external forcing is highly complex due to the variability of environments around the Mediterranean and the large diversity of planting systems (structure and management). Hence, conducting this assessment depends on the ability to simulate such complex system since replicating future conditions in the field for different combinations of orchard type, soil characteristics and sub-climate is deemed implausible. In this regard, crops models are essential tools to investigate the relationship between crop productivity and climate change. In particular, process-based models are able to simulate crop physiology under different environmental conditions. Some models are designed to be responsive to climate change by simulating not only the impact of variations in temperature and precipitation but also to include the increased CO_2 concentration according to the simulated future scenarios (Moriondo et al. 2015).

Several studies have addressed the impacts of climate change on olive orchards either on local or regional level such as the Mediterranean (Rodríguez-Díaz et al., 2007; Tanasijevic et al., 2014; Brilli et al. 2019; Lorite et al., 2018; Fraga et al. 2019). Some were based on statistical approaches quantifying potential changes in water requirements and yield due to changes in temperature and rainfall (Rodríguez-Díaz et al., 2007; Tanasijevic et al., 2014). These simplified approaches neither accounted for the impacts of such variations on the physiology of olive trees nor considered the positive effect of the expected increase in the atmospheric CO_2 concentration in the future. Lorite et al. (2018) used a simplified physically based model to assess olive orchard behaviour under future conditions. Even though the increase in CO_2 concentration was considered, this approach did not include physiological processes relative to olive cultivars adaptation to environmental stress (e.g. heat stress impacts on flowering and chilling requirements, impacts of CO_2 on stomatal conductance). Other studies adopted a dynamic approach using process-based models. Brilli et al. (2019), for example, used an adapted version of a biogeochemical model (DayCent) but limited his analysis to spot areas across the Mediterranean basin. Fraga et al. (2019) did use a dynamic approach accounting the increase in CO_2 concentration, but the process-based model used in their study (Viola et al., 2012) does not simulate a dynamic biomass allocation (partitioning at organs level) nor a three-dimensional shape of the canopy, factors with high importance in the context of climate change for a better representation of carbon assimilation and water balance. Regardless of the different level of sophistication in the modelling approach, none of these studies did investigate, in a thorough analysis, the effects of modern farming techniques such as irrigation or intensification, which future implications under climate change conditions remain still unknown despite the popularity they have already acquired.

Given the prominence of olive cultivation in the Mediterranean, a detailed analysis of the combined impacts of future climate changes and farm management on olive orchards productivity and environmental performance is required. In this context, López-Bernal et al. (2018) have formulated a process-based model, OliveCan, capable of simulating the impact of environmental conditions (including water deficit) and management practices on the water relations, carbon assimilation, growth and productivity of olive orchards. OliveCan simulate the canopy in a three-dimensional geometry considering the different types of orchard structure. Biomass allocation follows a dynamic approach of assimilates partitioning at organs level. This enables the comprehension of olive orchard dynamics under heterogeneous conditions of climate and agricultural practices and hence the identification of appropriate farming practices able to improve olive groves sustainability for specific environmental scenarios.

A first question regarding the future sustainability of olive is how climate change (CC) will affect its productivity and its capacity for carbon capture. Current technological trends (adoption of hedgerow systems and conversion to irrigation) should also be evaluated in the context of CC. Finally, adaptation of olive orchards phenology by change in cultivars may be required.

Therefore, we tried to address the following questions:

I. How will olive productivity change under CC?
II. Are olive irrigation requirements going to increase in the future?
III. How will olive orchards perform under actual irrigation supply in the future?
IV. Will irrigation of new intensive orchards become unsustainable under CC?
V. Should olive varieties be changed?

The questions raised above were approached with simulation experiments using the model OliveCan for the main olive growing areas around the Mediterranean.

2. Materials and methods

2.1. Climate data

Future climate is partly determined by the magnitude of future emissions of greenhouse gases (GHG) forcing. A range of assumptions about the magnitude and pace of future GHG emissions are formulated in a set of scenarios entitled Representative Concentration Pathways (RCPs) (IPCC, 2014). We used an intermediate and a very high GHG concentration scenarios, RCP4.5 and RCP8.5 respectively. RCP4.5 is a stabilization scenario where CO_2 emissions are projected to increase until the mid-21st century, soothing afterwards. In contrast, RCP8.5 is characterized by a continuous increase in CO^2 emissions until the end of the 21st century (IPCC, 2014). The outputs of GUF-CCLM4 Regional Circulation Models (RCM, 0.44°x0.44°) for RCP4.5 and RCP8.5 were statistically downscaled using a Delta change approach over observed daily data which were obtained starting from an EOBS gridded dataset (Moreno and Hasenauer, 2015) for the period 1980-2010 according the procedure described in Mairech et al. (2020). Basically, the original dataset, consisting of 5700 grid points (10Km x 10Km) over the Mediterranean basin including daily minimum and maximum temperatures (Tmin and Tmax, °C), global radiation (Rad, MJm^{-2}), cumulated rainfall (R, mm), wind speed (WS, ms^{-1}) and relative humidity (RH, %) was clustered by aggregating each grid point according to the relevant affinity to a set of climatological indexes. This process identified 22 homogeneous climatic regions across the basin, within which daily data were obtained by averaging the weather variable of the respective grid points according to Mairech et al. (2020).

According to Delta change approach procedure, the biases or random model errors of RCMs are removed by calculating the monthly differences of the considered meteorological variables between a baseline and future time slices (delta change). This difference is then added to the relevant observed data to produce an unbiased dataset describing future climate. In our specific case, the monthly differences in Tmin and Tmax (absolute difference), R (ratio), RAD (ratio), WS (ratio) and RH (ratio) between the baseline (1980-2010) and two future time slices (2041-2070, 2071-2100) of GUF-CCLM4 were calculated for each RCM grid point over the basin and then averaged over the relevant 22 clustered regions. Finally, these deltas were applied, month by month, over the respective daily dataset, where Tmin and Tmax were summed up and the remaining parameters were multiplied. The resulting datasets were then used for feeding the simulation of OliveCan for future periods.

2.2. OliveCan description

A detailed description of the model is given by López-Bernal et al. (2018). In brief, OliveCan is a process-based model of olive trees. The model simulates the main components of the water and carbon balances of olive orchards and enables the user to assess the impacts of environmental conditions and management operations on tree growth, development and yield, both under potential and water-limiting conditions.

The water balance module in OliveCan is derived from a previously developed approach that considers the soil heterogeneity due to localized irrigation: a fraction of the soil surface is kept wet while the remaining part is dependent on rainfall (Testi et al., 2006). Water balance is simulated for the two soil compartments. Each soil zone is subdivided in a number of layer defined by the user. Fluxes of effective precipitation, runoff, drainage, water redistribution, and root water uptake are computed for each soil zone and layer. Soil evaporation and direct evaporation of rain water intercepted by the canopy are also considered. The model considers the canopy divided in two fractions: sunlit and shaded. For each fraction, gross assimilation, stomatal conductance, intercellular CO_2 concentration and leaf water potential are computed. The model is therefore able to couple water and carbon balances through leaf water potential and stomatal conductance. The model requires explicitly the environmental CO_2 concentration and computes the intercepted photosynthetically active radiation according to the canopy geometrical structure, leaf density and size.

The carbon balance module simulates the growth and development of the tree and the carbon exchange of the orchard by computing the different fluxes of C assimilation and respiration in the tree and soil. The model allocates assimilates, at organs level (leaves, shoots, branches, coarse roots, fine roots and fruits), which are routed to organs growth and respiration (maintenance respiration and growth respiration). Photosynthesis is calculated with a combination of Farquar (1980) and Leuning and Tuzet (2003) models that makes it correctly responsive to atmospheric CO_2 concentration and to the stomatal behaviour induced by water stress. Flowering date is simulated according to the model of Melo-Abreu et al. (2004) that takes into account two stages which duration depend on temperature. The first stage corresponds to the accumulation of chilling units (CU) enabling the tree buds to overcome dormancy while the second stage requires a given thermal time to reach flowering. Fruit photosynthesis and remobilization of CO_2 assimilates are also taken into account. The balance of C in the soil is computed by adding the inputs (i.e. senescence of fine roots, fall of leaves due to frost damage and senescence and incorporation of pruning residues) and subtracting the outputs (heterotrophic respiration) of C to/from the system. Finally, after computing all fluxes of assimilation and respiration between the orchard and the atmosphere, OliveCan provides net ecosystem productivity (NEP).

The model requires weather, soil, environmental and orchard management inputs. Maximum and minimum air temperatures, average vapour pressure, solar radiation, average wind speed, and precipitation are input at daily time step. The CO_2 atmospheric concentration is also specified by the user: it can be either a fixed concentration or a variable calculated by the model as a function of the year. A fit to Mauna Loa Observatory CO_2 measurement (Keeling et al., 1976; Thoning et al., 1989) or CO_2 concentration projections of the Representative Concentration Pathways (RCP4.5 and RCP8.5) spanning the range of year 2100 (Moss et al. 2010) are used. Soil characteristics include the water contents at field capacity, wilting point and saturation and hydrological condition (an indicator of the capacity of infiltration of the soil when it is wet) according to the method of Soil Conservation Service (US-SCS)), bulk density and pH. Besides, the initial values of water and carbon contents for each soil compartment and soil layer are to be defined. Planting density, row orientation, latitude and initial values of age, ground cover and leaf area density are set for each orchard typology.

The management operations considered by the model are irrigation, tillage, harvesting and pruning. Different pruning intensities can be simulated through a customizable parameter representing the fraction of Leaf Area Index removed in each operation. The user is also required to decide whether the residues are exported from the field or chipped and incorporated into the top soil layer. Irrigation may be input by the user or calculated by the model as a fraction of the evapotranspiration (ET) lost since the last irrigation event.

The model is capable to function at different user-defined time steps (from minutes to 1 day). All the simulations performed in this work were set at daily time step.

2.3. Soil characteristics

We used a single soil type in all clusters as a representative of the soil existing in traditional most common olive groves within the Mediterranean basin. We chose a medium texture soil of 1 m depth. Soil water content at the permanent wilting point, field capacity and saturation were set to 0.10, 0.21 and 0.31 $cm^3\ cm^{-3}$ respectively. pH was set at 8.5 and bulk density at 1.5 $g\ cm^{-3}$. Soil organic carbon was initialized at 0.7%.

2.4. Orchard types and management

Three main olive groves types were considered for the simulations: low density LD (100 trees ha^{-1}), high density HD (400 trees ha^{-1}) and super high density SHD (1650 trees ha^{-1}) under no tillage and no cover crop. For each level of intensification, we assigned the orchard characteristics and management parameters shown in Table 1. Initial state of the canopy dimension (fraction of ground cover) is set for each orchard typology. Simulations are performed without re-initialization following a dynamic approach reflecting evolution of vegetative growth and hence changes in canopy dimension. In terms of water supply, rainfed, deficit and full irrigation were simulated. For each orchard type and for each climate cluster, irrigation requirements were calculated by the model. Irrigation was scheduled every two days during an irrigation season lasting from May 15th to October 10th. Harvesting was set on December 11th for actual climate. A preliminary simulation under future climate conditions showed that an advance in the flowering date is expected. This implies an increase in the length of the fruit filling period. To avoid any resulting bias in potential yield between reference and future simulations, we advanced the date of harvesting by the same number of days of anticipation in flowering for each cluster and for each future simulation. Pruning was simulated by removing a fixed fraction of the canopy biomass 10 days after harvest. The fraction of pruning and the pruning intervals were pre-defined for each orchard type (Table 1).

2.5. Simulation experiments

The simulation experiments were performed with OliveCan for recent past and for future climates. We considered the reference period 1980-2010 as a baseline for our analysis. Knowing the heterogeneity of environmental conditions existing in our study area we adopted some assumptions (i.e. use of a single soil type and clustering climate data) in order to reduce the complexity of our methodology and highlight the impact of only climate and agricultural management on olive orchard dynamics. Thus, the goal of our analysis was not a precise prediction of olive yield across the Mediterranean Basin but rather an estimation of the relative magnitude and direction of yield and water need changes for olive under projected climate conditions across the Basin. Therefore, all impacts of future climate change on olive orchards were evaluated as deviations between the baseline case (1980-2010) and two future periods (2041-2070 and 2071-2100) across all clusters.

HD and SHD orchard typologies were simulated under deficit irrigation while LD orchard was simulated under both rainfed and deficit irrigation. Full irrigation requirements were determined by exploratory simulations forcing the model to irrigate automatically with the exact amount of water depleted from the soil - thus avoiding stomatal closure at all times. Deficit irrigation was set to 30% of full irrigation requirements so that amounts of water applied (ranging between 50mm and 200mm) consider, regarding the purposes of our analysis, the actual limitations in water allocated for irrigation and the potential future decrease in water resources. The atmospheric CO_2 concentration was set according to the measurements of the Mauna Loa Observatory for the reference period.

Future simulations were conducted using bias corrected data of GUF-CCLM4 model according to RCP4.5 and RCP8.5 scenarios as inputs for OliveCan for 2041-2070 and

2071-2100 horizons.. The atmospheric CO_2 concentration in the future was set according to RCP scenarios. Table 2 summarizes all simulations conducted.

Throughout this work yields are always expressed as dry matter of fruits (kg ha^{-1}); NEP as tons of CO_2 per ha and year and water supply (or requirements) in mm per year. Results for near future horizon (2041-2070) are only shown in the supplementary material while the main paper focus on the far future ones (2071-2100).

2.5.1. Experiment I: How will olive productivity change under CC?

We assessed the responses of HD orchards yield to climate change. Impact response surfaces of yield to variation in water inputs (irrigation + total rainfall) and atmospheric demand (represented here by the reference evapotranspiration or ET_0 - Allen et al, 1998) were analysed. Local polynomial regression fitting (loess), (R Core Team, 2020), was used to fit yield response to a polynomial surface determined by water inputs and ET_0 as predictors. Outputs of increasing irrigation amounts applied (30%, 50%, 70% and 100% of irrigation requirement) were used as observed points.

2.5.2. Experiment II: Are olive irrigation requirements going to increase in the future?

We used the full irrigation simulations to quantify the future irrigation requirements (mm $year^{-1}$) for the different orchard typologies (LD, HD and SHD orchards), climate clusters and climate change scenarios.

2.5.3. Experiment III: How will olive orchards perform under actual irrigation supply in the future?

We simulated rainfed and irrigated olive orchards in all climate clusters over Southern Europe. In irrigated simulations (LD, HD and SHD orchards), the same amounts of deficit irrigation (30% of full irrigation requirements) applied during reference period 1980-2010 for each climate cluster were applied for the future simulations.

Dry matter yield and Net Ecosystem Productivity (NEP) ($NEP = GPP - R_{eco}$, where GPP is the Gross Primary Productivity and R_{eco} the Total Ecosystem Respiration) were evaluated.

2.5.4. Experiment IV: Will irrigation of new intensive orchards become unsustainable under CC?

To better evaluate the performance of different orchards considered, we fixed the same amount of water available for irrigation for all orchards types (LD, HD and SHD). Irrigation was set to cover approximately the full irrigation requirements found for the LD orchard type for each climate cluster in the reference period 1980-2010. This amount ranged between 130 mm year^{-1} and 200 mm year^{-1} depending on the local rainfall and ET_0 regimes.

2.5.5. Experiment V: Should olive varieties be changed?

This section was focused on flowering, one of the most sensitive and critical stages of olive phenology. Specifically, we compared the potential for chilling accumulation and the expected flowering date among clusters and climate scenarios. The simulation of these processes in OliveCan is based on the sequential model by De Melo-Abreu et al. (2004). Chilling potential was determined as the maximum amount of chilling units (CU) that can be accumulated over each winter. Estimates of the chilling potential were compared with the chilling requirements of five olive cultivars, namely, ‘Arbequina’, ‘Picual’, ‘Leccino’, ‘Frantoio’ and ‘Moraiolo’. Variability in the flowering date across clusters and climatic scenarios was evaluated for ‘Arbequina’, an early flowering cultivar, and ‘Moraiolo’, a late flowering cultivar. The cultivar specific parameters required to run the simulations were taken from De Melo-Abreu et al. (2004) and Aybar et al. (2015).

3. Results

3.1. Climate trends in the future

Projected climate is warmer and drier over the Mediterranean by 2071-2100. Both future scenarios foresee an increase in temperature reaching by the end of the century, according to RCP4.5 and RCP8.5 respectively, 1.6 °C and 3.4 °C for minimum temperature and 2°C and 4 °C for maximum temperature. A decrease in total annual precipitation is expected. Regional distribution of annual rainfall presents a high gradient between the centre of the Mediterranean (wet region) and the western part especially the centre and south of the Iberian Peninsula (dry region). Decrease in annual precipitation is higher than 15% mainly over the centre and eastern coastlines of Spain according to RCP4.5. The decrease exceeds 30% according to RCP8.5 scenario. High seasonal variability in rainfall is also expected. Future scenarios foresee an increase in ET_0 reaching maxima mainly over the Iberian Peninsula. A detailed description of climate future conditions is given in Supplementary Material.

3.2. Experiment I: How will olive productivity change under CC?

Figure 1 shows the response of yield to combined effect of ET_0 and water inputs for HD orchards under the reference period, RCP4.5 and RCP8.5 future scenarios. The plot corresponding to the reference scenario shows that yield isolines are rather flat at low values of ET_0, reflecting the high weight of water inputs on yield response. However, at very high ET_0 yield isolines become more diagonal indicating that such high ET_0 acts as an additional limiting factor for yield. The future scenarios made the yield isolines to be closer (specially the RCP8.5), implying a higher yield sensitivity to water inputs and ET_0 in relation to the baseline. For the same levels of ET_0, providing that the climatic variables remain under the predicted range of respective RCP, the potential yields resulted higher in both future scenarios. Contour plots for LD and SHD typologies have similar pattern of yield response change between the three scenarios (data not shown).

3.3. Experiment II: Are olive irrigation requirements going to increase in the future?

Estimates of irrigation requirements varied among clusters and climate scenarios. In the reference period (Supplementary Fig. 7), the highest irrigation requirements are found over the centre and south of the Iberian Peninsula, the south of Italy, Greece and west of Turkey; this regional distribution is maintained in the future scenarios. In terms of the expected changes as compared to the reference period, the general pattern is quite similar in all orchard types and scenarios (Fig. 2). In terms of relative changes, the north east of Spain, south of France, centre and eastern coastlines of Italy and eastern regions of Greece present higher increase in irrigation than the east of Turkey, the centre and southern region of the Iberian Peninsula. In general, the absolute values of irrigation increase were lower than 20mm year^{-1}, 50mm year^{-1} and 100mm year^{-1} for LD, HD and SHD respectively (Supplementary Fig. 18). For RCP4.5, all orchards types present similar variation in IR reaching a maximum increase of 10%, 13% and 15% for LD, HD and SHD respectively. For RCP8.5, the increase in IR is higher: LD, HD, and SHD orchards will need as maximum 14%, 20% and 27% more water, respectively, to reach their potential yield.

3.4. Experiment III: How will olive orchards perform under actual irrigation supply in the future?

Figure 3 presents the changes in yield between the reference and future period for RCP4.5 (Fig. 3a) and RCP8.5 for rainfed LD orchards, i.e. the still prevalent typology of olive orchard in Mediterranean landscapes (Fig. 3b). We notice a high gradient between the yield changes over the centre of the Mediterranean and the Iberian Peninsula. In fact, according to RCP4.5, it is predicted that rainfed conditions will result in a decrease in yield up to 18% over the Iberian Peninsula with an increase in inter-annual coefficient of variation over the region of 12%. Over the rest of the Mediterranean, an increase is predicted ranging between 12% and 20% with no significant changes in inter-annual variability. This gradient is even stronger for RCP8.5. Increase in yield around 25% is expected in the centre of the Mediterranean while over the Iberian Peninsula yields are expected to decrease more than 20%, with an increase in inter-annual variability (CV) of 20%. The remaining region covering the south of Italy, the east of Greece and Turkey did not present significant changes in the yield compared to the reference period.

Figure 4 presents the performance of LD, HD and SHD olive orchards in the future according to RCP4.5 and RCP8.5. Irrigation applied for these simulations correspond to the 30% of maximum irrigation requirements of each typology during reference period 1980-2010.

When analysing the productivity of different orchards typologies according to each RCP scenario, we notice that the increase in the level of intensification is accompanied with an improvement of the yield (Fig. 4). According to RCP4.5, yield for deficit irrigated LD orchard (Fig. 4a) decreases in the Iberian Peninsula up to 10% with an increase in inter-annual variability of 11% while in all remaining regions an increase is predicted with no significant change in the inter-annual variability. Contrastingly, in the western coastlines of Italy, Greece and Turkey, an increase of 15% is predicted. For HD (Fig. 4b), the same pattern as for LD is predicted in the future, with only a slight tendency for higher yield. On the contrary, for SHD (Fig. 4c), yield increases are predicted in all climate clusters with no significant change in the inter-annual variability. Increases in yield are more relevant in the centre and the eastern part of the Mediterranean and exceed 30%. Changes in yield observed for RCP4.5 simulations are intensified under RCP8.5 conditions. In fact, lower yields of 21% less for LD and 15% for HD are expected over the Iberian Peninsula. For SHD, the yield increase is even higher under RCP8.5 exceeding 45%. Olive evapotranspiration changed in parallel with yield, having the highest decrease over the Iberian Peninsula. The decrease in the consumptive average ET reached a maximum of 27% for LD, 25% for HD and 23% for SHD according to RCP8.5 (Supplementary Fig. 21).

The sustainability of olive groves as ecosystem services in future climate conditions was analysed by means of NEP trends (Table 3). Over the Iberian Peninsula, future changes estimated a neutral condition in LD rainfed orchard, reaching a decrease pinpointed over the centre and south east of Spain (Supplementary Fig. 19). According to RCP4.5, this decrease is slightly higher reaching a maximum of 18% while according to RCP8.5 it is around 14%. Over the remaining region of the study area, an increase is estimated. This increase is of 15-23% according to RCP4.5 and is higher than 18% according to RCP8.5 exceeding 30% in the centre of the Mediterranean.

Under deficit irrigation (Supplementary Fig. 20), NEP tends to increase along with intensification. According to RCP4.5, the centre and eastern coastlines of Spain were the only regions presenting a small change in NEP, with lower values for LD and HD (<10% and <5%, respectively) and a slight increase for SHD (<12%). On the remaining regions, NEP is projected to increase. SHD orchards show the highest increase in NEP reaching values of 36%. According to RCP8.5, the Iberian Peninsula presents the lowest increase of NEP, close to neutrality over the southeast of Spain for LD. NEP is estimated to increase in all remaining regions and for all orchard types. This increase reaches the highest values for SHD with values exceeding 50%.

3.5. Experiment IV: Will irrigation of new intensive orchards become unsustainable under CC?

Figure 5 shows the yield for different orchard types under present and future climate conditions when the same amounts of irrigation (full irrigation requirement for LD in each location) are applied for all types. The regional distribution of yield is quite similar for all typologies. Yields always increase with the level of intensification both in actual and future climatic conditions (Fig. 5). For reference period (Fig. 5a, b, c), the lowest increase in productivity (25-40% for HD and SHD orchard with respect to the productivity of LD orchards) is estimated in the centre and south-east of the Iberian Peninsula. The highest increase (around 55% for HD and higher than 60% for SHD) is mainly located in the centre of the Mediterranean covering Italy and Greece. Scenarios RCP4.5 (Fig. 5d, e, f) and RCP8.5 (Fig. 5g, h, i), show similar distributions of yield but the increase is higher and as compared to the reference period is highest for SHD in RCP8.5 (mean increase of 45% over all study area).

3.6. Experiment V: Should olive varieties be changed?

Figure 6 presents the impact of climate change on the accumulation of chilling requirement during the winter in each climate cluster. When comparing between reference period and future scenarios, we notice that chilling units accumulated are decreasing in the future while presenting larger interannual variability. This tendency is observed in all climate clusters. RCP8.5 showed the highest decrease. According to this scenario, chilling units accumulated will not reach every year the minimum chilling requirement for Moraiolo, Frantoio and Leccino cultivars over clusters covering the south of the Iberian Peninsula.

Figure 7 shows the impact of climate change on the date of flowering for ‘Arbequina’ (early flowering) (Fig. 7a, b), and ‘Moraiolo’ (late flowering) (Fig. 7c, d). An advance of flowering date is predicted in all regions. According to RCP4.5, anticipation is lower than 15 days for both cultivars. For RCP8.5, flowering date anticipation ranges from 12 to 30 days for Moraiolo while for ‘Arbequina’ the advance is higher than 20 days. The southeast of Spain, the centre of Italy, Greece and the west of Turkey are the more affected regions with values higher than 25 days for ‘Moraiolo’ and 30 days for ‘Arbequina’.

DISCUSSION

As transpirable water is the main limit to olive productivity, in the assessment of climate change impacts on olive orchard dynamics, we focused first on the analysis of olive orchards water production function variation under reference, RCP4.5 and RCP8.5 scenarios. We analysed HD orchard yield in response to variations in water inputs (irrigation + rainfall) and ET_0 as a proxy of the atmospheric water demand (Fig. 1). Results shows that yield is not dependent on water inputs only but also on evaporative demand. At high ET_0, impact surface responses show a noteworthy increase in ET_0 impact on yield variation with respect to water inputs, reflecting a low water use efficiency (WUE), which was somewhat expected. This effect is even higher according to RCP8.5. Under these conditions, atmospheric vapour pressure deficit (VPD) is the main driver for the regulation of the tree water balance. In fact, at high VPD, for a given amount of CO_2 entering the stomata, a larger amount of water vapour is lost (Testi et al., 2008). These outcomes reaffirm that water is the main limiting factor of olive productivity in the Mediterranean, and VPD (or its proxy ET_0) is always modulating the productivity even under unrestricted irrigation. Yield surface responses can serve as a summary model to estimate olive productivity for a specific case study. For a given CO_2 concentration pathway and estimated annual evaporative demand, the summary model of Fig.1 can approximate theoretical olive productivity in response to water inputs for actual and future conditions. Comparing the three climatic scenarios under the same water conditions (ET_0 and water inputs), yield reaches the highest values under RCP8.5 scenario. Olive orchard productivity is therefore increasing with the increase of CO_2 concentration as, for the same stomatal conductance, it would enhance photosynthesis increasing both radiation use and water use efficiencies (Tognetti et al., 2001; Tubiello and Ewert, 2002). Olive trees may thus be able to partially, totally or even over compensate for the negative consequences of increased temperature and reduced rainfall that can be expected over the course of the current century. Nonetheless, the increased possibility of extreme events occurrence in the future is a factor that may adversely affect future yield production due to the high uncertainty in its prediction.

The seasonal amount of water available for transpiration is the main driver for the productivity of any olive grove (Connor and Fereres, 2010); the maximum (optimal) irrigation requirements are thus an important descriptor of the dependence on external water supply to match high productivities in future climate. In spite of -generally speaking- the higher CO_2 availability will require lower stomatal conductance to attain a given photosynthesis rate, future irrigation requirements will be generally higher. At the actual state of RCP forecasting, regions with the highest irrigation requirement are the most affected by the predicted decrease in annual rainfall and the increase in ET_0. Compared to the reference period, an increase in irrigation requirements for all orchard types is expected and is higher under RCP8.5 (Fig. 2). Our results agree partly with previous studies that estimated higher water requirements in the future (Rodríguez Díaz et al., 2007; Tanasijevic et al. 2014; Fraga et al. 2019, although only the last seems to have taken into account the future reduced conductance). Even though the distribution of future relative changes shows that dry regions (centre and south of the Iberian Peninsula) are having lower predicted increases in irrigation requirements compared to the wet regions (mainly centre of the Mediterranean), the absolute increases in irrigation amounts (in mm year^{-1} in Supplementary Fig.18) differ little between clusters. In fact, coefficient of variation between clusters for each orchard typology is around 40% for RCP4.5 and is lower than 20% for RCP8.5. The increase in irrigation requirements was proportional to the level of intensification and distinctly under RCP8.5. In fact, the improvement of photosynthesis in response to the increase in CO_2 concentration resulted in an increase in growth and hence a larger canopy and leaf area. This effect was stronger in wet than in dry regions and resulted in a higher evapotranspiration level. This dynamic aspect of vegetative growth was not addressed in previous studies. The expected future changes in irrigation requirements can be, in this case, modulated by changing the pruning frequency or intensity to better control the changes in trees size in the future.

In this research, we focused also on the sustainability of current agricultural management; in particular, irrigation gives rise to concerns, as water resources available to irrigation of crops seems to have already peaked in the Mediterranean area (Gerten et al. 2011). We simulated the dynamics of olive orchards while keeping the same actual irrigation management under future climate scenarios RCP4.5 and RCP8.5. The traditional rainfed orchards (Fig. 3), will undergo a decrease in yield over the Iberian Peninsula in the future, along with an increase in inter-annual variability whereas an increase in productivity of these orchards is predicted over the centre of the Mediterranean, mainly Italy and Greece. These results are in agreement with previous studies showing a decrease in yield over the western part of the Mediterranean and an increase over the eastern part (Ponti et al. 2014; Fraga et al. 2019). Tanasijevic et al. (2014) showed a decrease in the suitability of rainfed olive cultivation over Italy and Greece. This may be related to the fact that this study did not consider the effect of the increase in CO_2 concentration and its complex links with plant stomatal behaviour. By using a single soil type as representatives of the medium soil quality existing in traditional most common olive groves within the Mediterranean basin, our analysis removes the impacts of soil quality on olive productivity while it emphasizes those of climate and management. According to the simulations conducted, results show the vulnerability of rainfed orchard to future climate conditions over arid/semi-arid regions. Conversely, the predicted decrease in rainfall and increase in ET_0 were not critical for the productivity over centre and eastern part of the Mediterranean. In fact, over these less water demanding environments, traditional olive orchards will benefit from the increase of atmospheric CO_2 concentration more than they will suffer from water scarcity induced by the reduced precipitation regime expected. Hence, to overcome predicted dry conditions, the incorporation of at least a supplementary irrigation management over most vulnerable regions will likely be indispensable to preserve the productivity and sustain traditional olive orchards under future climate conditions.

Under deficit irrigation (Fig. 4), the Iberian Peninsula was the region with the largest decrease in yield, especially for LD. In contrast, SHD showed higher yield in all clusters. The centre of the Mediterranean had the highest increase in yield for all typologies. These predicted changes were intensified under RCP8.5. The pattern of changes is highly correlated to the future variability in annual rainfall and ET_0. Deficit irrigation in the amounts applied during the reference period (1980-2010) does not compensate the reduction in annual rainfall and the increase in ET_0 expected in the future especially over dry regions (mainly centre and south of the Iberian Peninsula). For example, according to RCP8.5, over the centre of Italy, orchard evapotranspiration is expected to decrease by 7% and 8% (average of 30 years) for LD and SHD respectively (Supplementary Fig. 12). Over the centre of the Iberian Peninsula, the most impacted region, evapotranspiration is expected to decrease by 23% and 20% for LD and SHD respectively, due to the stomatal closure caused by the water deficit that these dry regions will face. Soil water deficits will be, in these cases, more limiting than the effects of VPD on the modulation of water balance. Deficit irrigation, therefore, should be adjusted at local level for a better improvement of productivity. In general, except regions that are prone to future dry conditions, application of deficit irrigation showed positive results as it helps increase irrigation water use efficiency (Iniesta et al., 2009; Gucci et al., 2019).

Intensive and super-intensive orchards respond better to climate change than traditional ones when applying the same irrigation amounts for all types (Fig.5). Even though water applied covered full requirement of the LD orchard and approximately 30% of irrigation requirement of SHD, the latter presented the highest productivity compared to LD and HD, reflecting higher water use efficiency (i.e., the marginal effect of the main driver for the productivity of olive - which is the available water - is maximized in denser plantations). The regional variability of productivity is associated to climate. The improvement of yield with the level of intensification is explained by the increased radiation interception (Villalobos et al., 2006; Proietti et al., 2015). Under future scenarios and especially RCP8.5, productivity of all the simulated orchards was higher than in the reference period and SHD presented the best performance (Fig. 5). In fact, the mean increase in yield over our study area reached 45% for SHD compared to 25% for traditional orchards (Fig. 5). Intensive plantations seem to benefit more from the increase in CO_2 level. Nevertheless, these results must be considered a general statement: considering the regional variability observed in our results, implementation of this management require local assessment for a better evaluation of its potential performance under specific environmental conditions.

We investigated also the carbon capture capacity of olive orchards under global warming (Table 3). The centre and south-eastern part of the Iberian Peninsula are the regions expecting a decrease for rainfed LD orchard, with lower intensity approaching neutrality for irrigated LD and HD orchard (Supplementary Fig. 19 and 20). On a general view, the predicted changes in NEP vary along with those in yield. Brilli el al. (2016) showed that rainfall amounts and timing are the main drivers of carbon sequestration in the rainfed orchard they simulated in a dry environment and that higher spring rainfall increased both spring and summer NEP. In our study, regions expecting a decrease in NEP are those expecting the largest decrease in spring rainfall: for example, the centre and southern regions of the Iberian Peninsula had the highest decrease in NEP for rainfed LD orchard under RCP 4.5 and had the highest decrease in spring rainfall of 30%. Regarding the different components of NEP, the increase in maintenance respiration - especially on leaves - due to higher temperatures was larger than that of GPP (data not shown), because of the inhibition of photosynthesis. In parallel to yields, NEP for irrigated orchards is expected to increase mainly in the centre and eastern parts of the Mediterranean. This is at odds with the results of Brilli et al. (2019) showing a substantial decrease in NEP in the future for traditional olive groves all over the Mediterranean area. This is probably due to the use of an adapted version of the biogeochemical model DAYCENT that does not take into account all the specific factor of the plant. In fact, the sub model that simulates the arboreal part is not very developed which may impact olive photosynthesis estimation and therefore the increase of CO_2 concentration in the future. Our results proved that irrigation and intensification could compensate the climate impacts and promote the increase in NEP by improving net photosynthesis. Even though some traditional olive orchards types over dry regions presented a decrease in NEP in the future (Supplementary Fig. 19), the carbon capture capacity is still important.

Regarding the projected alterations in the phenological development, we found that chilling units accumulated during the winter will decrease in the future and will show a higher interannual variability (Fig. 6). The highest impact is estimated over the Iberian Peninsula where some cultivars such as Moraiolo, Frantoio and Leccino would not reach the chilling requirements needed to break winter dormancy. Fraga et al. (2019) also found a lower/higher chilling portion for southwestern/eastern Europe particularly under RCP8.5. The increase in temperature will induce an advance of flowering date reaching 30 days for RCP8.5 (Fig. 7), which agrees with previous studies (Orlandi et al. 2013; Avolio et al., 2012). These projections of insufficient chilling for some olive varieties may potentially threaten olive cultivation over the Mediterranean. Nevertheless, among the cultivars we tested and for which data of chilling requirement exist, none seems at risk of flowering failure in its traditional or actual cultivation area. Moraiolo, for example, is not cultivated in the areas where our model forecasts probabilities of flowering failure (central Portugal, southern Spain, and southern Italy) and no threats are expected in its traditional area of central Italy even under the worst scenarios of the end of the century. The forecasted advance in flowering will lead to changes in the timing of the different phenological phases. The phenological shifting is a consequence of temperature, thus flowering is expected to occur at approximately the same thermal environment as now (and this is actually what OliveCan predicts – data not shown). This implies that the frequency of extreme temperatures during flowering is not expected to increase significantly. Some studies suggest a gradual northward shift of current olive cultivation areas in the coming decades (Tanasijevic et al. 2014, Moriondo et al, 2008, Moriondo et al. 2013). Expanding our analysis beyond the already cultivated areas and existing varieties requires models that take into account not only cultivar differences but also the complex response of olive photosynthesis and growth to radiation, temperature and CO_2 concentration.

Uncertainty is almost unavoidable in impact modelling due to the input data used and the set of assumptions adopted in the modelling approach. Uncertainty associated to input data arises from the cascade of uncertainty from GHG emissions scenarios to regional climate model. In fact, GHG scenarios describe plausible but unpredictable conditions in the future (IPCC, 2014). These scenarios incorporate therefore substantial uncertainties about their plausibility and robustness. Likewise, climate model uncertainty is the incomplete knowledge about the climate system. Although the physical processes simulated are the same, internal variability, boundary conditions and parameterizations may differ between the various existing climate models (Flato et al. 2013). Owing to uncertainties in climate models and emission scenarios, any individual simulation represents only one of the possible pathways the climate system might follow. Therefore, we performed a multi-scenarios assessment using RCP4.5 and RCP8.5 scenarios in order to span the range of possible projections and highlight the corresponding uncertainties. Even though the use of relative change and multiyear average data (reference period) enabled a robust estimate of the relative magnitude and direction of yield and water need change for olive under projected climate change across the Mediterranean, there is still a need to perform comprehensive assessments based on multi-model ensembles to derive more robustness to the predicted relative changes and to provide a measure of its uncertainly under future climate conditions (Deser et al., 2012). Another class of uncertainties relates to the assumptions adopted in the modelling approach. In fact, knowing the heterogeneity of environmental conditions existing in our study area we adopted some assumptions (i.e. use of a single soil type and clustering climate data) in order to reduce the complexity of our methodology and highlight only the impact of climate and agricultural management on olive orchard dynamics. Thus, results of the present analysis on olive dynamics are intended to be exploratory rather than predictive. Uncertainty in this case can be reduced via the development of smaller-scale assessments parameterized and validated with local or regional data. Taking into account all sources of uncertainties will improve the evaluation of impacts related to natural climate variability as well as anthropogenic climate change.

We are confident that the presented analysis is the more complete to date with the modelling tools available today, but unfortunately is still far to be comprehensive of all the possible CC effects on olive crop. OliveCan also models explicitly the response to the increased frequency of extreme meteorological events (heatwaves, frost and extreme drought). Heat stress in future climates may affect oil concentration and quality (Ayerza and Sibbett, 2001); advanced submodels of oil accumulation, fatty acids composition and minor quality components are essential to this appraisal, but unfortunately still to come.

CONCLUSION

The use of OliveCan allowed the evaluation of the productive and environmental performance of olive orchards under different climate change scenarios and management strategies, considering explicitly the effect of CO_2 concentration over photosynthesis and all its links and feedbacks from plant water status through the stomatal behavior. Future climate is expected to show tendencies with large regional variability over the Mediterranean. Drier and warmer conditions are expected all over the study area, with the most negative impacts over the Iberian Peninsula. Findings of this research answered the questions we raised regarding the future sustainability of olive in the context of CC:

I. How will olive productivity change under CC?

The increase in CO_2 concentration may offset the negative effects of higher temperature/VPD, and diminished rainfall, resulting in an increase of productivity.

II. Are olive irrigation requirements going to increase in the future?

Maximum water requirements will be higher in the future especially over most affected regions by the predicted decrease in annual rainfall and the increase in ET_0.

III. How will olive orchards perform under actual irrigation supply in the future?

Rainfed low density orchards will be most vulnerable to climate expected changes, in particular in the driest areas. Deficit irrigation will improve olive orchard productivity and carbon sequestration capacity. Although the maximum water requirements will be higher in the future, olive orchards will be able to produce satisfactorily at the end of the century without requiring more irrigation water resources.

IV. Will irrigation of new intensive orchards become unsustainable under CC?

Intensification will improve olive orchard productivity and benefit more from the increase in CO_2 level than traditional orchards under the same irrigation regime.

V. Should olive varieties be changed?

A decrease in chilling units accumulation is expected with no significant flowering anomalies or failures in the whole study area assuming the present distribution of cultivars. The predicted advance of flowering date has limited practical implications.

Even though this study proved that irrigation and intensification could compensate the climate impacts and improve olive productivity and carbon sequestration potential, assessment of management alternatives at local scale will be a must for a better adaptability of olive orchards.

ACKNOWLEDGMENTS

This study was supported by the Spanish Ministry of Economy and Competitiveness (project AGL-2015-69822-R) and co-funded by ERA-NET FACCE SURPLUS and INIA (project OLIVE-MIRACLE, grant No. 652615) and by EU-FEDER and the department of Economy, Knowledge, Companies and Universities of the Andalusian Regional Government (project UCO 27425). Besides, H-M was funded by a research doctorate scholarship from The Italian Ministry of Education, University and research - University of Perugia. L-R was funded by the EU project LIFE OLIVE4CLIMATE (LIFE15 CCM/IT/000141).

REFERENCES

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration - guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. Food and Agriculture Organization, Rome.

Avolio, E., Orlandi, F., Bellecci, C., Fornaciari, M. and Federico, S., 2012. Assessment of the impact of climate change on the olive flowering in Calabria (southern Italy). Theoretical and Applied Climatology, 107, 531–540. https://doi.org/10.1007/s00704-011-0500-2.

Aybar, V.E., De Melo-Abreu, J.P., Searles, P.S., Matias, A.C., Del Rio, C., Caballero, J.M., Rousseaux, C.M., 2015. Evaluation of olive flowering at low latitude sites in Argentina using a chilling requirement model. Spanish Journal of Agricultural Research. 13 (1). e09-001. doi:http://dx.doi.org/10.5424/sjar/2015131-6375.

Ayerza, R., Sibbett, G.S., 2001. Thermal adaptability of olive (Olea europea L.) to the arid Chaco of Argentina. Agriculture, Ecosystems and Environment. 84, 277–2.

Brilli, L., Gioli, B., Toscano, P., Moriondo, M., Zaldei A., Cantini, C., Ferrise, R., Bindi, M., 2016. Rainfall regimes control C-exchange of Mediterranean olive orchard. Agr. Ecosyst. Environ. 233, 147-157. http://dx.doi.org/10.1016/j.agee.2016.09.006

Brilli, L., Lugato, E., Moriondo, M., Gioli, B., Toscano, P., Zaldei, A., Leolini, L., Cantini, C., Caruso, G., Gucci, R., Merante, P., Dibari, C., Ferrise, R., Bindi, M., Costafreda-Aumedes, S., 2019. Carbon sequestration capacity and productivity responses of Mediterranean olive groves under future climates and management options. Mitigation

Adapt. Strategies Global Change. 24 (3), 467-491. https://doi.org/10.1007/s11027-018-9824-x.

Caruso, T., Campisi, G., Marra, F.P., Camposeo, S., Vivaldi, G.A., Proietti, P., Nasini, L., 2014. Growth and yields of 'Arbequina' high-density planting systems in three different olive growing areas in Italy. Acta Horticulturae. 1057, 341-348.

Challinor, A., Watson, J., Lobell, D., Howden, S., Smith, D., Chhetri, N. 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change, 4, 287–291, doi:10.1038/nclimate2153.

Connor, D.J., Fereres, E., 2010. The Physiology of Adaptation and Yield Expression in Olive. Horticultural Reviews. Volume 31. https://doi.org/10.1002/9780470650882.ch4.

D. Keeling D. C., Bacastow R. B., Bainbridge A. E., Ekdahl Jr. C. A., Guenther P. R., Waterman L. S., Chin J. F. S., 1976. Atmospheric carbon dioxide variations at Mauna Lao Observatory, Hawaii. Tellus. 28(6). https://doi.org/10.1111/j.2153-3490.1976.tb00701.x

De Melo-Abreu, J.P., Barranco, D., Cordeiro, A.M., Tous, J., Rogado, B.M., Villalobos, F.J., 2004. Modelling olive flowering date using chilling for dormancy release and thermal time. Agric. For. Meteorol. 125, 117–127.

Deser, C., Phillips, A., Bourdette, V., Teng, H., 2012. Uncertainty in climate change projections: The role of internal variability, Clim. Dyn., 38(3–4), 527–546, doi:10.1007/s00382-010-0977-x.

FAOSTAT (2017). Available at: http://faostat.fao.org (Accessed August 2019)

Farquhar, G. D., von Caemmerer, S., and Berry, J. A., 1980. A biochemical model of photosynthetic CO2 assimilation in leaves of C3 species. Planta 90, 78–90. doi: 10.1007/BF00386231

Flato, G., J. Marotzke, B. Abiodun, P. Braconnot, S.C. Chou, W. Collins, P. Cox, F. Driouech, S. Emori, V. Eyring, C. Forest, P. Gleckler, E. Guilyardi, C. Jakob, V. Kattsov, C. Reason and M. Rummukainen, 2013: Evaluation of Climate Models. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Fraga, H., Pinto, J.G., Santos, J.A., 2019. Climate change projections for chilling and heat forcing conditions in European vineyards and olive orchards: a multi-model assessment. Clim Change. 152(1):179-93. https://doi.org/10.1007/s10584-018-2337-5.

Fraga, H., Pinto, J.G., Viola, F., Santos, J.A., 2019. Climate change projections for olive yields in the Mediterranean Basin. Int. J. Clim. 1-13. https://doi.org/10.1002/joc.6237.

Gabaldón-Leal, C., Ruiz-Ramos, M., De la Rosa, R., León, L., Belaj, A., Rodríguez, A., Santos, C., Lorite, I. J. (2017). Impact of changes in mean and extreme temperatures caused by climate change on olive flowering in southern Spain. Int. J. Climatol. 37 (Suppl.1): 940-957. DOI: 10.1002/joc.5048

Galán, C., García-Mozo, H., Vázquez, L., Domínguez-Vilches, E., 2008. Modelling Olive Crop Yield in Andalusia, Spain. Agron. J. 100, 98-104. doi:10.2134/agronj2006.0345

Gerten, D., Heinke, J., Hoff, H., Biemans, H., Fader, M., Waha, K., 2011. Global water availability and requirements for future food production. Journal of Hydrometeorology, 12(5), 885-899.

Ghannoum, O., Way, D.A., 2011. On the role of ecological adaptation and geographic distribution in the response of trees to climate change. Tree Physiology. 31, 1273-1376. doi:10.1093/treephys/tpr115.

Giorgi, F., 2006. Climate change hot-spots. Geophys. Res. Lett. 33(8), L08707.

Giorgi, F., Lionello, P., 2008. Climate change projections for the Mediterranean region. Global Planet Change, 63, 90-104. doi:10.1016/j.gloplacha.2007.09.005

Gualdi, S., Somot, S., Li, L., Artale, V., Adani, M., Bellucci, A., Braun, A., Calmanti, S., Carillo, A., Dell'Aquila, A., et al., 2013. The CIRCE simulations: Regional Climate Change Projections with Realistic Representation of the Mediterranean Sea. Bull Am Meteorol Soc. 94(1):65-81.

Gucci, R., Caruso, G., Gennai, C., Esposto, S., Urbani, S., Servili, M., 2019. Fruit growth, yield and oil quality changes induced by deficit irrigation at different stages of olive fruit development. Agric. Water Manage. 212, 88-98. https://doi.org/10.1016/j.agwat.2018.08.022.

Hertig, E., Seubert, S., Paxian, A., Vogt, G., Paeth, H., Jacobeit, J., 2013. Statistical modelling of extreme precipitation indices for the Mediterranean area under future climate change. International Journal of Climatology. 34(4), 1132-1156. https://doi.org/10.1002/joc.3751

Iniesta, F., Testi, L., Orgaz, F., Villalobos, F. J., 2009. The effects of regulated and continuous deficit irrigation on the water use, growth and yield of olive trees. Eur. J. Agron. 30, 258–265. doi: 10.1016/j.eja.2008.12.004.

IPCC, 2013. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF, D Qin, G-K Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia, V Bex and PM Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

Koubouris, G. C., Metzidakis, I. T., Vasilakakis, M. D., 2009. Impact of temperature on olive (Olea europaea L.) pollen performance in relation to relative humidity and genotype. Environmental and Experimental Botany 67(1):209-214. DOI:10.1016/j.envexpbot.2009.06.002

Leuning, R., Tuzet, A., Perrier, A., 2003. Stomata as part of the soil-plant-atmosphere continuum. In Forests at the Land–Atmosphere Interface (eds M. Mencuccini, J. Grace, J. Moncrieff, K. McNaughton). CAB International, Edinburgh, Scotland.

Lloyd, J., Farquhar, G.D., 2008. Effects of rising temperatures and CO_2 on the physiology of tropical forest trees. Philos. Trans. R. Soc. B. 363(1498), 1811-1817. doi:10.1098/rstb.2007.0032

López-Bernal, Á., Morales, A., García-Tejera, O., Testi, L., Orgaz, F., De Melo-Abreu, J.P., Villalobos, F.J., 2018. OliveCan: A Process-Based Model of Development, Growth and Yield of Olive Orchards. Front. Plant Sci. 9:632. https://doi.org/10.3389/fpls.2018.00632.

Mairech, H., López-Bernal, Á., Moriondo, M., Dibari, C., Regni, L., Proietti, P., Francisco J. Villalobos, F.J., Testi, L., 2020. Is new olive farming sustainable? A spatial comparison of productive and environmental performances between traditional and new olive orchards with the model OliveCan. Agricultural system. 181, 102816. https://doi.org/10.1016/j.agsy.2020.102816

Marra, F.P., Marino, G., Marchese, A., Caruso, T., 2016. Effects of different irrigation regimes on a super-high-density olive grove cv. “Arbequina”: vegetative growth, productivity and polyphenol content of the oil. Irriga. Sci. 34 (4), 313-325.

Massaccesi, L., De Feudis, M., Agnelli, A.E., Nasini, L., Regni, L., D'Ascoli, R., Castaldi, S., Proietti, P., Agnelli, A., 2018. Organic carbon pools and storage in the soil of olive groves of different age. European Journal of Soil Science. 69 (5), 843-855.

Montanaro, G., Xiloyannis, C., Nuzzo, V., Dichio, B., 2017. Orchard management, soil organic carbon and ecosystem services in Mediterranean fruit tree crops. Sci. Hortic. 217, 92–101. http://dx.doi.org/10.1016/j.scienta.2017.01.012.

Moriana, A., Orgaz, F., Pastor, M., Fereres, E., 2003. Yield responses of a mature olive orchard to water deficits. J. Am. Soc. Hortic. Sci. 128, 425-431.

Moriondo, M., Ferrise, R., Trombi, G., Brilli, L., Dibari, C., Bindi, M., 2015. Modelling olive trees and grapevines in a changing climate. Environmental Modelling & Software 72, 387-401. http://dx.doi.org/10.1016/j.envsoft.2014.12.016.

Moriondo, M., Stefanini, F.M., Bindi, M., 2008. Reproduction of olive tree habitat suitability for global change impact assessment. Ecol. Model. 218 (1-2),95–109.

Moriondo, M., Trombi, G., Ferrise, R., Brandani, G., Dibari, C., Ammann, C.M., Lippi, M.M., Bindi, M., 2013. Olive trees as bio-indicators of climate evolution in the Mediterranean Basin. Global Ecol. Biogeogr. 22 (7), 818-833. http://dx.doi.org/10.1111/geb.12061

Orlandi, F. Garcia-Mozo, H., Ben Dhieb, A., Galan, C., Msallem, M., Fornaciari, M., 2013. Olive tree phenology and climate variation in the Mediterranean area over the last two decades. Theo Appl Climatol. 115: 207-218. DOI 10.1007/s00704-013-0892-2

Orlandi, F., Avolio, E., Bonofiglio, T., Federico, S., Romano, B. and Fornaciari, M., 2012. Potential shifts in olive flowering according to climate variations in Southern Italy. Meteorological Applications, 20, 497-503. https://doi.org/10.1002/met.1318.

Ponti, L., Gutierrez, A.P., Ruti, P.M., Dell’Aquila, A., 2014. Fine-scale ecological and economic assessment of climate change on olive in the Mediterranean Basin reveals winners and losers. Proc. Natl. Acad. Sci. U.S.A. 111 (15), 5598-5603

Proietti, P., Nasini, L., Ilarioni, L., 2012. Photosynthetic behavior of Spanish Arbequina and Italian Maurino olive (*Olea europaea* L.) cultivars under super-intensive grove conditions. Photosynthetica. 50 (2), 239-246. https://doi.org/10.1007/s11099-012-0025-7.

Proietti, P., Nasini, L., Reale, L., Caruso, T., Ferranti, F., 2015. Productive and vegetative behavior of olive cultivars in super high-density olive grove. Sci. Agricola. 72 (1), 20-27. 750 http://dx.doi.org/10.1590/0103-9016-2014-0037.

Proietti, P., Sdringola, P., Brunori, A., Ilarioni, L., Nasini, L., Regni, L., Pelleri, F., Desideri, U., Proietti, S., 2016. Assessment of carbon balance in intensive and extensive tree cultivation system for oak, olive, polar and walnut plantation. J. Cleaner Prod. 112, 2613-2624.

Proietti, S., Sdringola, P., Desideri, U., Zepparelli, F., Brunori, A., Ilarioni, L., Nasini, L., Regni, L., Proietti, P. (2014). Carbon footprint of an olive tree grove. Applied Energy, 127, 115-124. https://doi.org/10.1016/j.apenergy.2014.04.019

Proietti, S., Sdringola, P., Regni, L., Evangelisti, N., Brunori, A., Ilarioni, L., Nasini, L., Proietti, P., 2017. Extra Virgin Olive oil as carbon negative product: Experimental analysis and validation of results. J. Cleaner Prod. 166, 550e562. http://dx.doi.org/10.1016/j.jclepro.2017.07.230.

R Core Team, 2020. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Regni, L., Nasini, L., Ilarioni, L., Brunori, A., Massaccesi, L., Agnelli, A., Proietti, P., 2017. Long-term amendment with fresh and composted solid olive mill waste on olive grove affects carbon sequestration by prunings, fruits and soil. Front. Plant Sci. 7, Article number 2042. http://dx.doi.org/10.3389/fpls.2016.02042.

Rodriguez Diaz JA., Weatherhead EK., Knox JW., Camacho E., 2007. Climate change impacts on irrigation water requirements in the Guadalquivir river basin in Spain. Regional Environmental Change. 7(3): 149-159. DOI 10.1007/s10113-007-0035-3

Rossi, L., Regni, L., Rinaldi, S., Sdringola, P., Calisti, R., Brunori, A., Dini, F., Proietti, P. 2020. Long-Term Water Footprint Assessment in a Rainfed Olive Tree Grove in the Umbria Region, Italy. Agriculture. 10, 8. https://doi.org/10.3390/agriculture10010008

Sofo A., Manfreda S., Fiorentino M., Dichio B., Xiloyannis C., 2008. The olive tree: A paradigm for drought tolerance in Mediterranean climates. Hydrology and Earth System Sciences. 12(1):293-301. DOI: 10.5194/hessd-4-2811-2007

Tanasijevic, L., Todorovic, M., Pereira, L.S., Pizzigalli, C., Lionello, P., 2014. Impacts of climate change on olive crop evapotranspiration and irrigation requirements in the Mediterranean region. Agric. Water Manage. 144, 54-68.

Testi, L., Orgaz, F., Villalobos, F. J., 2008. Carbon exchange and water use efficiency of a growing, irrigated olive orchard. Environ. Exp. Botany. 63, 168–177. http://dx.doi.org 10.1016/j.envexpbot.2007.11.006.

Testi, L., Villalobos, F. J., Orgaz, F., Fereres, E., 2006. Water requirements of olive orchards: I simulation of daily evapotranspiration for scenario analysis. Irrig. Sci. 24, 69–76. https://doi.org/10.1007/s00271-005-0011-y.

Thoning et al., 1989

Tognetti, R., Sebastiani, L., Vitagliano, C., Raschi, A., Minnocci, A., 2001. Responses of two olive tree (Olea europaea l.) cultivars to elevated CO2 concentration in the field. Photosynthetica. 39 (3), 403e410.

Tous, J., Ferguson, L., 1996. Mediterranean Fruits. In: Janick, J., Ed., Progress in New Crops, ASHS Press, Arlington, 416-430.

Tubiello, F.N., Ewert, F., 2002. Simulating the effects of elevated CO2 on crops: approaches and applications for climate change. Eur. J. Agron. 18 (1e2), 57e74. http://dx.doi.org/10.1016/S1161-0301(02)00097-7.

Tuzet, A., Perrier, A., and Leuning, R. (2003). A coupled model of stomatal conductance, photosynthesis and transpiration. Plant Cell Environ. 26, 1097–1116. doi: 10.1046/j.1365-3040.2003.01035.x

Villalobos, F.J, Mateos, L., Orgaz, F., Fereres, E., 2016. The water budget, in: Villalobos, F.J, Fereres, E. (Eds.), Principles of agronomy for sustainable agriculture. Springer International Publishing. 91-105. https://doi.org/10.1007/978-3-319-46116-8.

Villalobos, F.J., Testi, L., hidalgo, J., Pastor, M., Orgaz, F., 2006. Modeling potential growth and yield of olive (Olea europaea L.) canopies. Eur. J. Agron. 24 (4), 296-303. http://dx.doi.org/10.1016/j.eja.2005.10.008.

Table 1: Characteristics of olive orchard types. DDX: distance between rows; DDY: distance between trees in a row

Orchard Density	Irrigation	DDX (m)	DDY (m)	Ground Cover (fraction)	Leaf Area Density ($m^2\ m^{-3}$)	Pruning Interval (years)	Pruning Intensity (fraction of LAI)
Low density	rainfed	10	10	0.2	0.85	2	0.1
Low density	irrigated	10	10	0.25	0.85	1	0.05
High density	irrigated	7	3.5	0.4	1.2	1	0.05
Super high density	irrigated	4	1.5	0.4	1.5	1	0.2

Table 2: Summary of simulation experiments

	Simulations	Typologies	Water supply
I	How will olive productivity change under CC?	LD, HD, SHD	30%, 50%, 70% and 100% of irrigation requirement during reference and future periods
II	Are olive irrigation requirements going to increase in the future?	LD, HD, SHD	100% of irrigation requirement during reference and future periods
III	How will olive orchards perform under actual irrigation supply in the future?	LD, HD, SHD	LD: rainfed LD, HD, SHD: 30% of irrigation requirement during reference period
IV	Will irrigation of new intensive orchards become unsustainable under CC?	LD, HD, SHD	Irrigation supply equal for the 3 typologies and equal to 100% of irrigation requirement for LD during reference period
V	Should olive varieties be changed?	LD	100% of irrigation requirement

Table 3: NEP changes (ranges over study area in %) for LD, HD and SHD during future period 2071-2100 according to RCP4.5 and RCP8.5 with comparison to reference period 1980-2010. LD-RF are rainfed orchards. LD-IR, HD-IR and SHD-IR are irrigated orchards: the same amounts of irrigation (30% of irrigation requirements) estimated for each climate cluster during reference period are applied for future simulations.

	RCP4.5		RCP8.5	
	Min	Max	Min	Max
LD-RF	-18%	23%	-14%	35%
LD-IR	-8%	22%	-2%	34%
HD-IR	-4%	23%	11%	37%
SHD-IR	9%	36%	26%	70%

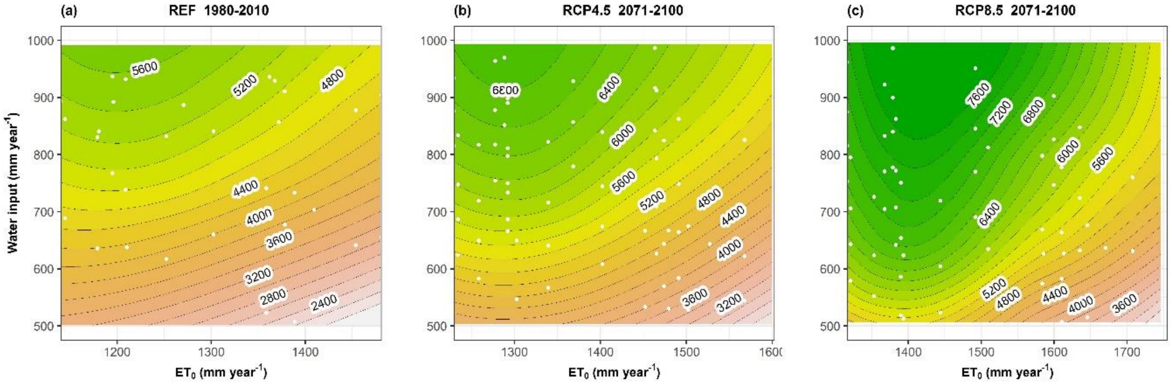

Figure 1: Contour plots of dry yield (kg ha^{-1}) to variation in ET_0 (mm year^{-1}) and total water input (mm year^{-1}) for High Density (HD) during reference period 1980-2010 (a) and 2071-2100 according to RCP4.5 (b) and RCP8.5 (c). Colour gradient from beige to green refers to the increase of yield. White dots are the outputs of the simulations used.

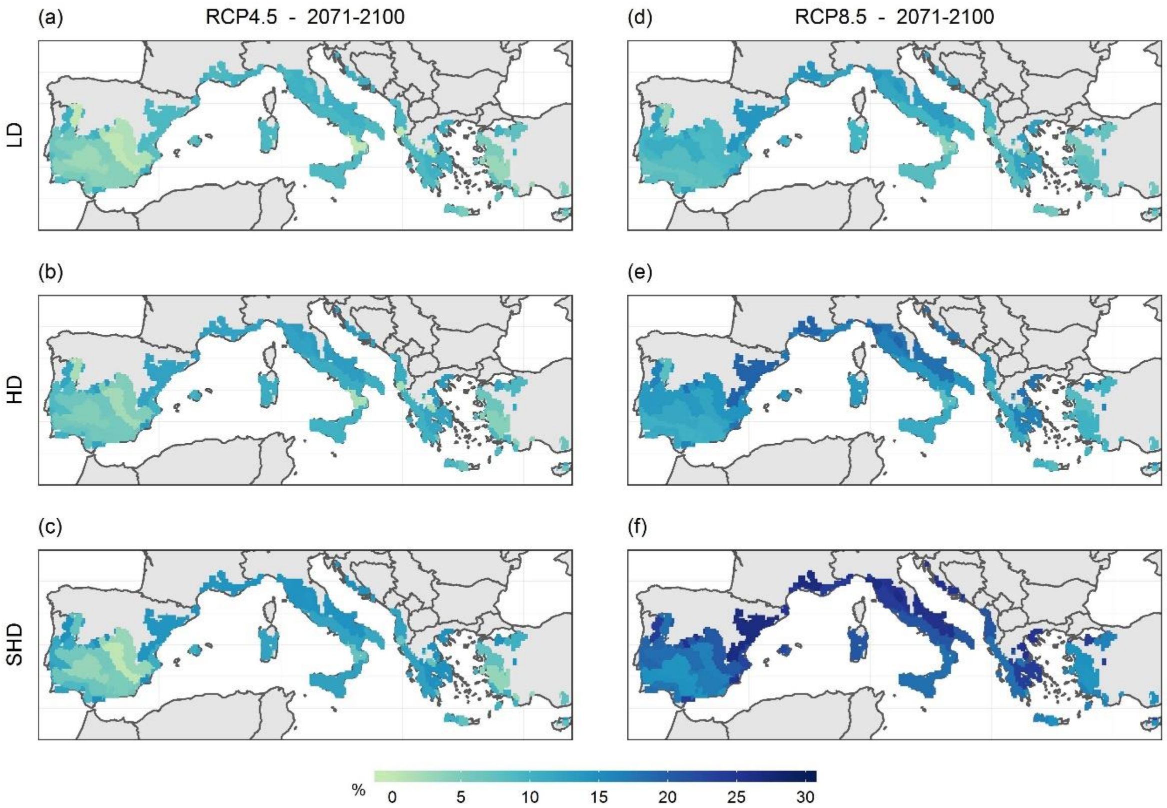

Figure 2: Changes in maximum irrigation requirement (in %) for LD, HD and SHD during 2071-2100 according to RCP4.5 (a, b, c) and RCP8.5 (d, e, f) as compared to the reference period 1980-2010 (shown in fig. 7 of supplementary materials).

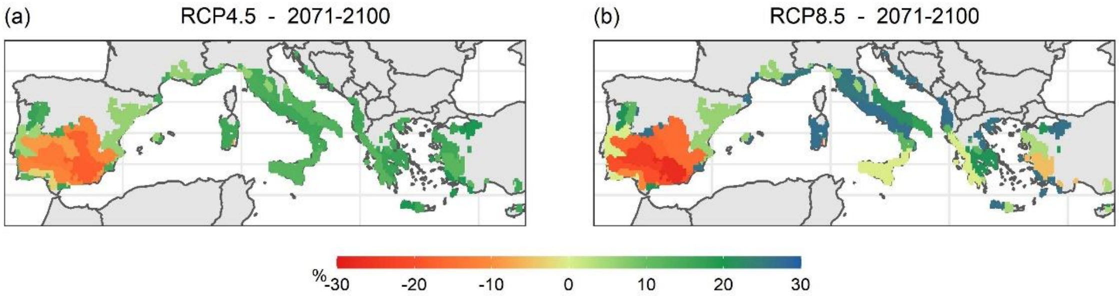

Figure 3: Changes in yield (in %) for rainfed LD orchards for future period 2071-2100 according to RCP4.5 and RCP8.5 compared to reference period 1980-2010

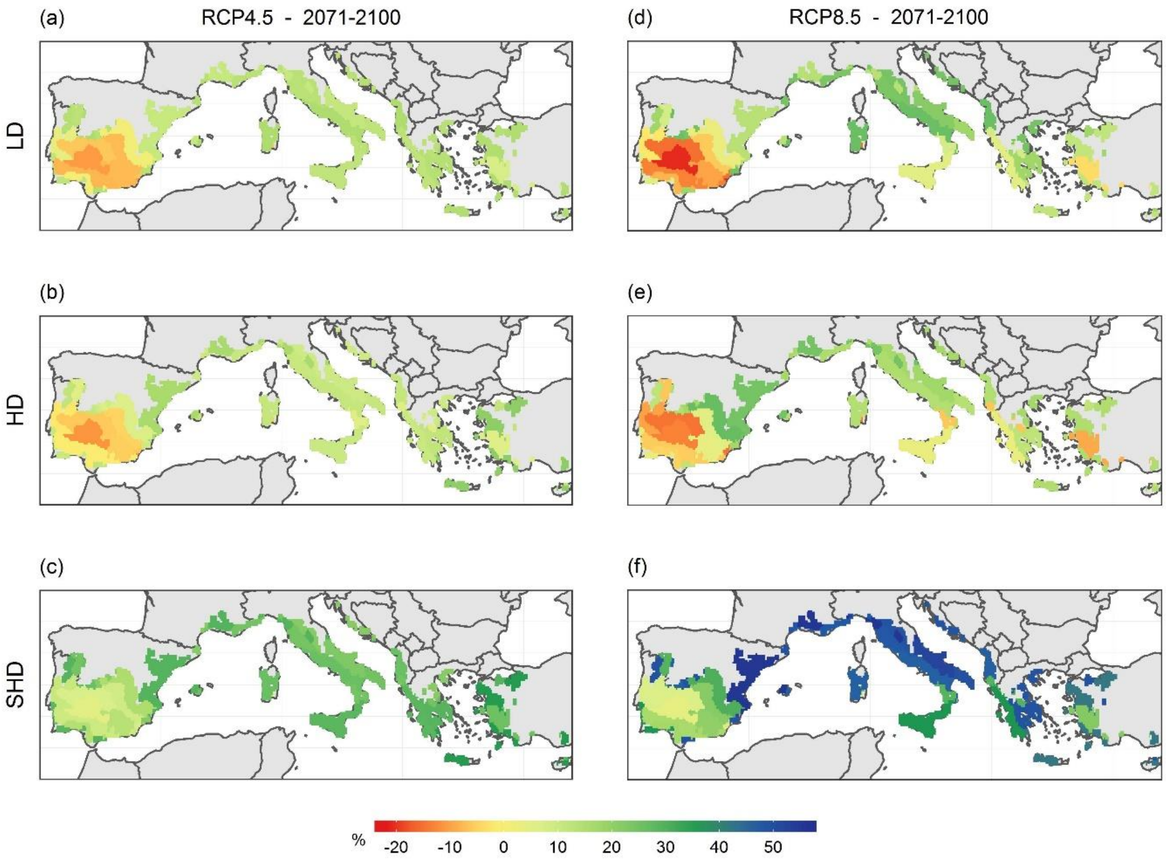

Figure 4: Yield changes (in %) for deficit irrigated LD, HD and SHD olive orchards for 2071-2100 according to RCP4.5 (a, b, c) and RCP8.5 (d, e, f) as compared to the reference period 1980-2010.

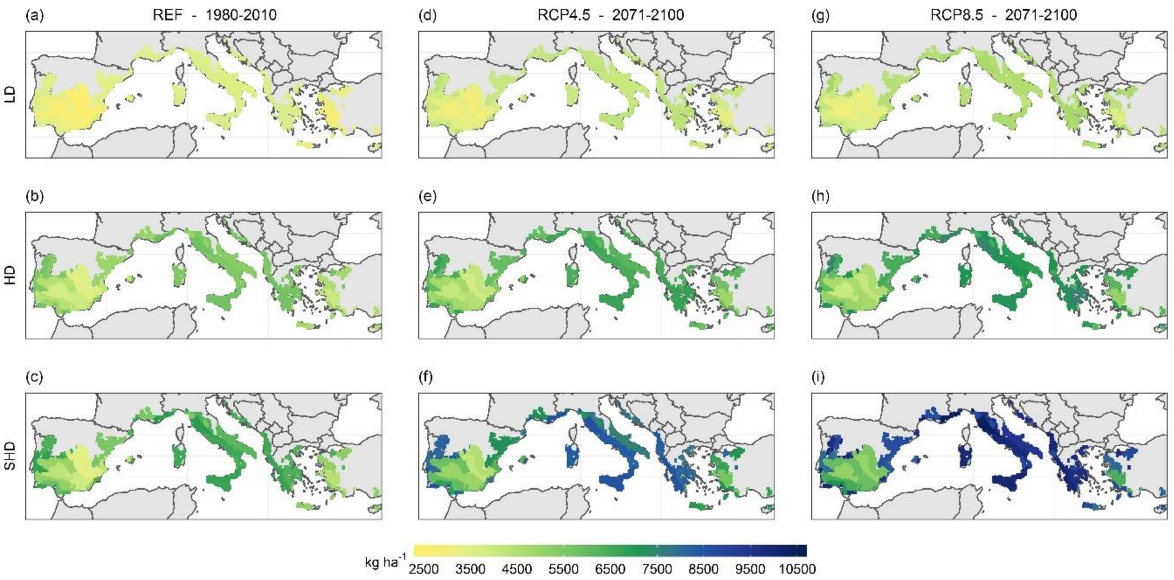

Figure 5: Yield (in kg ha-1) for LD, HD and SHD during reference 1980-2010 (a, b, c) and 2071-2100 period according to RCP4.5 (d, e, f) and RCP8.5 (g, h, i). The same amounts of irrigation estimated in each climate cluster for full-irrigated LD orchard in the reference period are applied for all orchard types.

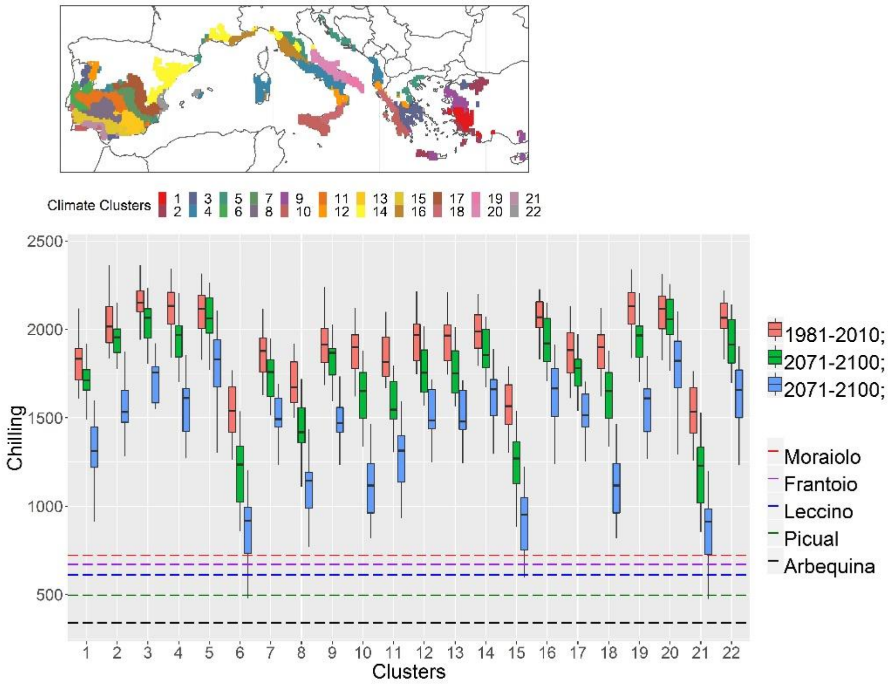

Figure 6: Accumulated chilling units during reference period 1980-2010 and future period 2071-2010 according to RCP4.5 and RCP8.5 for each climate cluster. Dashed lines are the chilling requirement for each cultivar. The box shows the interquartile range (IQR: 25th percentile (Q1) and 75th percentiles (Q3)). The whiskers extend to Q1-1.5*IQR and Q3+1.5*IQR.

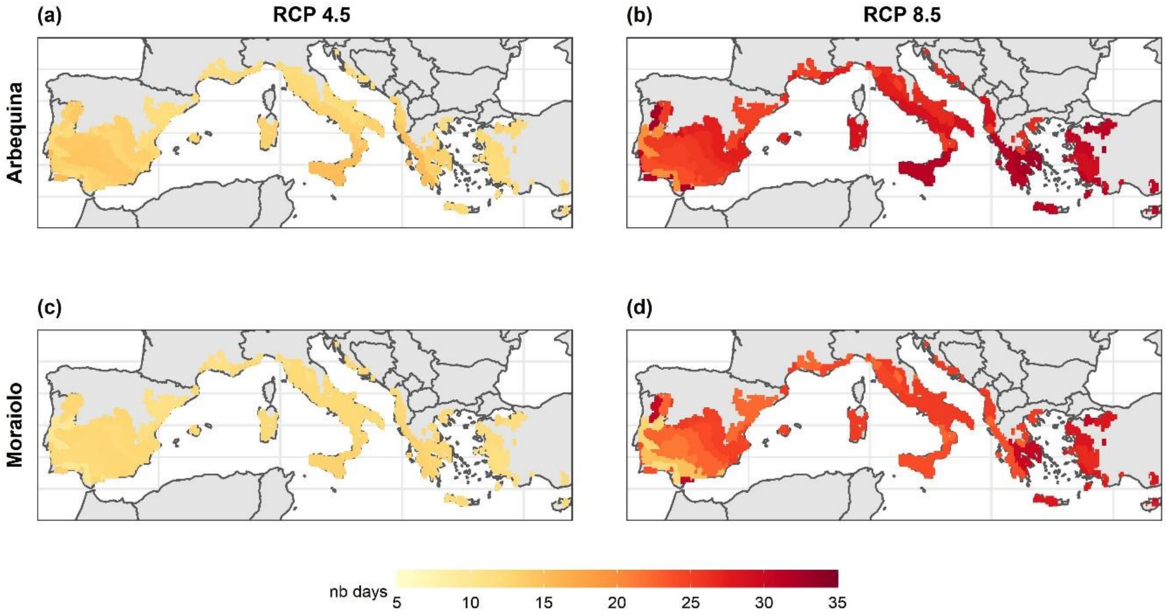

Figure 7: Advance in flowering date (days) for 'Arbequina' (a, b) and 'Moraiolo' (c, d) for 2071-2100 according to scenarios RCP4.5 and RCP8.5 as compared to reference period (1980-2010).