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Is new olive farming sustainable? A spatial comparison of productive and environmental performances between traditional and new olive orchards with the model OliveCan

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 (*Olea europaea* L.) is a widely spread tree species in the Mediterranean. In the last decades, olive farming has known major management changes with high economic and environmental impacts. The fast track expansion of this modern olive farming in these recent years casts doubts on the sustainability of such important tree plantation across the Mediterranean. In this work, we performed a spatial modelling analysis to investigate the implications of climate variability and farming management on the productivity and environmental performances of olive orchards around the Mediterranean. Implementation of this research is based on the use of OliveCan; a process-based model able to illustrate responses of water and carbon balances to weather variables, soil characteristics and management techniques enabling the comprehension of olive orchard dynamics under heterogeneous conditions of climate and agricultural practices. Four main intensification levels were adopted to reflect the main olive grove types from traditional to new intensive plantations: low density LD (100 trees ha^{-1}), medium density MD (200 trees ha^{-1}), high density HD (400 trees ha^{-1}) and super high density SHD (1650 trees ha^{-1}). Managements tested were intensification, water supply (rainfed, deficit and full irrigated) and the fate of pruning residues (exported or left on the soil). Two cases studies in two of the main Mediterranean olive-growing regions with contrasting environmental conditions, Tuscany and Jaen regions, focused on mitigation alternative managements for carbon sequestration. Results showed that olive orchards responses in terms of yield and Net Ecosystem Productivity (NEP) vary along with climatic conditions. Water supply was the main driver with a production function that varies for different atmospheric demands. Application of deficit irrigation proved to boost water use efficiency. Besides, intensification from LD to SHD, presented the greatest improvements, 28-73% for yield and 50-100% for NEP. The C sequestration potential of olive orchards was confirmed. In fact, soil organic carbon (SOC) increased continuously over 400 years of simulation, reaching a state of equilibrium. Moreover, intensification and irrigation improved total carbon sequestration. Management of incorporating pruning residues in the soil increased SOC of 10.5 t C ha^{-1} for Tuscany and 10.8 t C ha^{-1} for Jaen. Findings of this research enabled the identification of the main drivers influencing the productive and environmental performance of olive groves in the

different Mediterranean sub-climates. Impacts of management innovations on olive farming sustainability were also quantified which may help improve production systems for a more sustainable olive cultivation.

Keywords:

Olea europaea; Climate; Agricultural management; OliveCan; Carbon sequestration; Mitigation

1. INTRODUCTION

Olive (*Olea europaea* L.) is the basic tree species among those cultivated in the Mediterranean basin and dominates its rural landscape. Over 10.8 Mha are cultivated worldwide, 95% of which are in the Mediterranean region (FAOSTAT, 2017). All along its history of cultivation, olive has been given considerable prominence regarding its socioeconomic and ecological importance for the area (Tous and Ferguson, 1996; Ponti et al., 2014; Moriondo et al., 2015, Montanaro et al., 2017). Olive groves also provide several ecosystem services. They help preserve natural resources by protecting the soil and sequestering carbon. In fact, agricultural management of olive trees has the potential to increase the accumulation of soil organic matter (Nieto et al., 2010; Massaccesi et al., 2018). The potential of olive tree plantations for storing stable organic carbon acting as CO_2 sinks has been confirmed under some soil conservation practices (Sofo et al., 2005; Proietti et al., 2014; Lopez-Bellido et al., 2016; Proietti et al., 2016; Brunori et al., 2017; Proietti et al., 2017). Nevertheless, the modelling of carbon sequestration by olive groves has been limited to non–specific models simulating general vegetation covers as carbon inputs, while the C production by the different olive grove types in response to climate and management remains little-known (Brilli et al., 2019).

Nowadays, olive sustainability is threatened by different factors including those linked to climate variability (Moriondo et al., 2013, Tanasijevic et al., 2014, Ponti et al. 2014, Fraga et al. 2019). Even though olive is considered a drought-tolerant specie since it lives in areas where water stress is frequent, availability of water has a large influence on vegetative growth (Moriana et al., 2003; Iniesta et al., 2009; Marra et al., 2016). Olive is also limited by frost and high temperatures and to a lesser extent by low soil fertility (Connor and Fereres, 2010, Fraga et al. 2019).

Since the 1950's, olive production techniques have been changing to improve economic sustainability (Fernandez et al., 2013). Traditional orchards present widely spaced trees (usually 50 to 160 trees ha^{-1}) with small canopy cover under rainfed conditions (Beaufoy, 2000). This structure was adapted to the characteristics of cultivation areas regarding soil type, topography and climate (Connor and Fereres, 2010). Starting in the 1970's, new techniques such as mechanical harvesting and localized irrigation have been widely adopted. The latter was an important factor allowing the increase in tree density up to 400 trees ha^{-1} and a substantial boost in productivity. Then, in the early 1990's, hedgerow orchards with densities up to 2000 trees ha^{-1} appeared as a planting system amenable to full mechanical harvesting (Fernandez et al., 2013). Nowadays, and as a result of the new olive growing management solutions adopted, orchards have densities ranging from high-density orchards of 350-700 trees ha^{-1} to super high-density orchards with densities of 1200-2500 trees ha^{-1}. Trees in these orchards are usually irrigated, fertilized and trained to be suitable for mechanical harvesting and pruning, thus increasing productivity and profitability.

The intensification techniques were first widely adopted in the Iberian Peninsula. This brand-new range of vegetation covers have little in common with the prevalent traditional ones. Even though environmental and productive performances of these modern olive groves are still under debate, their expansion has been on a fast track. Investigating economic and environmental impacts of olive farming development is therefore of high-priority not only on already cultivated areas but also on potential ones. Conducting such investigation is dependent on the ability to simulate such a complex system, especially when experimental data are costly to obtain, and difficult to extrapolate to different environments.

In this context, different process-based models have been developed to simulate olive physiology under different environmental conditions. Olive orchard modelling has evolved since the first attempt to estimate the productivity of olive orchards (Abdel-Razik, 1989). Recently 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 water relations, carbon assimilation, growth and productivity. The added value of this model is its ability to illustrate responses of water and carbon balances to weather variables, soil characteristics and management techniques, thus enabling the comprehension of olive orchard dynamics under heterogeneous conditions and identifying farming practices for keeping olive groves sustainable and resilient.

The main goal of this research is to shed light on modern olives groves sustainability on productive and environmental terms and in different Mediterranean sub-climates. Investigating olive orchards dynamics in heterogeneous environmental conditions is crucial to understand the interaction between olive trees and their environment and identify the main drivers influencing their productive and environmental performance. This analysis would help evaluate olive groves adaptation to current climate variability and quantify implications of agricultural management innovations on olive farming sustainability. Such assessment at a regional level covering the Mediterranean would help improve production systems for a more sustainable olive cultivation.

This study is structured on two main sections. The first is dedicated to the implication of olive groves evolution in terms of orchard structure and management practices adopted on productivity and Net Ecosystem Productivity (NEP). On these premises, we analysed different olive groves dynamics in the northern part of the Mediterranean region using the OliveCan model. The second section focuses on the potential of olive groves to mitigate greenhouse gases. In this regard, we assessed carbon sequestration capacities in relation to different management systems for two of the main olive-growing regions in the Mediterranean with contrasting environmental conditions.

2. MATERIALS AND METHODS

2.1. 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. OliveCan core is implemented on several basic components that compute water and carbon balances and simulate the impacts of environmental conditions and management operations on water relations, growth and productivity under both well-irrigated and water-limiting irrigation strategies.

The water balance module in OliveCan is derived from previous developed approach that considers the soil heterogeneity due to localized irrigation: a fraction of surface soil is kept wet while the remaining part is dependent on rainfall (Testi et al., 2006). Soil is discretized into two soil compartments. For each soil zone, the fluxes of effective precipitation, runoff, drainage, water redistribution, and root water uptake are computed for each layer. Soil evaporation and direct evaporation of rain water intercepted by the canopy is also considered. The water balance module is strictly linked - through leaf water potential and stomatal conductance - to the photosynthesis module, which calculates the CO_2 assimilation rate, correctly resolving the dependence between the water and carbon balances of olive trees.

Carbon balance module aims at simulating 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 calculates carbon stocks in tree organs (leaves, shoots, branches, coarse roots, fine roots and fruits) and the fluxes of carbon through the system (photosynthesis, maintenance respiration and growth respiration also at organ level). Fruit photosynthesis and remobilization of CO_2 assimilates are also taken in consideration in the allocation of assimilates. The balance of C in the soil is computed by accounting the inputs (i.e. senescence of fine roots, fall of leaves due to frost damage and senescence and, if so-defined by the user, incorporation of pruning residues) and outputs (heterotrophic respiration) of C to/from the system. The model provides at the end estimates of the NEP rates in the orchard.

Initialization of the model requires weather, soil, environmental and orchard management inputs. Meteorological data correspond to daily values of maximum and minimum air temperatures, average vapour pressure, solar radiation, average wind speed, and precipitation. The atmospheric CO_2 concentration is also required; either as a fixed parameter introduced by the user or as a variable calculated by the model as a function of the year using a fit to Mauna Loa Observatory CO_2 measurement (Keeling et al., 1976; Thoning et al., 1989). 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 layer (whose number and depth are user-defined) and for each soil compartment are to be defined. Inputs on orchard typology (planting density, row orientation, latitude, age, ground cover and leaf area density) are also required.

The management operations simulated by the model are irrigation, tillage, harvesting and pruning. Management operations' attributes should be introduced to the model. The user should define the dates for pruning, tillage and harvest. Different pruning intensities can be simulated through a customizable parameter representing the fraction of foliage removed in each operation. The user is also required to decide whether the residues are exported or incorporated into the top soil layer. Irrigation is applied as a fraction of the evapotranspiration (ET) lost since the last irrigation event. The implementation of this approach needs specification of starting and ending dates of irrigation season, the time interval between irrigations and the mentioned fraction of cumulative ET lost since the last irrigation.

2.2. Meteorological data and climate clustering

Daily data for minimum and maximum temperature (T_{min}, T_{max}, °C) and cumulated rainfall (R, mm) over the olive tree cultivated area were obtained from the gridded E-OBS dataset (version 8.0 at 0.25° resolution) (Cornes et al., 2018). It was downscaled from its original resolution (25 km) to 10 km for the period 1980-2010 as a baseline for the present period (5700 grid points) (Moreno and Hasenauer, 2015). This dataset was further integrated with global radiation (Rad, MJd^{-1}), calculated for each grid point as a function of daily temperature range using the Bristow-Campbell model (Bristow and Campbell, 1984). Observed daily mean wind speed (WS, $m\ s^{-1}$) and daily minimum and maximum relative humidity (RH_{min}, RH_{max}, %), for about 700 weather stations covering the Mediterranean basin, were downloaded from the Global Historical Climatology Network (GHCN-Daily, Version 3) (Menne et al., 2012) hosted by NOAA National Climatic Data Center (NOAA-NCDC, 2017) (Fig. 1).

These data were linearly interpolated, on a daily time step, to the grid point centroid of E-OBS using a weighted inverse-distance approach.

Since E-OBS data of version 8 suffers of important biases especially in rainfall estimation (Hofstra et al., 2009), the approach proposed in Fibbi et al. (2016) was applied to test and correct the eventual errors in rainfall daily data. According to the proposed procedure, the mean annual rainfall over the period 1980-2010 was extracted from 1300 weather stations over the basin. These data were interpolated at each centroid of E-OBS grid data using a local multi-regressive approach exploiting the relationship between annual rainfall, elevation and distance from the sea of the relevant weather stations (Fig. 1). Since the distribution of observed data is not uniform across the basin, with areas presenting a higher density of observation (e.g. Italy), we used a flexible approach to select the number of stations to be used for the calibration of the local multi-regressive approach. For each grid point 10x10 km to be estimated, we selected the closest observed values in a range between 5 and 30 weather stations. For each interval, we calibrated a local multi-regression, where the prediction error associated to each model was estimated via a leave-one-out cross validation. Finally, the model minimizing the RMSE was selected to predict the value of the missing point. This approach was firstly validated on the observed series for 1300 mean annual rainfall data. Finally, for each grid point the ratio between interpolated and E-OBS yearly rainfall data was used to rescale the relevant E-OBS daily rainfall data so that the average annual rainfall of E-OBS matched the observed data.

In order to limit the simulations to be performed over the basin, the entire dataset consisting of 5700 grid points was clustered by aggregating each grid point depending on their affinity for a set of yearly and seasonal climatological data. Accordingly, for each grid point we calculated the average T_{max}, T_{min}, total rainfall for autumn (SON), winter (DJF), spring (MAM) and summer (JJA), the average annual T_{max} and T_{min} and the average number of rainfall events per year. The High Dimensional Data Clustering approach (HDDC) implemented in R (HDclassif package, R-project), was used for clustering this dataset (Bergé et al. 2012). This approach is based on the Gaussian mixture model that is parameterized taking into account that high dimensional data are located in different sub-spaces with low dimensionality. This parametrization therefore, limiting the number of parameters to estimate, is particularly suitable for high dimensional data clustering. In HDDC algorithms, different models' complexity may be selected depending on the number of parameters to be estimated. Each of them is evaluated according to Bayesian Information Criterion (BIC). This parametric method, aiming at avoiding overfitting, considers the number of parameters in the model as a penalty term. HDDC algorithm will keep the model having the lowest BIC and the relevant clusters. The final output of HDDC indicated 22 significant clusters and the meteorological data associated to each cluster where then averaged on a daily time step. Since in the aggregation process, rainfall events, being a discontinuous variable may suffer of over prediction of frequency, a specific threshold was selected for each identified cluster so that the average number of rainfall events obtained for the cluster matched the average rainfall events calculated singularly for each E-OBS grids and averaged over the cluster.

These datasets (climate clusters) over South Europe were then used as inputs for olive orchard simulations using OliveCan.

2.3. Soil characteristics

We performed the simulations for 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 cm^3 g^{-1} (Villalobos et al. 2016). Soil organic carbon was initialized at 0.7%. These soil characteristics were considered as representatives of the medium soil quality existing in traditional olive groves within the Mediterranean basin. The same type of soil was used in all clusters.

2.4. Alternative management scenarios

Given the large variability of olive orchard types and managements over the region of study, four main intensification levels were adopted to reflect the main olive grove types from traditional to new intensive plantations: low density LD (100 trees ha^{-1}), medium density MD (200 trees ha^{-1}), high density HD (400 trees ha^{-1}) and super high density SHD (1650 trees ha^{-1}). Alternative management scenarios were produced for each level of intensification by defining the fate of pruning residues (i.e.

either exported or left on the soil) and water supply (rainfed or irrigated conditions). When irrigated, watering events were scheduled every two days during an irrigation season covering from May 15 to October 10. Deficit and full irrigation scenarios were simulated. Irrigation requirements for full irrigation were calculated by the model for each cluster and for each level of intensification. Pruning was simulated by removing a fraction of the canopy on December 21. The fraction of pruning and the pruning intervals were pre-defined for each typology (Table 1). Harvesting date was simulated on December 11. The main characteristics of the simulated orchards types are shown in Table 1.

2.5. Simulation experiments

2.5.1. Productive and environmental impacts of technical innovation in olive groves

OliveCan was used to simulate olive orchards in all climate clusters over Southern Europe. For each cluster, the combination of orchard typologies and management scenarios were run for the reference period 1980-2010 with no tillage and pruning residues being exported. The atmospheric CO_2 concentration was set according to the measurements of the Mauna Loa Observatory.

Three sets of runs were conducted (Table 2):

- Simulation of conventional typology: the low density rainfed orchard was considered as the conventional typology for the study area.
- Simulation of irrigation impacts: deficit and full irrigation strategies corresponding to the application of, respectively, 30 % and 100% of irrigation requirements were simulated for the low density orchard in each cluster.
- Simulation of increasing intensification: low, medium, high and super high densities (LD, MD, HD, and SHD) were simulated according to the characteristics shown in Table 1. Irrigation was simulated by the application of 30% and 100% of irrigation requirements.

Dry matter yield, irrigation amounts, and water use efficiency (WUE-IR = g of dry matter yield / mm of irrigation; WUE-ET = g of dry matter yield / mm of ET) were analysed. Net Ecosystem Productivity (NEP) was also evaluated ($NEP = GPP - R_{eco}$, where GPP is the Gross Primary

Productivity and R_{eco} the Total Ecosystem Respiration). The NEP flux was considered positive when C moves from the atmosphere to the ecosystem.

Impact response surfaces of yield to variation in water inputs (irrigation + total rainfall) and atmospheric demand (ET_0) for LD, MD, HD and SHD was also analysed. Local polynomial regression fitting (loess), (stats package, R-project), was used to fit yield response to a polynomial surface determined by water inputs and ET_0 as predictors. Outputs of increasing intensification simulation were used for fitting.

2.5.2. Mitigation alternative managements for carbon sequestration

For this analysis two climate clusters having different climate characteristics and with important olive land cover were chosen. The first cluster covers mainly the region of Tuscany in Italy, characterized by average annual rainfall of 725 mm, mean maximum and minimum temperature of 18.5 and 9.3 ºC, respectively. The second cluster covers the province of Jaen in Spain, with annual rainfall 429 mm, and mean maximum and minimum temperature of 20.3 and 8.4 °C, respectively. The soil used for these simulations is the same 1 m medium texture soil with very low organic carbon (0.2%). This type of soil was chosen to emphasize the potential of olive orchards for C sequestration in the soil. Atmospheric CO_2 concentration was fixed to 400 µmol mol^{-1}.

Three simulation experiments were conducted for both regions:

- Exp. 1. Long term carbon sequestration capacity in olive groves: CLIMAGEN, an adaptation of WGEN (Richardson and Wright, 1984) and SIMMETEO (Geng et al., 1986, 1988) weather generators, (Villalobos, unpublished) was used to create a climate data series of 400 years for the two main olive-growing regions selected. A long run was conducted simulating low density orchard under rainfed conditions. The two treatments compared in terms of soil organic carbon (SOC), were a) incorporating pruning residues in the soil (mitigation alternative), b) residues exported outside the farm.

- Exp. 2. Effects of intensification on C sequestration in soil and tree biomass: clustered climate data of 30 years was used. Low, medium, high and super high densities were simulated under rainfed and full irrigation conditions.
- Exp. 3. Effects of water supply on C sequestration in the soil and tree biomass: clustered climate data of 30 years was used for this simulation. High density orchards were simulated under rainfed and different irrigation regimes, namely 30%, 50%, 70% and 100% of irrigation requirements for maximum evapotranspiration.

3. RESULTS

3.1. Climate clustering

Climate clustering analysis shows heterogeneity between olive growing clusters in the Mediterranean region. Over the reference period, a large difference is observed between the centre and the south-western part of the Mediterranean (Fig. 2). The latter presents the driest clusters with the lowest amount of annual rainfall with values between 398 mm and 430 mm. Low annual rainfall is also observed in some clusters over Turkey. The highest annual rainfall is registered in centre and north-east of Portugal, south of France, some regions of Greece and in Italy. The highest value is registered in the centre and western coastlines of Italy with annual precipitation exceeding 800 mm. A gradient in precipitation between the western and the eastern coastlines of Italy is also evident.

Reference evapotranspiration decreases from West to East with values higher than 1400 mm year^{-1} in the south-west of the Iberian Peninsula. The centre of Spain, some regions of Turkey and the south of Italy show annual ET_0 higher than 1350 mm year^{-1}. Lower values of ET_0 are in the centre of the study area with most of Italy having less than 1200 mm year^{-1}.

3.2. Productive and environmental impacts of technical innovation in olive groves

3.2.1. Conventional typology

Climatic clusters covering all olive production regions in Italy and Greece had the highest yield (>2500 kg ha^{-1} of dry matter). These clusters cover also some regions in Portugal. The yield inter-annual coefficient of variation is at its minimum (<15%) in these regions. Clusters covering the south and north-east of Spain, south of France and Turkey have yield between 2000 and 2700 kg ha^{-1} with coefficient of variation around 30%. The lowest yield (<1800 kg ha^{-1}) occurs in clusters located in centre and south-eastern coastlines of Spain and some regions in the south of Italy. These clusters present also the highest CV with values over 40%.

Simulated NEP is always positive across the study area, although it approaches carbon neutrality (NEP=0) in very dry years (data not presented). NEP is higher in some more humid areas of Italy and Greece with mean annual values above 8 t CO_2 ha^{-1}. The lowest annual values of NEP, (<5 t CO_2 ha^{-1}) occurs in centre and south-eastern coastlines of Spain. The south of Spain and parts of Turkey have annual NEP around 6 t CO_2 ha^{-1}. These regions present low annual rainfall and high mean annual temperature.

3.2.2.Impacts of irrigation

Figure 4 shows the impact of irrigation on yield (Fig. 4a, b) and NEP (Fig. 4c, d) on low density olive orchards. Deficit irrigation covering 30% of total irrigation requirements increases yields from 16% to 34% and NEP between 19% and 35% in the studied areas, with the highest increases being predicted in those with low rainfall or low evaporative demand (ET_0 below 1200 mm $year^{-1}$). These clusters cover the centre and eastern coastlines of Spain and the centre and eastern part of the study area, mainly Italy and Greece. The lowest impact is estimated for areas with higher evaporative demand (ET_0 above 1400 mm $year^{-1}$), which cover mostly the south of the Iberian Peninsula.

The impact of full irrigation shows a different spatial pattern. The highest increase appears in the centre and south-eastern coastlines of Spain and a small region in the south of Italy, i.e. the driest parts of the study area. In these regions, the increases range between 56% and 88% in yield and between 62% and 109% for NEP. In all remaining regions, the increases are lower than 35% for yield and 40% for NEP.

3.2.3.Intensification in olive orchards

Figure 5 shows water amounts needed according to different levels of intensification under deficit and full irrigation. Under the conditions of our simulations, intensification is accompanied by an increase in applied irrigation. Dry clusters present higher irrigation requirements compared to the wet clusters but coefficient of variation between clusters is lower than 14% in the four orchard types simulations.

The impact of intensification is analysed by evaluating the change of irrigation requirement (Fig. 5), yield and NEP (Fig. 6) for each orchard type (MD, HD, SHD) compared to the LD irrigated orchard under deficit irrigation.

The spatial pattern of changes in yield and NEP is similar for all the typologies showing a high influence of climate conditions (Fig 6). The highest increases of yield and NEP predicted are in clusters covering the centre of the Mediterranean namely Italy and Greece corresponding to the regions with the highest rainfall and lowest ET_0. The lowest values of increase are predicted in the regions of the west of Turkey, small region in the south of Italy and mainly the south of the Iberian Peninsula especially the centre and south-eastern coastlines of Spain. Moderate increases are predicted for the south of Spain, Portugal, north-east of Spain, south of France and north of Turkey.

Switching from LD to MD presents moderate increases in yield and NEP of 8-20% and 10-23%, respectively. Intensification to HD types of orchard would increase yield between 18% and 49% corresponding to an increase of irrigation requirements between 33 mm and 48 mm. NEP increases, in this case, between 25% and 58%. Regions presenting the highest improvements reach increases higher than 35% for yield and 40% for NEP corresponding to irrigation around 35 mm. Meanwhile, in regions with the lowest improvements, yield and NEP are lower than 21% and 35% respectively while increases in irrigation reach values higher than 42mm. The case of extreme intensification, from LD to SHD, presented the greatest increases, 28-73% for yield, 62-87 mm for irrigation and 50-100% for NEP. Regions presenting the highest improvements correspond to increases in yield (>60%), NEP (>84%) and irrigation (62-78 mm). Besides, regions with moderate improvements have increases in yield of 37-50%, NEP of 60-72% and irrigation of 63-87 mm.

Analysis of average water use efficiency for ET (WUE-ET) for the study area shows its increase with intensification from 0.56 g L^{-1} for LD to 0.62 g L^{-1} for MD, 0.66 g L^{-1} for HD and 0.73 g L^{-1} for SHD.

Cluster with higher rainfall reaches the maximum values of 0.75 g L^{-1}, 0.83 g L^{-1} and 0.95 g L^{-1} for MD, HD and SHD, respectively.

Figure 7 shows the response of yield to combined effect of ET_0 and water inputs for LD, MD, HD and SHD orchards. The pattern of yield increase differs according to the type of orchard. On a general overview, the yield increases as the ET_0 decreases and water inputs increases, albeit the peak of potential yield is not totally centred at the lowest ET_0 and highest water inputs. Curves of the highest potential yield are tilted from the highest water inputs showing that the impact of water input is restrained by the ET_0. For LD orchard (Fig. 7.a), high water inputs in regions with ET_0 lower than 1200 mm does not increase the yield to its potential highest value. For LD and MD (Fig. 7.a, b), yield isolines are more diagonal at higher ET_0 showing the higher weight for ET_0 than water inputs on yield response. The rate of change of yield response is higher at higher densities, HD and SHD (Fig. 7.c, d). For SHD (Fig. 7.d), yield isolines are more plain reflecting a higher weight of water inputs than ET_0 in potential yield response.

3.3. Mitigation alternative managements for carbon sequestration

3.3.1.Long term carbon sequestration potential in olive groves

The long-term variation of soil organic carbon for 400 years (Exp. 1) is presented in Fig. 8. The SOC increases until it tends to a plateau. Increase in SOC is higher in Jaen than in Tuscany reaching at the end of the simulation a total accumulation of 21.6 t C ha^{-1} and 10.9 t C ha^{-1}, respectively.

Simulation of incorporating pruning residues in the soil results in a continuous increase of SOC for both clusters, maintaining the same difference between the two clusters in SOC accumulation. By the end of the simulation, this management compared to the conventional one increases the SOC for the cluster of Jaen by 10.8 t C ha^{-1} and for the cluster of Tuscany by 10.5 t C ha^{-1}.

All the simulations tend to equilibrium. The levels of average null C flux are 20.6 t C ha^{-1} and 31.4 t C ha^{-1} for Tuscany cluster and 30.6 t C ha^{-1} and 42.3 t C ha^{-1} for Jaen cluster, for respectively exporting and incorporating in the soil of olive pruning residues managements.

3.3.2. Effect of intensification on C sequestration

The patterns of total carbon sequestration (C stored in the soil and in the standing biomass) expected for different intensification levels are shown in Fig. 9. In the dry cluster (Jaen) all orchard types present the same pattern of carbon sequestration under rainfed conditions (Fig. 9a), accumulating an average of 19 t C ha^{-1}, with the exception of HD which has higher carbon sequestration of 26.8 t C ha^{-1}. Under full irrigation (Fig. 9b), carbon sequestration increases for all types. HD and SHD show the same pattern of C accumulation and have the highest rates, sequestering 51.4 and 51.9 t C ha^{-1}, respectively, compared to LD (26.9 t C ha^{-1}) and MD (34.3 t C ha^{-1}) in 30 years. In general, irrigation almost doubles the carbon sequestration for all the typologies excluding low density.

In the wet cluster (Tuscany) under rainfed conditions (Fig. 9c) simulations shows paired patterns for carbon sequestration, LD and MD having lower carbon accumulation (25 and 27.5 t C ha^{-1}, respectively after 30-year cultivation) compared to HD and SHD with 52.6 t C ha^{-1} and 48.1 t C ha^{-1}. The HD orchard has slightly higher carbon sequestration than SHD. Under full irrigation (Fig. 9d), all typologies present different patterns of carbon sequestration with values between 31.4 and 64.6 t C ha^{-1}. Under this more humid climate, the relative advantage of irrigation over rainfed in terms of C sequestration is much lower.

3.3.3. Irrigation effect on olive groves carbon sequestration

Figure 10 shows the effect of different level of irrigation on the C sequestration. In the wet cluster (Tuscany) irrigation has no significant effect on SOC, while the effect is strong in the dry cluster (Jaen) (Fig. 10a). SOC remains almost constant for irrigation amounts higher than 70% (Fig. 10a). For higher amounts of irrigation (>=70%), SOC in the dry cluster almost equals that of the wet cluster.

Fig. 10b shows the same irrigation effect but over the total carbon sequestrated (i.e. soil O.M + tree roots + above ground biomass). Irrigation increases total carbon in both clusters. Even though total carbon in the wet cluster is higher than in the dry cluster, the increase is more significant in the latter. Hence, irrigation reduces the gap between the wet and the dry cluster. Under full irrigation, total carbon increases compared to the rainfed condition increased by 19.6 t C ha^{-1} for the dry cluster and 7.2 t C ha^{-1} for the wet cluster.

4. DISCUSSION

4.1. Productive and environmental impacts of technical innovations in olive groves.

4.1.1. Conventional orchard typology

On a regional scale and during the reference period, simulations shows higher yield over the central regions of the Mediterranean namely Italy and Greece (Fig. 3). The lowest yield is over centre and south-east- of Spain and some areas in the south of Italy. The remaining regions presents moderate average yields. This regional distribution of yield and NEP is strongly associated with climate. The annual rainfall and ET_0 are directly and inversely proportional to productivity, respectively.

By using a single soil type our analysis removes the impacts of soil quality on olive productivity while those of climate and management remain. Considering the latter, we compared some of our productivity results to experimental data. Over Andalusia region, simulated olive yield was comparable to findings of Pastor et al. (1999) reporting yield of 2030 kg ha^{-1} for rainfed traditional orchard. Statistics reported an average yield for Andalusia region around 1000 kg ha^{-1} (MAPA, 2018). This lower value can be linked to the fact that we are simulating potential yield. In fact, there are also some factors with high influence on olives that are not simulated by the model, namely diseases and pests, which may have generated some bias mainly in wetter and mild regions. Those areas showed the highest simulated productivity while the actual value is usually lower in real-life commercial farms.

4.1.2. Impacts of irrigation

The contribution of irrigation to increasing productivity in our study (Fig. 4) confirms previous works (Moriana et al., 2003; Gucci et al., 2007, 2009). Even though our study area presents a high climate variability and water availability differs between clusters, deficit irrigation proved to be a sustainable management option, able to save water and increase water use efficiency in all clusters. With full irrigation, water use efficiency of irrigation water (WUE-IR) was below 2.8 g L^{-1} (fruit dry matter) for all the study area. Applying deficit irrigation boosts water use efficiency, which ranged between 3.4 g L^{-1} in the centre of Spain and 9.3 g L^{-1} over the centre west of Italy. The variability can be explained by the atmospheric vapour pressure deficit (VPD) effect over water productivity. In fact, at low VPD, the evaporative driving force of water transport is reduced which decreases water loss and modulates water balance (Testi et al., 2008).

Advantages of deficit irrigation application to rationalize water consumption and increase water use efficiency in the arid and semi-arid areas was already a matter of consensus in previous studies (Iniesta et al., 2009; Caruso et al., 2013; Gucci et al., 2019) but our work shows that the improvement in WUE is very much dependent on local climatic conditions. Therefore, calibration of deficit irrigation should be set at local level for a better efficiency.

4.1.3. Intensification in olive orchards

Impacts of intensification in olive orchards are assessed regarding variations in yield, irrigation required and NEP of medium, high and super-high density compared to the behaviour of the low density orchard. Considering the difference of environmental conditions between simulations conducted in our study and actual orchard, we compared some of our results in term of olive productivity to some experimental data. Over Andalusia region, olive yields resulting of the increase of intensification level were comparable to findings of Pastor et al. (2007) reporting yield of 2280, 4200, 5330 kg ha^{-1} for MD, HD and SHD respectively and also comparable to findings of Diez el al. (2016) reporting yield of 5540 kg ha^{-1} for SHD orchards. Over centre of Italy, our results were in accordance with observations of Gucci et al. (2019) for full irrigated SHD orchard with a yield of 5400 kg ha^{-1}. In general, olive yield is proportional to the level of intensification. This can be linked to the higher interception of radiation that is associated with denser planting (Villalobos et al., 2006; Proietti et al., 2012). Many studies have verified a significant linear increase in olive yield with increased density (Villalobos et al., 2006; Proietti et al., 2015).

The spatial variation of the impact of intensification is associated to that of climate (Fig. 6). Clusters with the lowest rainfall has the lowest increase in yield under all typologies. The irrigation amounts (Fig. 5) differ little between the clusters with highest and lowest evaporative demand (south of Spain and centre Italy respectively). Coefficient of variation of water amounts applied under deficit irrigation in all simulations are lower than 14%. This is explained by the distribution of rainfall that tends to be lower during the irrigation season (spring, summer) in all olive production areas.

Water use efficiency for ET (WUE-ET) for the study area shows its increase with intensification. In general, intensification imply an increase in applied irrigation which helps increasing root biomass and density. The result is a reduction of drainage and an increase in yield even when only 30% of the full requirement is applied. Furthermore, intensification means a higher ground cover which reduces soil evaporation and therefore increases transpiration (data not shown). This is an important finding, as it suggests that - throughout different climates - intensification entails *per se* a better use of water.

Our results show that increase in yield is not driven by water inputs only but depends also on evaporative demand (Fig. 7). For low density orchard, high amount of water inputs at low level of ET_0 are not sufficient to reach the highest value of potential yield. At higher ET_0, the response of yield is more driven by ET_0 than water inputs. This can be explained by the effect of atmospheric VPD on the regulation of tree water stress and the maintenance of water balance. Intensification of olive orchards gave more weight to water inputs than ET_0 in the response of yield. This is mainly linked to the reduction of soil evaporation due to a higher ground cover in intensive orchard. This finding showed that production function is not stable for different water demands and that water is the most important limiting factor for olive production. Yield surface response of Fig. 7 can be presented as a summary model for potential productivity. Knowing the demand (evaporative demand) and offer (rainfall+irrigation) of water, this summary model can be used as a quick tool to assess the potential productivity for a certain case study.

Intensification of olive orchards seems an interesting alternative for the new orchards with regard to productivity and water use efficiency. Even though this new system shows good results in all the study area, assessment at local scale remains critical to evaluate its suitability in other aspects not included in the model (e.g. pests, diseases). Several studies have focused on evaluating row distances (densities) for olive orchards in specific locations (e.g. Larbi et al., 2012). Our study is the first in evaluating the complex interaction between intensification and climate using a model as the only tool available for this goal. Our results indicate that the potential of HD and SHD orchards is higher in the more humid parts of the Mediterranean (e.g. Italy, southern France, Adriatic coast) rather than in the driest and warmer areas of southern Spain where most HD and SHD have been planted so far. Future incorporation of biotic factors in OliveCan will improve substantially its predictive capability in adaptation analyses.

4.2. Mitigation alternative managements for carbon sequestration

4.2.1. Long term carbon sequestration potential in olive groves

Long-term simulations (400 years) shows a continuous increase in soil organic carbon reaching a state of equilibrium; nevertheless, this equilibrium is reached much later in time than our simulation span (Fig. 8). This equilibrium differs according to the climate and to the management practices simulated. Differences between the two analysed clusters can be linked to differences in heterotrophic respiration rates (RESP-H). When pruning residues are exported, the wet cluster had mean annual RESP-H of 2.17 t CO_2 ha^{-1} while in the dry cluster RESP-H was 1.72 t CO_2 ha^{-1}. The lower RESP-H rates predicted for the driest cluster are due to the lower biomass production and therefore lower inputs of soil organic matter.

Long-term capacity of olive groves to store carbon in the soil was also confirmed by Nieto et al. (2010) and Massaccesi et al. (2018). While some estimations of carbon storage assume a linear relationship between carbon inputs and carbon stocks, results in our study lead to rejection of this hypothesis. Figure 8 shows that reaching a new equilibrium after any disturbance takes so long that no empirical experiment can be reasonably carried out nor envisaged, and second that whenever the carbon stock is changing, any extrapolation of experimentally obtained rates will be necessarily misleading. Our results agree with those of Stewart et al. (2007) and Regni et al. (2017) who found that SOC accumulation is limited by C input level. Although there is clearly a potential for SOC sequestration (Fig. 8), traditional olive groves are one of the cropping systems cultivated continuously for the longest time over the same soils, and even after thousands of years of olive growing, they certainly do not stand out for its high values of SOC.

Furthermore, our simulation points out the potential of some management options to foster the soil carbon pool. Simulations of incorporating pruning residues shows higher potential of SOC sequestration in both clusters. Nieto et al. (2010) showed the benefit of applying pruning residues as soil amendment by increasing carbon sequestration by 0.5 t C $ha^{-1}year^{-1}$ during the 6 years of the experiment (rate similar to our simulation results). Other researchers confirm also the efficiency of incorporating pruning residues in improving SOC (Gomez-Muñoz et al., 2016; Vicente-Vicente et al., 2016). The reuse of pruning debris generated in the olive grove as organic amendment to the soil proved to be an efficient way to increase the soil capacity to store carbon and to mitigate CO_2 emissions. Adoption of this system showed also high potential for increasing soil fertility, improving infiltration capacity and decreasing soil erosion (Sofo et al., 2005; Gómez-Calero et al., 2009; Repullo et al., 2012; Gómez-Muñoz et al., 2016). A soil management system with incorporation of olive orchard pruning residues can be considered as a good alternative for improving sustainability and increased mitigation.

4.2.2. Effect of intensification on C sequestration

Under rainfed conditions, HD presents the highest carbon sequestration potential in the driest cluster (Fig. 9a, 9c). In that case, the capacity for carbon sequestration in SHD is lower than that predicted for HD and even similar to that observed for MD and LD. This behavior can be explained by the reduced biomass accumulation in response to water deficit. In other words, SHD loses some of the environmental advantages when heavily stressed. In the wetter cluster, nevertheless, its sequestration potential is still very high and similar to HD (Fig. 9c).

Under full irrigation, SHD and HD have the highest total carbon sequestration with values of 65 t C ha^{-1} and 60 t C ha^{-1} in Tuscany and 52 t C ha^{-1} and 51 t C ha^{-1} in Jaen, respectively. The increase of intensification levels implies the increase of irrigation amounts. Irrigation boosts biomass production and thus the input of SOC from both above-ground and below-ground biomass residues (Entry et al., 2004), and also improves the soil microbial activity. It can be concluded that the higher the intercepted radiation, the higher is the input for the carbon pool accumulation.

Regression analysis between olive oil production and carbon sequestration for each orchard typology shows the dependency between these two variables. Production of 1 litre of olive oil increases the carbon sequestration in olive groves by 2.6, 3, 3 and 2.6 kg CO_2 for LD, MD, HD and SHD, respectively. These values are comparable with findings of Proietti et al. (2017) reporting carbon sequestration values ranging between 1.35 and 6.15 CO_2 L^{-1}. Estimation of the potential CO_2 sequestration will help quantify the environmental impacts of olive oil production. Such assessment emphasis the role of olive tree plantation as a sink of CO_2 and promote it as a production system able to mitigate climate change.

4.2.3. Irrigation effects on C sequestration

In the wetter regions, irrigation does not affect the SOC of the orchard (Fig. 10.a). This may be explained by the fact that in those regions already receiving high rainfall, irrigation adds little to biomass productivity and therefore for inputs of C in the soil. This is in accordance with results of Kavvadias et al. (2018), who found no differences in SOC between irrigated and rainfed orchards in Greece. The largest amount of irrigation in the wet cluster resulted in a slight decrease in SOC (Fig. 10.a). This can be linked to the small difference in RESP-H between 50% and full irrigation requirements corresponding to values of 3.5 t CO_2 ha^{-1} and of 3.7 t CO_2 ha^{-1}, respectively. In fact, higher amount of irrigation promotes higher RESP-H rates and therefore a reduction in SOC.

In the dry regions, deficit irrigation improves strongly SOC sequestration. The effect occurs up to a plateau of 70% of the full water requirement (Fig. 10.a). At these levels, the difference in SOC accumulation between the dry and wet cluster is reduced. Also, Gillabel et al. (2007) found that in dry regions with low C soils irrigation could increase SOC.

Our results show that irrigation impacts are not limited to orchard productivity but include also improvement of SOC and the olive orchard overall potential to sequestrate carbon. In fact, the improvement of soil water content brought about by irrigation favours the formation of humus (Stevenson, 1994; Karyotis et al., 2014).

For both clusters, increasing irrigation results in an increase in total carbon pool up to a plateau (Fig 10.b). The wet cluster has higher potential for total carbon sequestration due to the lower cost (in terms of respiration) of maintaining higher above ground biomass. The impact of irrigation is more pronounced in the dry cluster with a significant increase in total carbon (SOC and tree biomass) corresponding to an increase in irrigation amount applied (Fig. 9.b). In fact, irrigation enhances biomass production and hence additional above ground residues or below ground roots turnover resulting in larger inputs of soil organic matter (Entry et al., 2004).

Apart from increasing productivity, irrigation reinforces the mitigation potential of olives groves as carbon sinks.

CONCLUSION

Simulation of olive orchards around the Mediterranean using OliveCan has shown interaction between olive trees and their environment enabling the comprehension of olive orchard dynamics under heterogeneous conditions of intensification, water and residue management. The C sequestration potential of olive orchards is improved by increasing the level of intensification, irrigating and incorporating pruning residues, but the response varies along with climatic conditions. Findings of this research identify the drivers influencing the productive and environmental performance of olive groves in the different Mediterranean sub-climates and quantify their impact. They may help improve production systems for a more sustainable olive cultivation and highlight the environmental role of olive production and its potential implication in mitigating climate change.

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Table 1: Characteristics of orchard typologies. 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 (fraction)
Low density	rainfed	10	10	0.2	0.85	2	0.1
Medium density	rainfed	7	7	0.2	0.85	2	0.1
Low density	irrigated	10	10	0.25	0.85	1	0.05
Medium density	irrigated	7	7	0.3	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 olive orchards simulations over Southern Europe for reference period 1980-2010

Simulations	Orchard typologies	Irrigation
Conventional typology	LD	Rainfed
Irrigation impacts	LD	30 % and 100% of irrigation requirements
Increasing densities	LD, MD, HD, SHD	30 % and 100% of irrigation requirements

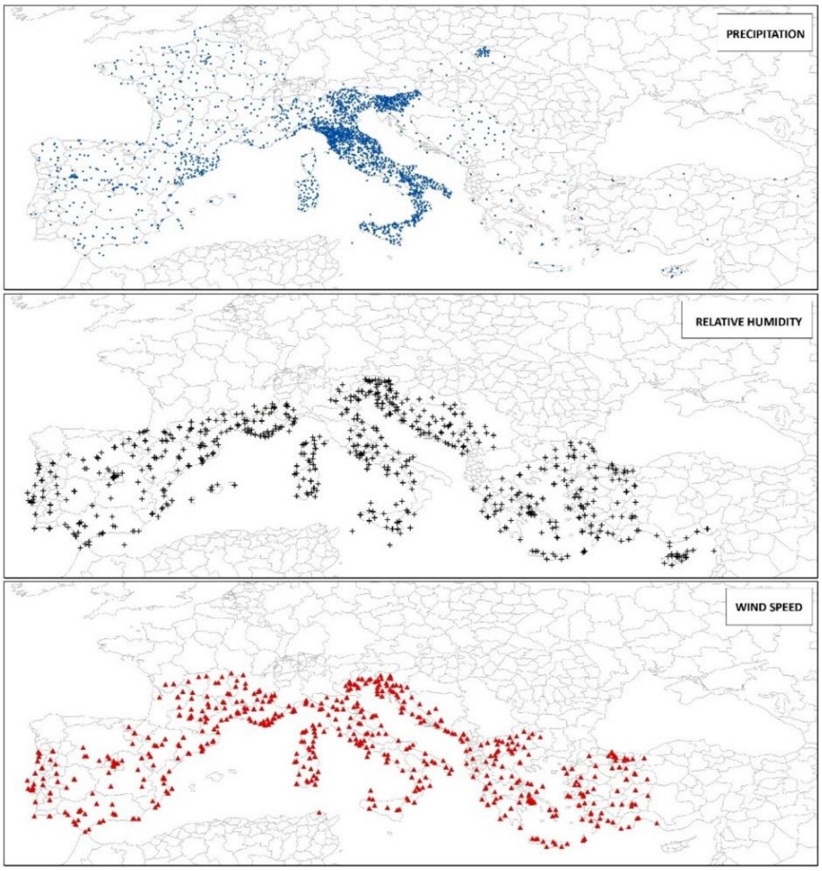

Figure 1: Weather station network for precipitation, relative humidity and wind speed over the study area

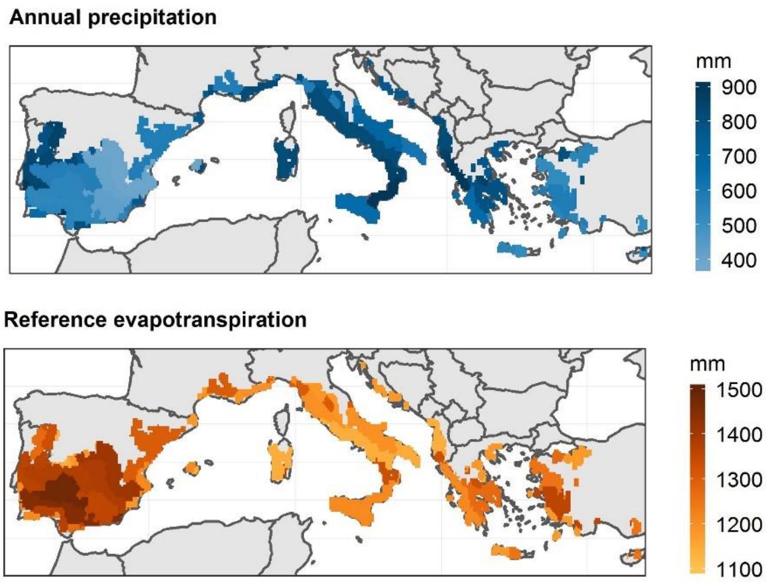

Figure 2: Precipitation and reference evapotranspiration (ET_0) for reference period 1980-2010

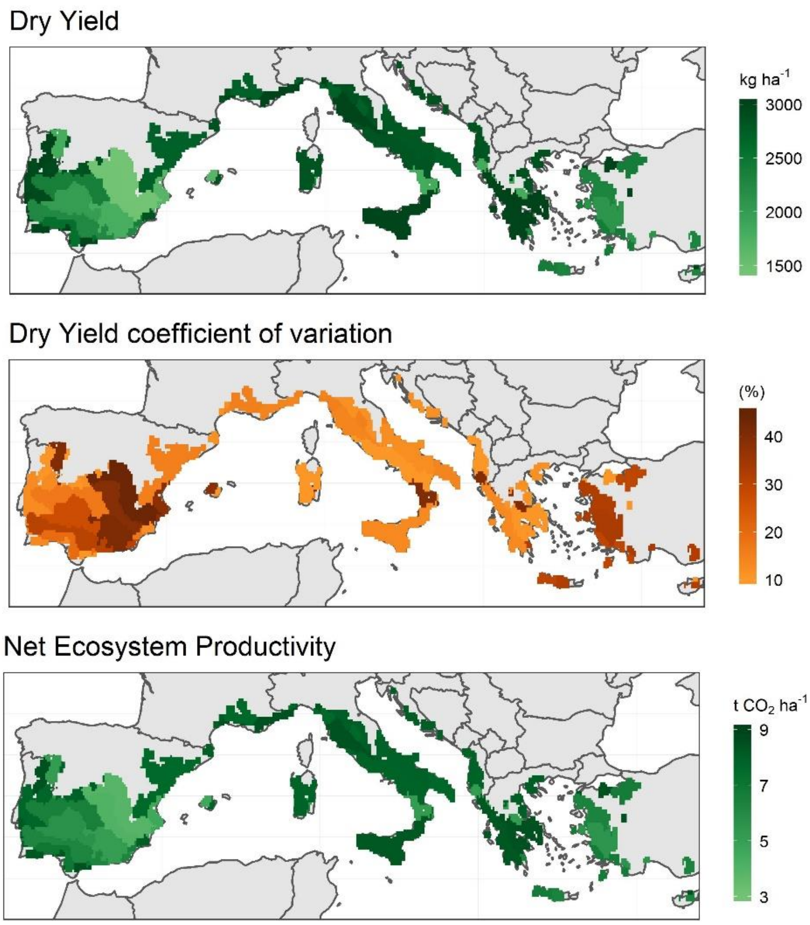

Figure 3: Simulated yield and NEP for conventional orchard typology

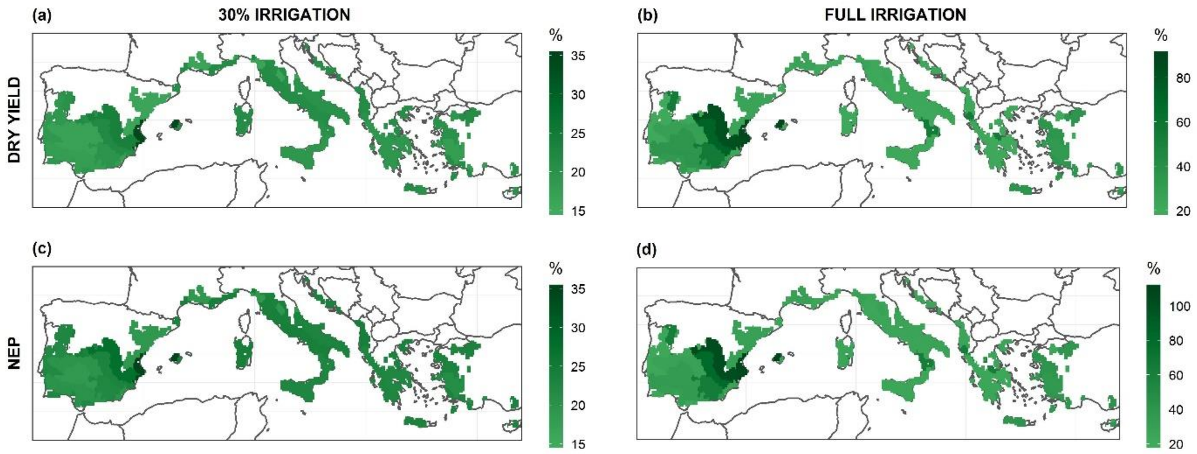

Figure 4: Impact of irrigation on Low Density (LD) orchard. Increase in yield and NEP due to irrigation expressed as percent of rainfed values shown in Fig. 3

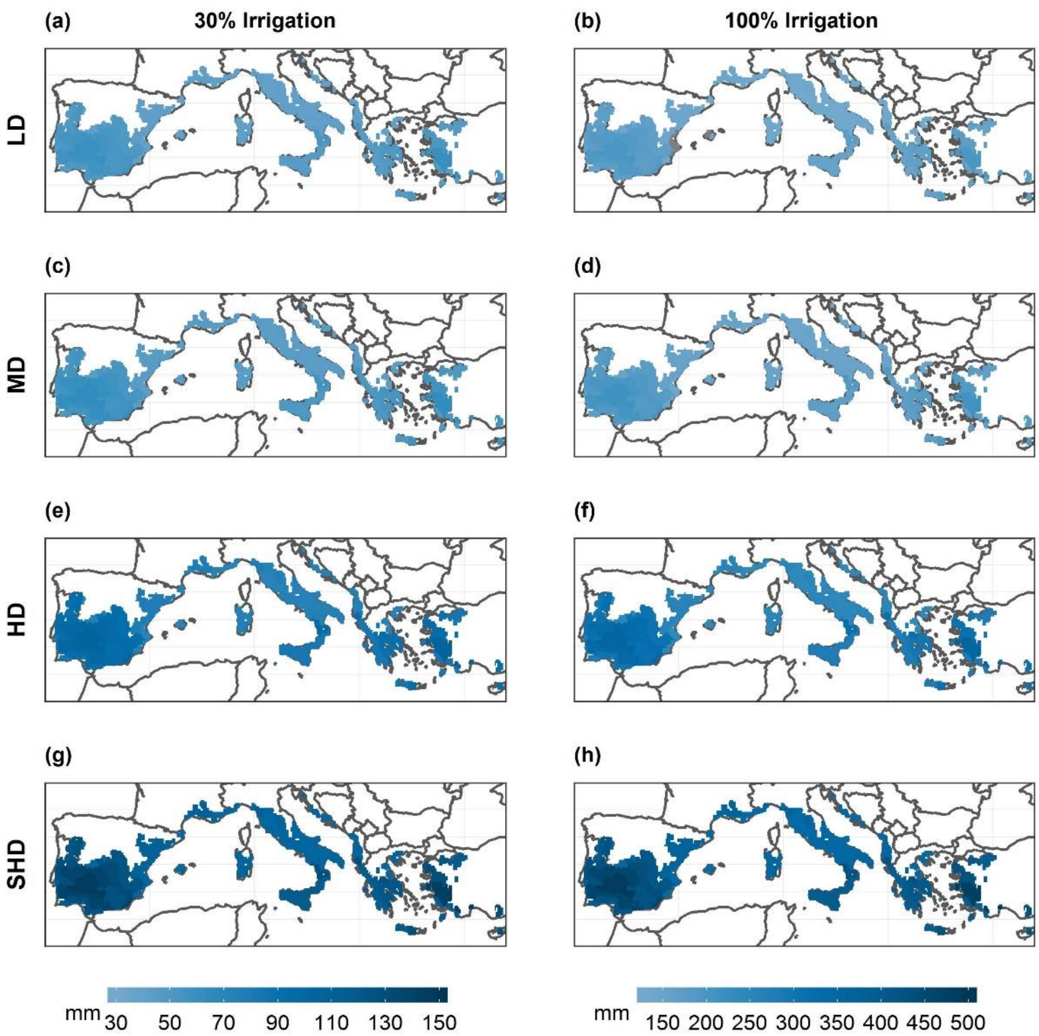

Figure 5: Irrigation amount required (mm) for Low, Medium, High and Super High densities receiving 30% and 100% of irrigation requirements

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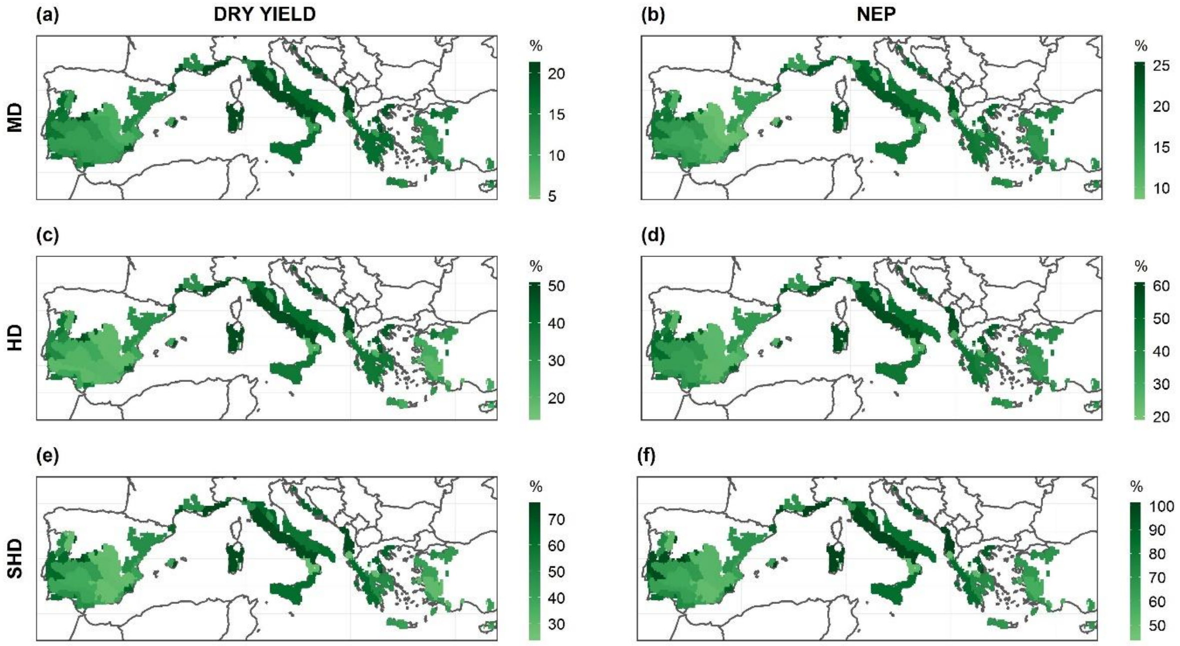

816 **Figure 6:** Impact of intensification. Changes in yield and NEP expressed in percentage compared to
817 low density irrigated orchard under deficit irrigation

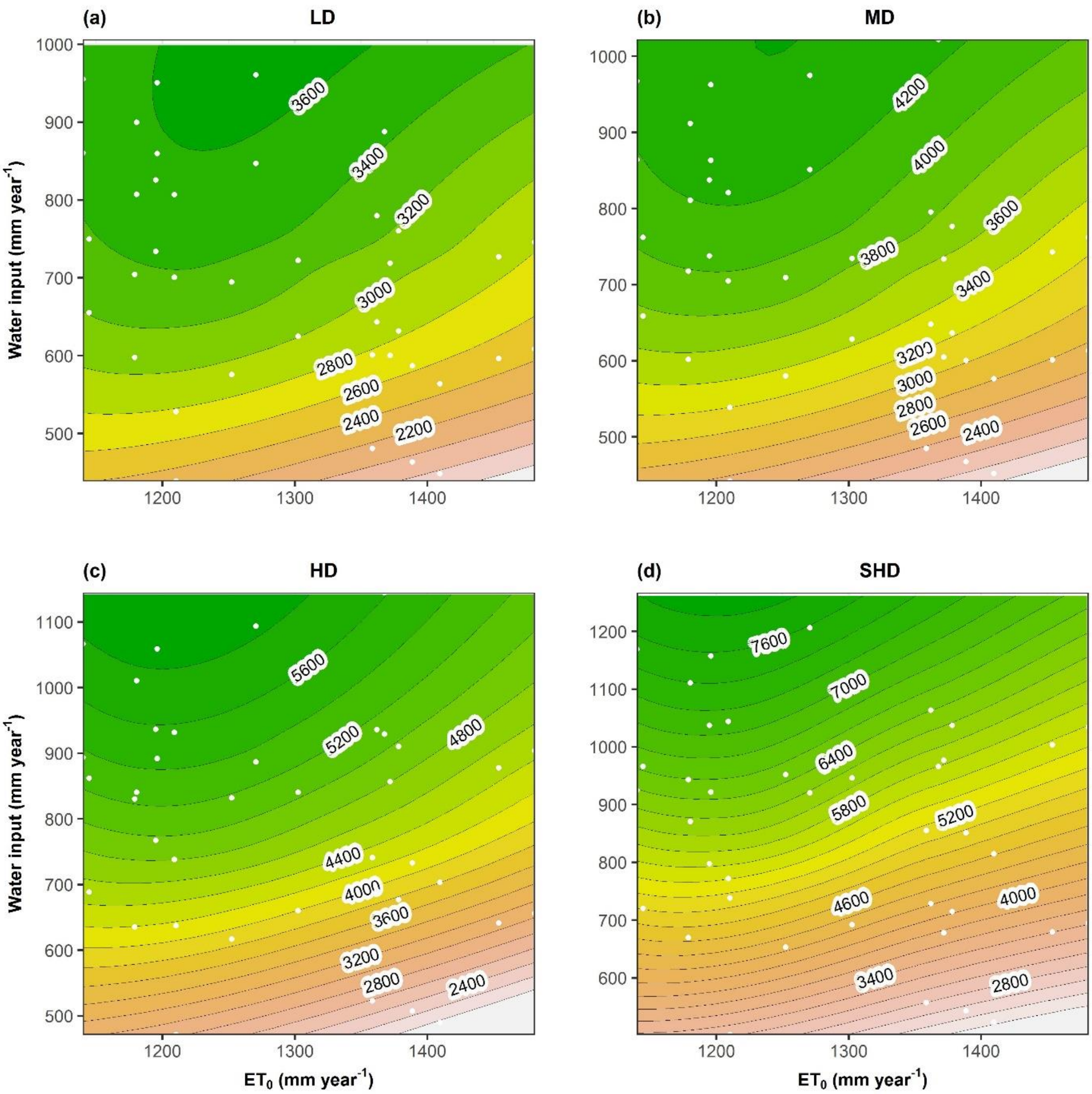

Figure 7: Impact surface response of dry yield (kg ha^{-1}) to variation in ET_0 (mm year^{-1}) and total water input (mm year^{-1}) for Low Density (LD), Medium Density (MD), High Density (HD) and Super High Density (SHD) orchards. Colour gradient from beige to green refers to the increase of yield. White dots are the outputs of the simulations used

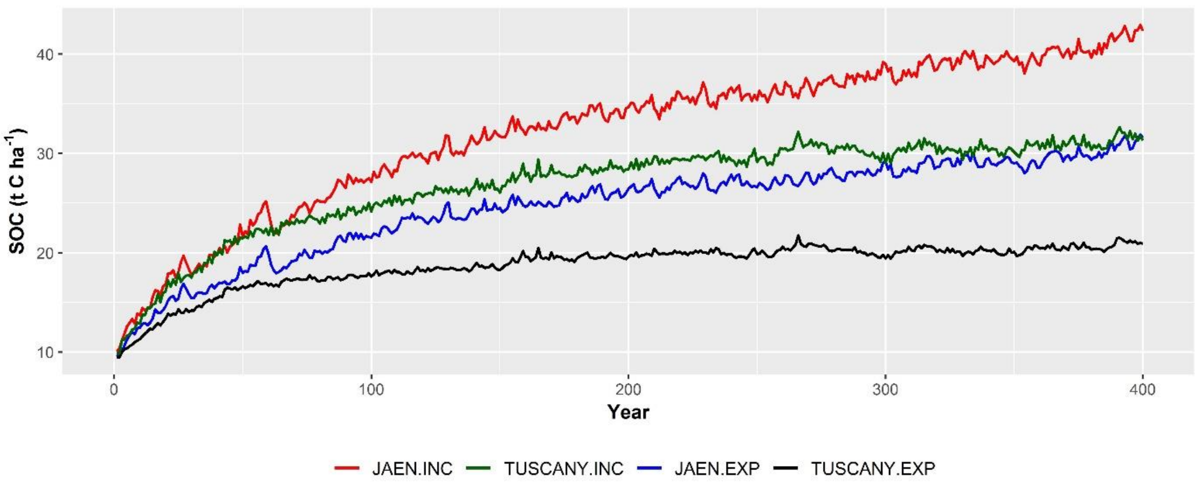

Figure 8: Soil organic carbon simulated in a Low Density (LD) rainfed orchard in Jaen and Tuscany when pruning residues are exported (EXP) or incorporated in the soil (INC). The soil is initially at 0.2% OC

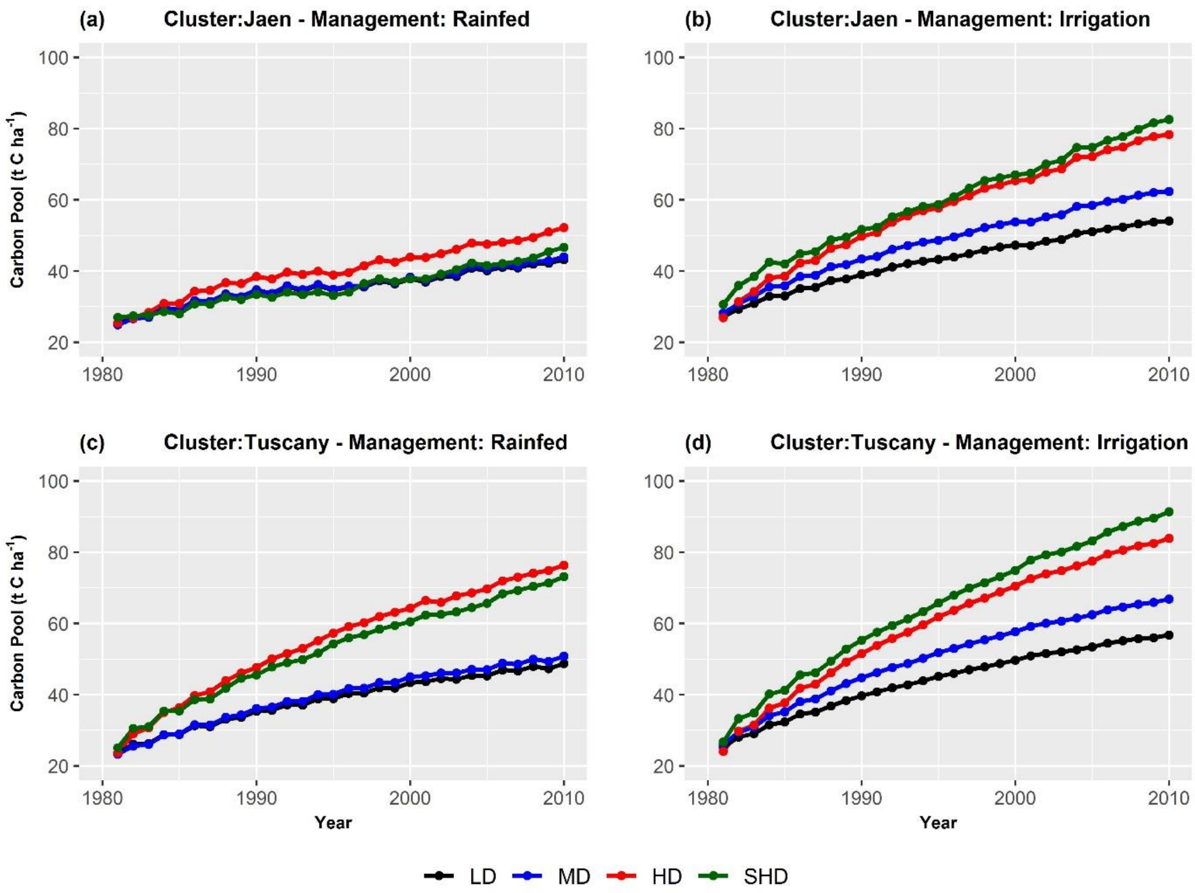

Figure 9: Time course of the total carbon pool (soil C + standing C) for Jaen - Spain and Tuscany - Italy clusters under full irrigation and rainfed management for Low Density (LD), Medium Density (MD), High Density (HD) and Super High Density (SHD) orchards

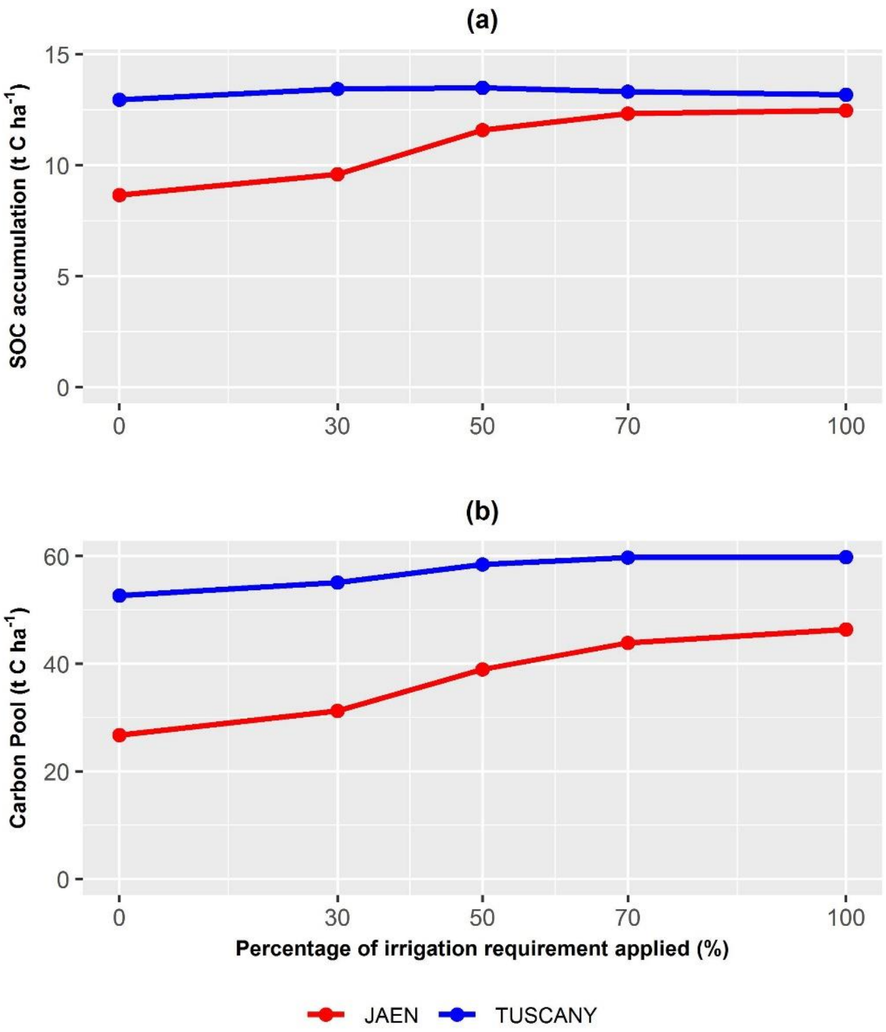

Figure 10: Total soil organic carbon accumulation over 30 years (a) and Total carbon (soil+tree) pool increase over 30 years (b) as a function of irrigation applied for the High Density orchard in Jaen-Spain and Tuscany-Italy