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Assessing the long-term impact of climate change on olive crops and olive fly in Andalusia, Spain, through climate indices and return period analysis

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A B S T R A C T

The objective of this study is to investigate the long-term effects of climate change on olive crops in Andalusia, one of the most important olive growing areas worldwide, using tailored climate indices and return period analysis. Both the climatic indices and the occurrence probabilities of bad years in terms of olive yield and olive fly risk are being calculated for the reference period 1971–2000 and for the near (2031–2060) and distant future (2071–2100) under two emission scenarios using an ensemble of five high-resolution, bias-adjusted Regional Climate Models. Three threshold-based temperature related indices (SPR32, SU36, SU40) as well as mean temperature and precipitation related climatic indices (SPRTX, WINRR) have been calculated, revealing increasing changes in the near and distant future and pointing out the challenges faced by the olive sector due to climate change; a robust increase of the threshold-based indices are found in central and northern Andalusia, mainly in the provinces of Seville, Cordoba and Jaen. Although the changes of the precipitation-related index are less pronounced for the near future, robust decreases are projected for the distant future period under a high emission scenario. The identification of the bad years is based on observational data from five monitoring stations in Andalusia (Malaga, Granada, Sevilla, Cordoba and Jaen). The role of certain meteorological parameters (precipitation, temperature, relative humidity) is investigated and the return levels of interest for the calculation of the occurrence probabilities are estimated by the upper tail of the reference distribution. The results indicate an overall tendency for increased occurrence probability of bad years in terms of olive yield due to future decreased precipitation; bad year occurrences with return periods of below 2 years may increase by about 20 % by 2060. Spatial variability is also evident with overall larger changes in western Andalusia. The range of the olive fly is expected to decrease in the northern areas of Andalusia.

1. Introduction

The olive tree (*Olea europaea L.*) is a perennial evergreen and is the most commonly cultivated tree in Andalusia, Southern Spain (Junta de Andalucía et al., 2003) – a region with Mediterranean climate, i.e. with mild wet winters and hot dry summers – where the olive oil production constitutes >30 % of the global production (Civantos, 2001). It reaches its maximum yield when it is 30–40 years old (Bonnet, 1950) and fruits are produced for centuries. Harvest varies from year to year; good and bad yields occur in alternate years. The optimum climate conditions for the cultivation of the olive tree are long, warm and dry summers and rainy winters. The plant can tolerate some frost, but sustained extremely low temperatures can destroy it. Due to the very demanding climatic requirements of the olive tree, virtually all olive trees are grown in a Mediterranean-type climate. However, since southern Europe has been identified as a climate change hotspot region by the Intergovernmental Panel on Climate Change (IPCC), the olive fruit production may be subject to unfavourable climatic conditions and farmers will be forced to adapt to global warming; the expected low precipitation in conjunction with higher temperatures are expected to cause earlier ripening of the fruits and affect adversely the olive oil quality (Dag et al., 2014). So far, several studies have been conducted for the assessment of climate risks on olive production in the Mediterranean region (e.g. Quiroga and Iglesias, 2009, Lionello et al., 2014, Arenas-Castro et al., 2020).

Another threat for the olive yield is the fruit infestation by the olive fruit fly (*Bactrocera oleae*), which is a Mediterranean endemic pest (Tzanakakis 2006). There are records of infestations in the Mediterranean region since the third century BC. Field studies indicate that olive fruit fly adult population decreases in mid- and late summer and then rebound from September to November (Rice et al., 2003; Yokohama et al., 2006). Heat stress that flies experience during summer is the reason for this decline. Moreover, increased temperatures also affect the fly's reproduction and immature stages within olive fruit. Normal fly activity occurs between 23 °C and 29 °C. At higher temperatures egg laying ceases and above 35 °C flies are motionless. When the daily maximum temperature exceeds 38 °C, a great number of adult flies dies especially if they don't have access to adequate water (Wang et al., 2009a). Wang et al. (2009a) also showed that eggs already laid within the olive fruit, have almost 50 % mortality rate if subject to 35 °C and in case of 10 days exposure to 38 °C, no eggs survived. The adverse effects

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Table 1
GCM-RGM pairs used for the calculation of the occurrence probabilities.

Institute	RCM	GCM
SMHI	RCA4	HadGEM2-ES
SMHI	RCA4	CNRM-CERFACS-CNRM-CM5
IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR
KNMI	RACMO22E	ICHEC-EC-EARTH
MPI-CSC	REMO2009	MPI-M−MPI−ESM−LR

of high temperature and low humidity are also shown and discussed in other studies conducted for southern Europe (e.g. Fletcher et al., 1978, Gonçalves and Torres, 2010, Pappas et al., 2011). The infested fruits are not appropriate for table olive, thus integrated pest management is of high importance for the olive sector and many agricultural practices, such as the removal of the remaining fruits on the trees after harvesting, have been recommended for reducing infestations (Yokoyama, 2015).

Given the socio-economic importance of the olive crops and the need to optimise the resources invested in olive production, it is important to investigate the climate change impacts on olive cultivations. Several studies suggest a decrease in the suitability of the olive orchards in southern Europe due to projected excessive heat and water stress for the future (e.g. Gutierrez et al., 2009; Ponti et al., 2014; Tanasijevic et al.; 2014, Fraga et al., 2019, Rodriguez et al., 2020). However, the climate response to global warming varies from region to region and the objective of this study is to examine the climate change in the long-term in Andalusia (South Spain), using an ensemble of high-resolution, bias-adjusted regional climate model (RCM) simulations from EURO-CORDEX database. Subsequently, we employ the return period method of bad years in terms of olive yield and fly infestations – for risk quantification and olive crop management. Also, certain climatic indices, identified as representative of the challenges faced by the olive sector, have been calculated and are projected into the future. The analyses of this study were performed in the frame of the Med-Gold project, a Horizon 2020 project, which aims to develop climate services for olive, grape and durum wheat crops, the hallmarks of the Mediterranean food system; the generated climate related information will be exploited by the end-users for operational decision-making.

Description of the data and methodologies used for this study is provided in Section 2. In Section 3, the results from the long-term projection of the climatic indices and the return period analysis in terms of olive yield and fly infestations are discussed. Finally, in Section 4 the main conclusions are presented.

2. Methodology

2.1. Climate data

In this study daily data for temperature, precipitation and relative humidity are used from a five member GCM-RCM sub-ensemble simulations (Bartok et al., 2019) from the EURO-CORDEX modelling experiment (Jacob et al., 2014) (Table 1) with a horizontal resolution of 0.11°. The daily data for all variables were bias adjusted using the empirical quantile mapping (Iturbide et al., 2018; Varotsos et al., n.d) and EOBSv23 (Cornes et al., 2018) as the reference dataset.

For the relative humidity data, a trend preserving method such as the unbiasing method (Deque, 2007) was chosen in order to bias adjust the climate projections. This method was selected as more appropriate because the quantile mapping affected considerably the bias adjusted relative humidity simulation trends compared to the raw model output. It should be mentioned that this behaviour has been discussed in previous studies (Canon et al., 2015; Tong et al., 2021), but did not affect the bias adjusted temperature and precipitation trends. After the bias adjustment, the simulated climate data (precipitation, temperature and relative humidity) for three climate periods – reference (1971–2000), near future (2031–2060) and distant future (2071–2100) – and under two future emission scenarios – RCP4.5 and RCP8.5 – were used in order to generate the selected climatic indices (section 2.3) and to calculate the future occurrence probabilities of certain meteorological conditions which may lead to either reduced olive production or damage to the fruit due to severe olive fly attacks. For each of the indices and for each grid point over Andalusia, the differences between the reference and the future period can be considered robust when the changes are statistically significant in at least three out of the five models and the changes in each model are of the same sign. The first criterion is examined by using the 95th percentile confidence intervals as derived by bootstrap. If only one of the criteria is met, the change at the specific grid point is not considered significant (Varotsos et al., n.d).

Table 2
Olive monitoring stations' location and period covered by observational data.

Site	Period	Elevation (m a.s.l.)	Coordinates (Lat, Lon)
Málaga (Pizarra)	2002–2018	71	36° 46′ N 04°42′ W
Granada (Iznalloz)	2001–2018	921	37° 24′ N 03° 33′ W
Sevilla (Finca Tomejil)	2002–2018	75	37° 24′ N 05°35′ W
Córdoba	2001–2018	94	37° 51′ N 04° 48′ W
Jaen (Ubeda)	2001–2018	343	37° 56′ N 03°18′ W

For the assessment of the impact of the meteorological conditions (temperature, precipitation and relative humidity) on the olive yield, meteorological data for the period 2001–2018 obtained from five monitoring stations (https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web, last access: 14 December 2020) – reported in Table 2 – were also used. In each one of the selected province the cultivated area is >100,000 ha. Yield data and information indicating the bad years in terms of olive production and olive fly attacks were provided by DCOOP in the frame of the MED-GOLD project. The yield data were obtained from the Ministry of Agriculture of the Government of Spain (https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/superficies-producciones-anuales-cultivos/): annual oil production of <800 Mg was set as a threshold for identifying the bad years. Accordingly, data from the Government of Andalusia reporting the amount of olive fruits infected by the olive fly on an annual basis (https://www.juntadeandalucia.es/agriculturapescaydesarrollorural/raif/balances-anuales), were used for the identification of bad years in terms of fly attacks. The results in both cases were corroborated by observations reported by the Field Technical Department of DCOOP.

2.2. Return periods analysis

The return period of a particular event is defined as the inverse probability of this event's occurrence in any given year. A return period can be interpreted as the time between exceedance events (Mays, 2001) and can also be defined as 'average recurrence interval' (ARI) (Bonnin et al., 2004). NOAA also uses the term 'annual exceedance probability' (AEP) (Bonnin et al., 2004). Although, return periods for evaluating the severity of a meteorological event linked to climate change, are more preferred than the probability of occurrence as more interpretable by the general public, in this study the latter was chosen as more appropriate for the interpretation of the results.

If the selected threshold of the studied variable x is x_o, the return period is $T = 1/F(x_o)$, where F(x) is the cumulative distribution function (CDF). More explicitly, if an event occurs when the selected variable is greater or smaller than a value x_o, the recurrence interval T is the time period between occurrences for the event. In addition, $F(x_o)$ can be defined as the occurrence probability of a given event in any year, therefore the return period can also be defined as the inverse occurrence probability.

2.3. Climatic indices

The essential climate values and bioclimatic indices used in this study were identified as appropriate for key farming decisions in the olive sector by professional agronomists in the frame of the Med-Gold project. With this aim, two workshops (June 2018 and May 2019) were held, during which the participants assessed the current needs of the olive sector and proposed the specific indices as potentially useful to support the main challenges faced by this sector due to climate change. The current study does not integrate how scientists of the agricultural sector agreed on the definition of the different climatic indices; the outcomes are based both on empirical and scientific knowledge and data information.

- SPRTX index; the mean spring (Apr-May) maximum temperature (tmax). The SPRTX index is considered as the best indicator of flowering date of the olive plants (Perez-Lopez et al., 2008). It is related to evapotranspiration and the evolution of certain pests during the flowering period and thus is essential for farming decisions regarding irrigation and treatment of olive fly. It is calculated by averaging the daily temperature maximums during spring time, between 1 April and 31 May (Eq. (1)).

$$SPRTX = \frac{1}{n}\sum_{1April}^{30May} tmax \tag{1}$$

- SPR32 index; number of spring days with tmax >32 °C. The high SPR32 index is connected to early flowering and thus to increased risk of pests and diseases (Ribeiro et al., 2009). According to the agronomists participating in the project's workshops, it is related to decisions regarding plant treatment and irrigation and can also contribute to a prediction of the crop yield. It is the total count of heat stress days for the period April 21st to June 21st (Eq. (2))

$$SPR32 = \sum_{21April}^{21June} [tmax > 32^{o}C] \tag{2}$$

- SU36 and SU40 indices; the number of summer days with tmax >36 °C and 40 °C, respectively. The high summer temperatures are related to an earlier ripening of the olives (Garcia-Inza et al., 2014), thus information on the SU36 and SU40 levels can contribute to the prediction of crop quality. SU36 and SU40 indices are related to decisions about harvest planning, pest treatments and extra irrigation to reinforce plants against extreme temperatures. Especially SU40 limits the photosynthetic rate of the olive plants (Mancuso and Azzarello, 2002) and since the response to such a high stress is strongly genotype-differentiated (Koubouris et al., 2009), the professionals of this sector could exploit the provided information towards producing tolerant olive varieties. These indices are the total count of heat stress days for the period June 21st to September 21st (Eq. (3)).

$$SUthreshold = \sum_{21June}^{21September} [tmax > threshold] \tag{3}$$

- WINRR index; the total precipitation from October to May. Water availability is an important factor for olive physiological activity (Aissaoui et al., 2016) and has been shown that water deficit during winter and early spring may strongly reduce the yield, however not affecting the quality of the olives (Palese et al., 2010). According to the workshops' outcomes, WINRR is one of the most important indices for decision making: it is related to crop yield and soil management and can even contribute to decisions in changing crop varieties in the long-term.

$$WINRR = \sum_{October}^{May} RR$$

3. Results and discussion

3.1. Olive yield and precipitation

In this section the relation of winter precipitation with olive production is investigated. Several studies have shown that precipitation over the months prior to flowering in spring is one of the most influential meteorological-related factor for flowering (e.g. Galán et al., 2001; Ribeiro et al., 2006) and therefore olive production. Although a recent study (Ben-Ari et al., 2021) has reported poor fruit sets in case of high temperatures during the blooming period (Apr-May), the correlation with olive yield in our dataset is weaker compared to the precipitation parameter. Since precipitation in Andalusia occurs due to low-pressure systems mainly between October and April (Ruiz-Sinoga et al., 2011), meteorological and yield data for five cultivation areas in Andalusia have been used and the relation between seasonal precipitation accumulation prior to flowering (Oct-Apr) and bad years in terms of olive yield is studied.

3.1.1. Bad years: Observations and thresholds

The observation and yield data analysis for 17 years for five stations in Andalusia validate the strong relation of olive production and

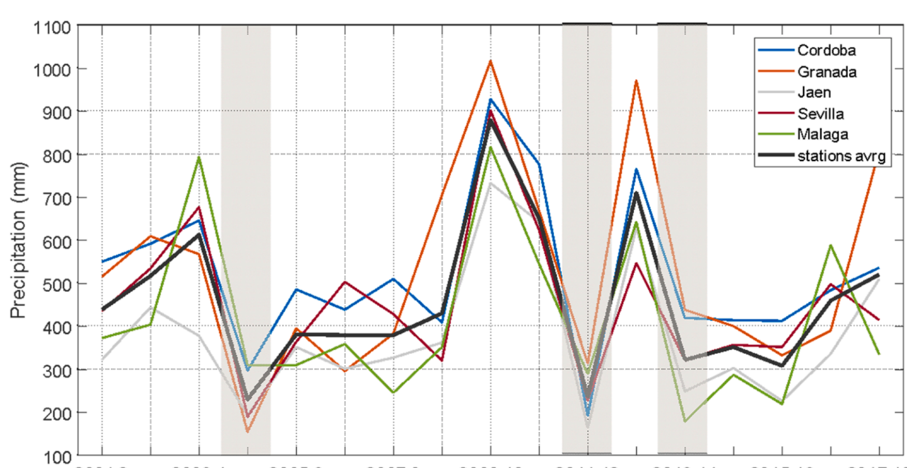

Fig. 1. Precipitation for the period October – April for five stations in Andalusia. The dark grey curve corresponds to the mean value of all five stations. The light grey boxes indicate the bad years in terms of olive yield.

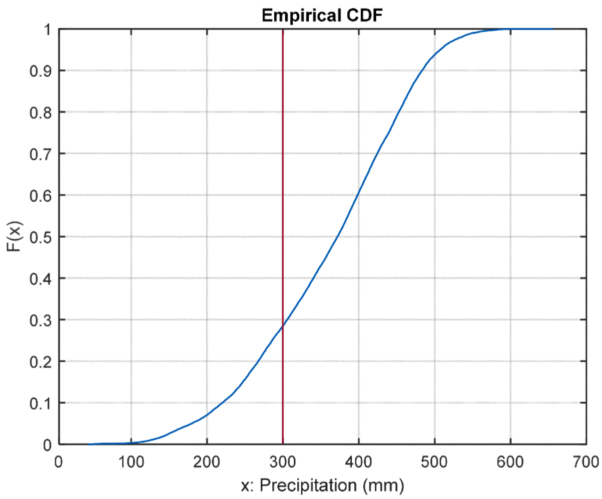

Fig. 2. Cumulative distribution function for the seasonal (Oct-Apr) precipitation based on the historical ensemble data for Andalusia and for the period 1971–2000.

seasonal (Oct-April) precipitation accumulation. The bad years in terms of olive yield coincide with low winter precipitation of <300 mm (Fig. 1).

To set a threshold (or return level) for defining a bad year, one must estimate the upper tail of a distribution. The cumulative distribution function (CDF), based on the ensemble model data for the reference period, was used for this reason. Winter precipitation percentiles of the historical ensemble data for Andalusia are shown in Fig. 2 for the reference period (1971–2000). The variable x denotes the winter precipitation and F(x) is a probability ranging from 0 to 1. In a statistical sense, seasonal precipitation is expected to exceed a certain value x with a probability of 1–F(x), and to fall below x with a probability of F(x).

The lower and upper quartiles (i.e. 25th and 75th percentiles) of a CDF have been used in several studies (e.g. Burn, 1990; Pongracz et al., 2014) as threshold indices for calculating return periods. Therefore, to set a threshold for defining a bad year in our case, the lower quartile of seasonal precipitation CDF (Fig. 2) is considered as the threshold value (300 mm). This threshold is also in very good agreement with the observations and yield data analysis over a 17-year period from five stations in Andalusia (Fig. 1).

3.1.2. *Occurrence probabilities of bad years*

The whisker plots for occurrence probabilities of total precipitation (October to April) <300 mm (bad years) for the historical period (1971–2000), the near (2031–2060) and the distant future (2071–2100) under the two selected emission scenarios are displayed in Fig. 3. Although there is an exception (distant future under RCP4.5), the analysis displays an overall tendency for increase in the occurrence probability of bad years in terms of olive yield and this finding is in agreement with other studies that forecast a 30–45 % reduction of olive yield in the Iberian Peninsula (Fraga et al., 2019). The strongest negative impacts are found under the RCP8.5 in the distant future.

The special topography of Andalusia affects the precipitation regime, which clearly distinguishes east and west; the eastern provinces are characterised as semiarid-to-arid areas (Argueso et al., 2011) due to the decreasing influence of the Atlantic Ocean (Climate-Data, 2020). Therefore, the analysis has been carried out separately for western and eastern Andalusia and illustrates a strong regional dependency of the projected changes, with overall larger changes in western Andalusia, where the exceedance probabilities for the reference period were almost zero. Medians are above the late-20th's century occurrence probability both for eastern and western Andalusia.

The occurrence probabilities of bad years are high, reaching almost 0.9, in eastern Andalusia, while for the western regions the

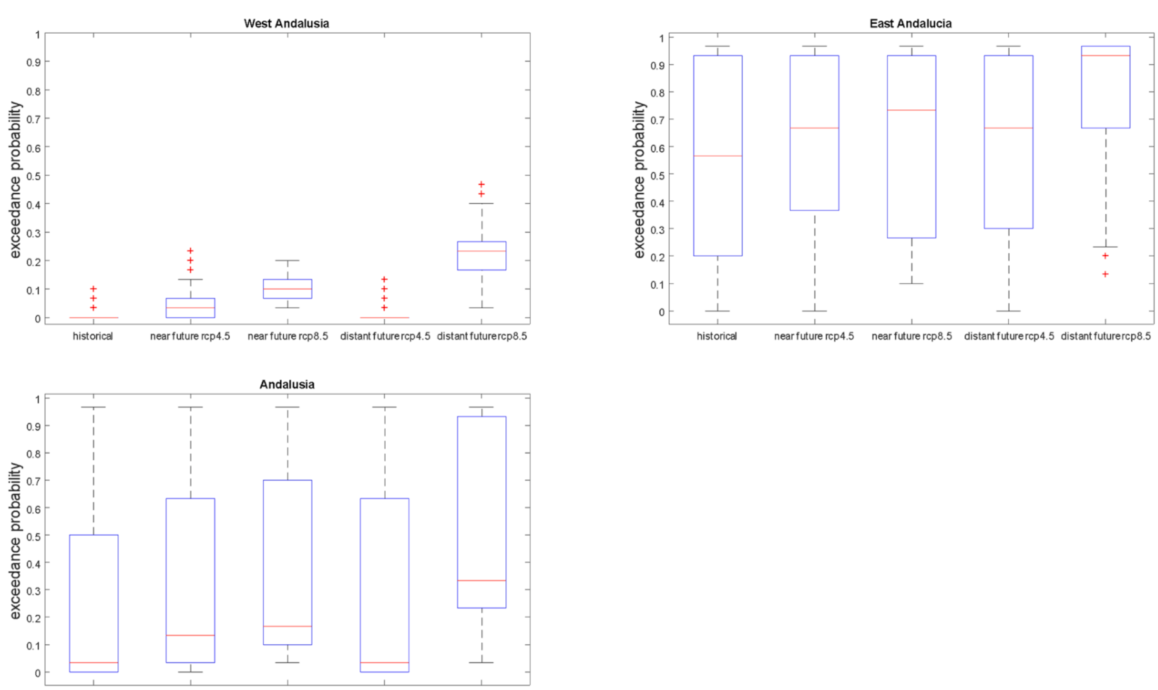

Fig. 3. Occurrence probability of total precipitation (October to April) <300 mm for the historical period (1971–2000), the near (2031–2060) and the distant future (2071–2100), under two emission scenarios (RCP4.5 and RCP8.5). Upper, medium and lower panels correspond to western, eastern and the whole region of Andalusia, respectively. On each box the central red line is the median, the edges of the box are the 25th and 75th percentiles. The whiskers extend to the most extreme data points, not considering outliers which are represented by the red crosses. The value considered as outlier is any value that lies more than one and a half times the length of the box from either end of the box. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

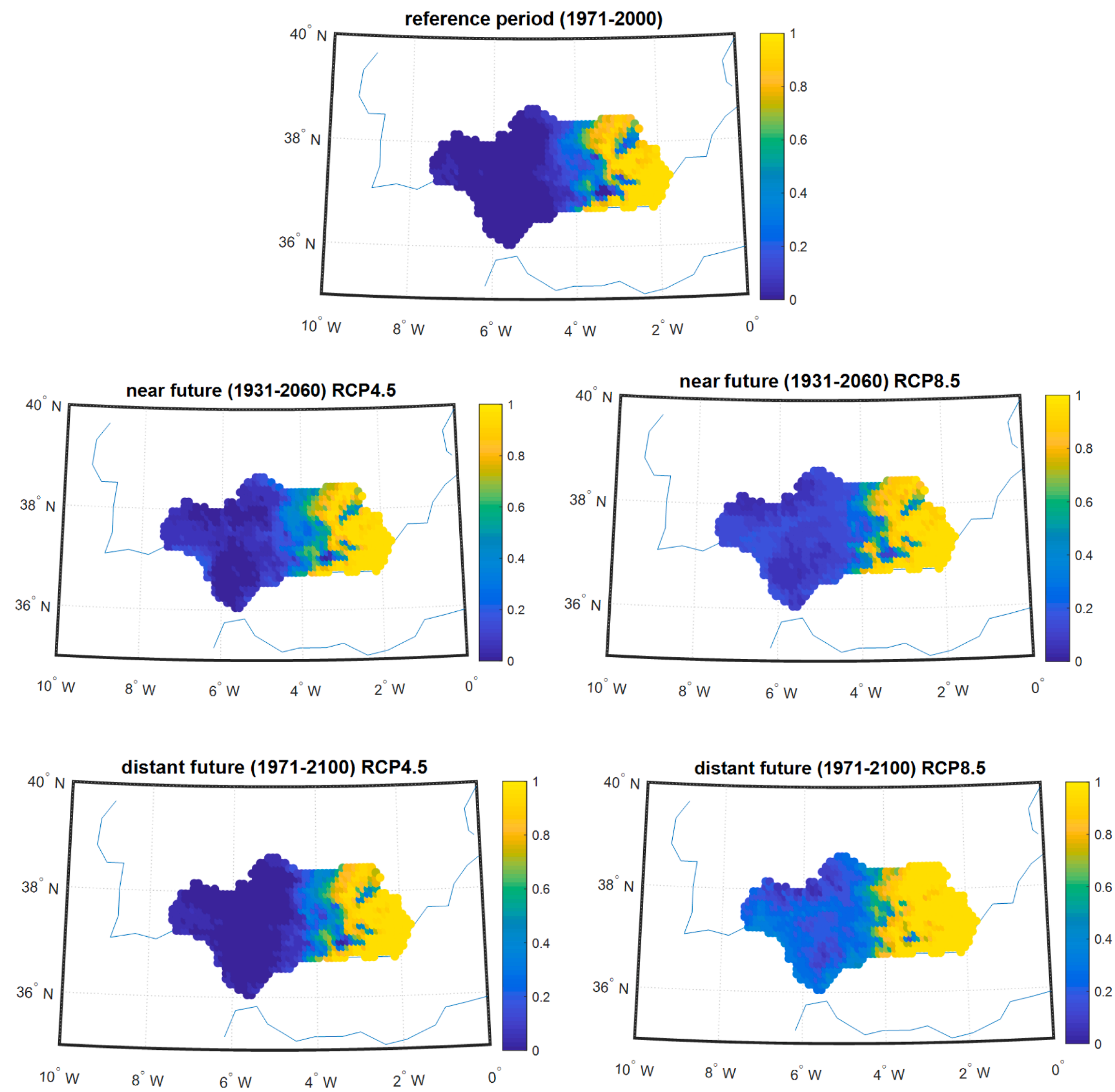

Fig. 4. Spatial distribution of occurrence probability of total precipitation (October to April) <300 mm for the reference period, the near and distant future under RCP4.5 and RCP8.5.

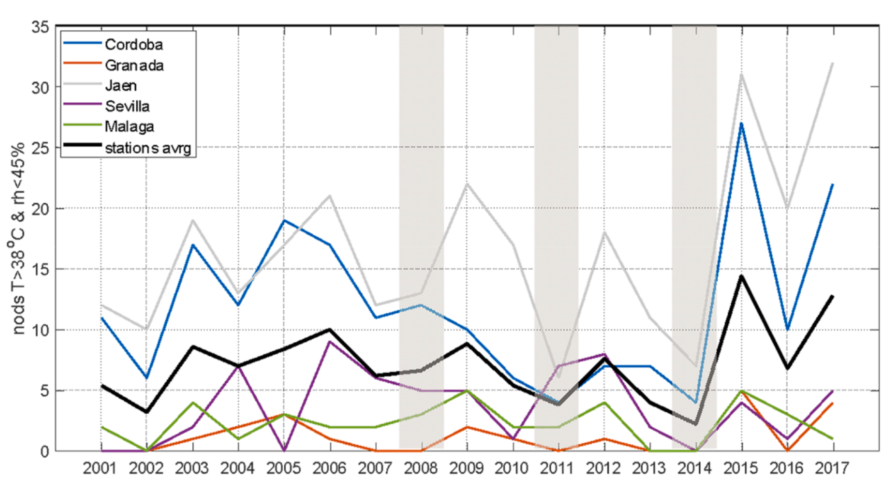

Fig. 5. Number of summer days with Tmax >38 °C and rh <45 % for five stations in Andalusia. The black curve corresponds to the mean value of all five stations. The light grey boxes indicate the bad years in terms of fly attack.

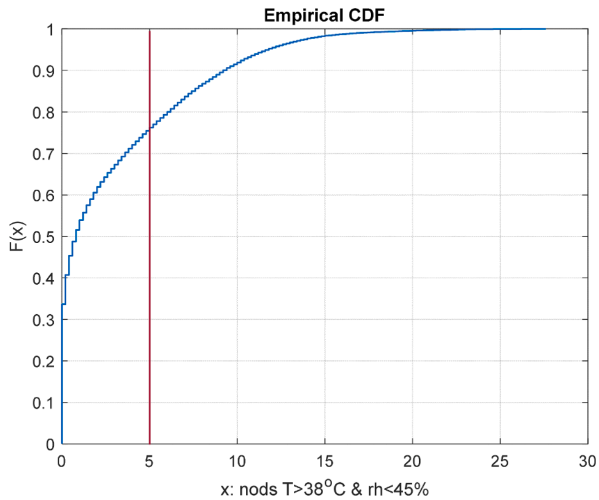

Fig. 6. Cumulative distribution function of the number of days with T >38 °C and rh <45 based on the historical ensemble data for Andalusia for the reference period (1971–2000).

corresponding probability ranges between 0 and 0.3 (Fig. 4). An increase is expected for the future and is worth mentioning that the regions with higher than 0.9 occurrence probability tend to expand towards the west in the future under both emission scenarios. The stronger emission scenario (RCP8.5) leads to stronger projected increases in the occurrence probability (i.e. decreases in the return period) of climatic conditions considered unfavourable for olive production. Bad year occurrences with return periods of below 2 years may increase by about 20 % until the year 2060. These results suggest that olive productivity will probably decrease in Andalusia and the decrease will expand westwards.

3.2. *Olive fly infestations and meteorological parameters*

It has been suggested that the olive fly ovarian maturation's pause and recommencement is an interaction of temperature and humidity (Fletcher et al., 1978). Wang et al. (2009) reported that 10 consecutive days with high temperatures lead to the mortality of eggs already laid on the olive fruits. Therefore, in this section the relation between meteorological parameters (summer temperature and relative humidity) and olive fly infestations is investigated. For this purpose, meteorological data and olive fly reports from five stations in Andalusia have been used.

3.2.1. *Bad years: Observations and thresholds*

Several publications report T >38 °C as a threshold for fly mortality (e.g. Wang et al., 2009, Johnson et al., 2011) and a threshold of 45 % ± 5 % for relative humidity (rh) has been reported (Fletcher et al., 1978) for the inhibition of ovarian maturation. Therefore, the number of days with T >38°c and rh <45 % were calculated for the five stations in Andalusia; it is demonstrated that summers with few days of high temperature and relative humidity coincide with bad years in terms of olive fly attacks (Fig. 5).

To define a bad year, the upper quartile of the CDF of the number of days above the set thresholds (Fig. 6) – based on the ensemble model data for the reference period – is considered, resulting in a threshold of <5 days as an indicator of risk assessment of bad years. This is also in good agreement with the observations (Fig. 5).

3.2.2. *Occurrence probabilities of bad years*

Climate change is expected to limit the fly abundance in Andalusia. As the high summer temperatures will become more frequent, the occurrence probabilities of bad years due to fly infestations are expected to decrease; the hot dry fruitless midsummer conditions will suppress maturation. The special topography of Andalusia also affects the spatial distribution of temperature; the climate becomes more continental with increasing distance to the coast (Massot, 2016). Therefore, just as with the analysis for the olive yield, a strong regional dependency is evident, with the northern regions (Cordoba and Sevilla provinces) having almost zero probabilities of bad years due to unfavourable conditions (warmer and drier areas) and the southern regions having almost 100 % probability in any given year to be affected by fly infestations (Fig. 7). Several inland areas of current high risk are predicted to have decreased risk in the future (Jaen and Granada provinces) – almost zero probability. High risk of fly infestations will remain along the southern coastal areas due to high relative humidity. The decrease of olive fly range in the future has also been projected for other olive cultivation areas in Europe (e.g. Gutierrez et al., 2008). However, the expected increase in spring maximum temperatures, as shown in section 3.3.1, could cancel out this positive effect for the olive plants; the increasing spring temperatures advance the flowering stage, which in turn leads to early attacks from olive fly which can complete its cycle before the summer heat (e.g. Fletcher et al., 1978, Abichou and Msellem, 2015).

3.3. *Spatial distribution of climatic indices*

The use of climatic indices can be a useful tool in describing climatic variability and in the investigation of climate change impacts on certain crops; they take into account climatic variables and they associate their thresholds or temporal evolution with the plant's response. Indices for the olive sector are based on primary production as a function of meteorological parameters (temperature, precipitation) or on the relationship between production and water availability (precipitation). Water availability is more important for the stages prior to flowering, while temperature plays significant role for the fruit development (Valencia-Barrera et al., 2002). In particular, high summer temperatures may affect negatively the surface of the olives and also lead to early ripening of the fruits (Orlandi et al., 2012). Although the use of indices for the correlation between olive phenology and climate change is empirical, it has been proven very useful for forecasting the impacts of climate change on the plants (e.g. García-Mozo et al., 2014). The region of Andalusia is characterized by significant climate variability and the climatic indices have been calculated for each model grid point. For ease of comparison between present and future periods, maps illustrating the differences in the selected climatic indices for each grid point are presented in the following subsections.

3.3.1. *SPRTX*

Climate warming will alter the spatial distribution of olive bloom phenology in Andalusia; the mean maximum temperature in April and May (SPRTX index) is considered as the best indicator of flowering date of the olive plants (Perez-Lopez et al., 2008). Given the expected temperature increase in the future and the subsequent higher maximum temperatures, the impact of climate change on the flowering dates is expected to be significant. Gabaldón-Leal et al. (2017) have shown an advance in the olive flowering dates of about 17 days by the end of the 21st century due to climate change.

A comparison of the spatial patterns of the differences of the SPRTX index between the reference (1971–2000) and the future periods is presented in Fig. 8. Robust increases are projected for the whole area of interest, for both near and distant future and under both RCP scenarios. In particular, the expected differences for the near future range from 1 °C to 5 °C; the spatially averaged increase, under RPC4.5 and RCP8.5, is 1.5 °C and 2 °C, respectively. Accordingly, for the distant future, the average increase is 2.4 °C and 4.4 °C. In all cases, greater increases are expected in eastern Andalusia and in particular, in the province of Granada, where the range of olive production is expected to contract. The projected higher spring temperatures will also limit olive's distribution in more northern areas (Cordoba and Jaen provinces).

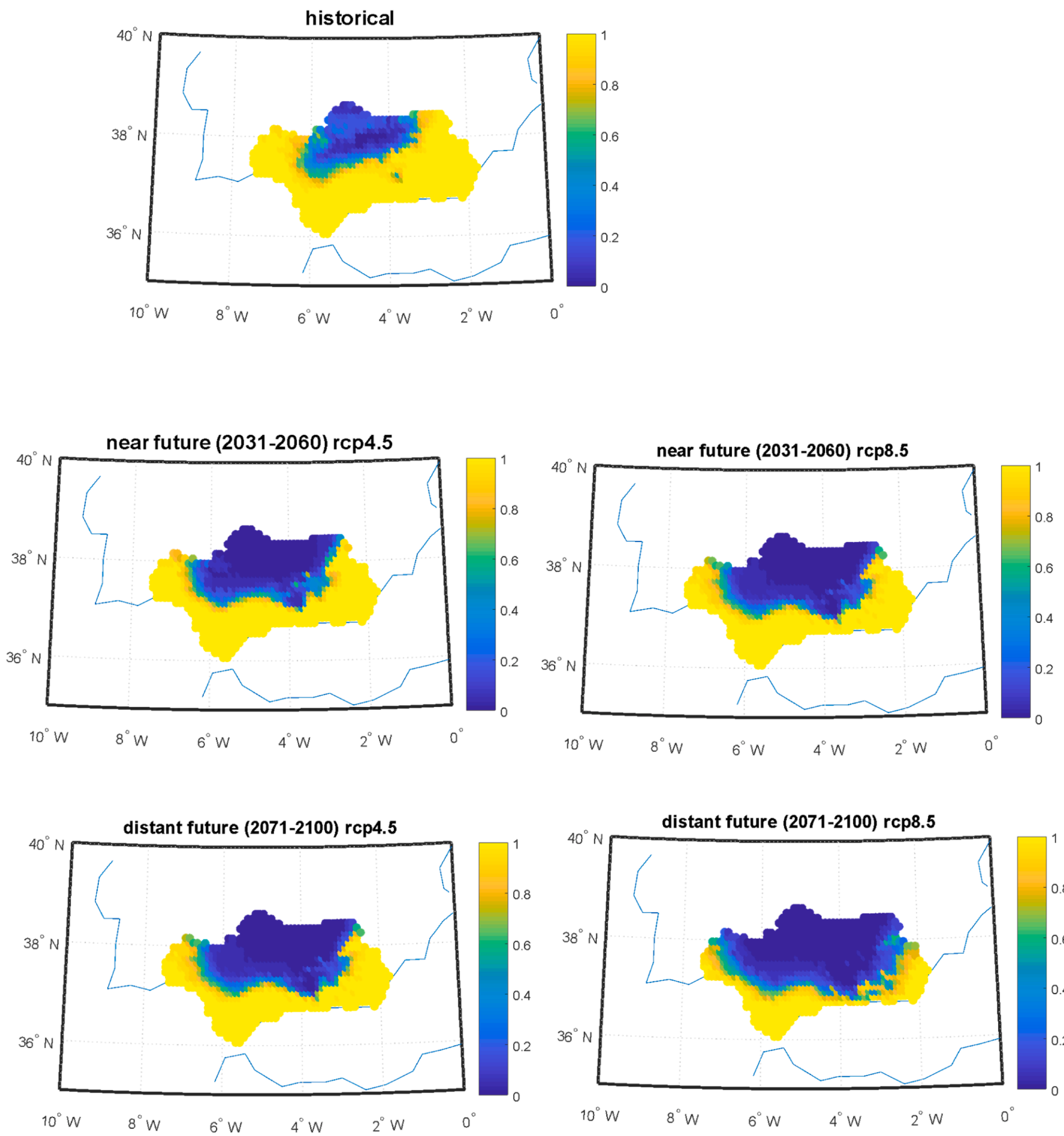

Fig. 7. Spatial distribution of occurrence probability of<5 summer days per year with Tmax >38 °C and rh <45 % under two climatic scenarios (RCP4.5, RCP8.5) and for three time periods (historical, near and distant future).

3.3.2. SPR32

The SPR32 index is closely connected to SPRTX, as it also has an effect on the flowering period, apart from the irrigation water need. Although the expected increase of SPR32 is connected to early flowering and thus to increased risk of pests and diseases (Ribeiro et al., 2009), this negative effect could be counterbalanced by the finding reported by Tura et al. (2009) that a warmer spring with sufficient rainfall has a positive effect on the composition of the produced olive oil. The projections for the SPR32 index, indicate increases for the larger part of Andalusia both for the near and distant future and under both RCP scenarios (Fig. 9). In particular, for the near future period the average increase ranges from about 1 to 2 extra days on annual basis under both emission scenarios for the near future. The changes are robust for 37 % and 80 % of the grid points under RCP4.5 and RCP8.5, respectively. In the distant future, the average absolute increase in SPR32 is about 2 and 4 extra days/year under RCP4.5 and RCP8.5, respectively. The percentage of grid points with robust changes is 81 % and 99 % for each emission scenario, respectively. The maximum increase for the near future reaches almost 4 and 5 extra days/year, while for the distant future the increase is 6 and 14 extra days/year for RCP4.5 and RCP8.5, respectively. The highest increases are projected for the northwestern Andalusia, in the provinces of Seville and Cordoba. Accordingly, the SPR32 grid value differences exhibit minimum values in the south and eastern Andalusia.

3.3.3. SU36

A latitudinal gradient is clearly visible in the SU36 patterns; larger differences are expected in the future in the northern regions. More specifically, the number of summer days with maximum temperatures >36 °C are likely to increase, with the exception of regions south of the 36.5° N latitude. Robust increases are projected for all periods and scenarios examined (Fig. 10); 14 and 18 extra days/year are projected

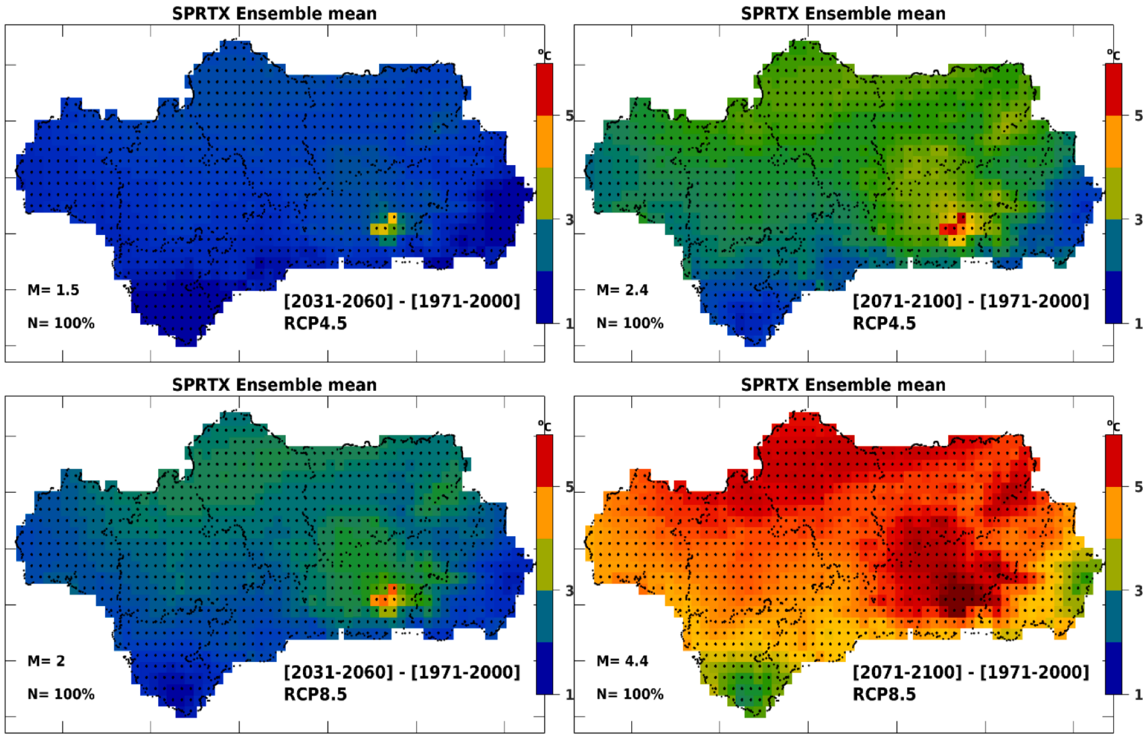

Fig. 8. Mean absolute differences in the April-May period maximum temperature (SPRTX) for the five member sub-ensemble model between the near (2031–2060) and distant future (2071–2100) and the reference period (1971–2000) under two RCP scenarios (RCP4.5 and RCP8.5). M denotes the spatial average change over all the grid points. All units are °C. Black dots indicate a robust change at the grid point scale while N denotes the percentage of grid points where robust changes are found.

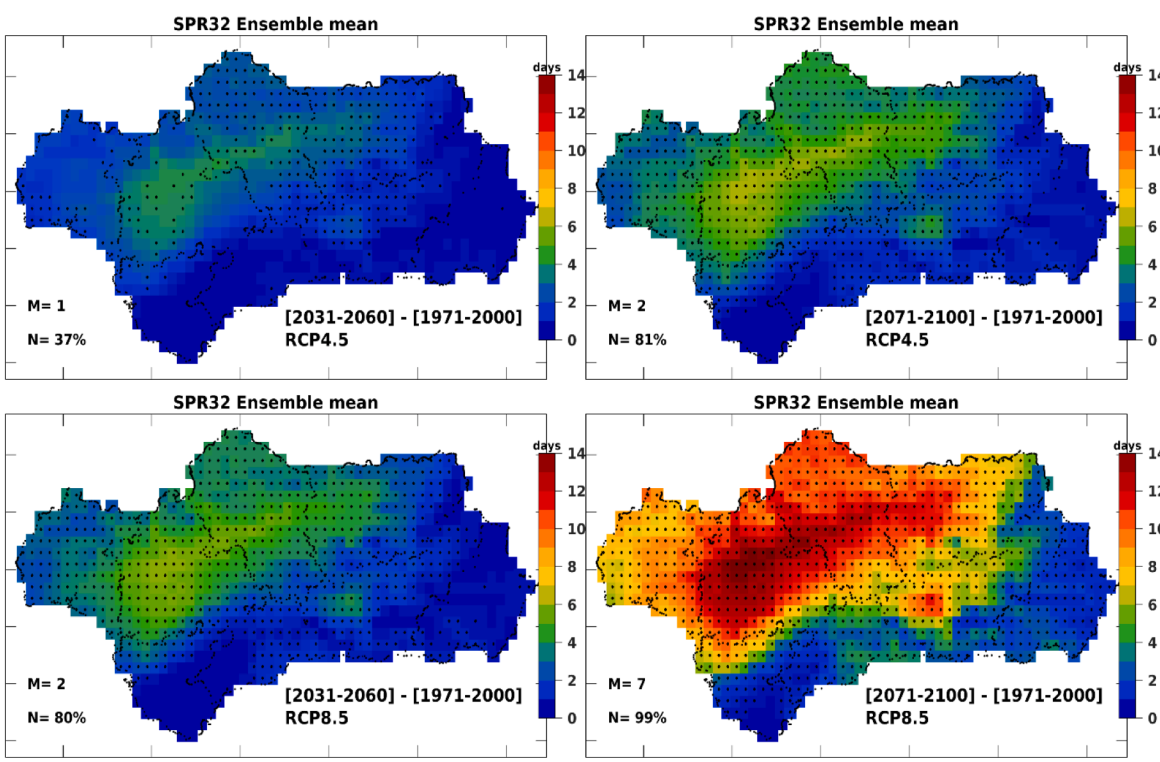

Fig. 9. Mean absolute differences in the number of spring heat days (SPR32) for the five member sub-ensemble model between the near (2031–2060) and distant future (2071–2100) and the reference period (1971–2000) under two RCP scenarios (RCP4.5 and RCP8.5). M denotes the spatial average change over all the grid points. All units are absolute values (number of days). Black dots indicate a robust change at the grid point scale while N denotes the percentage of grid points where robust changes are found.

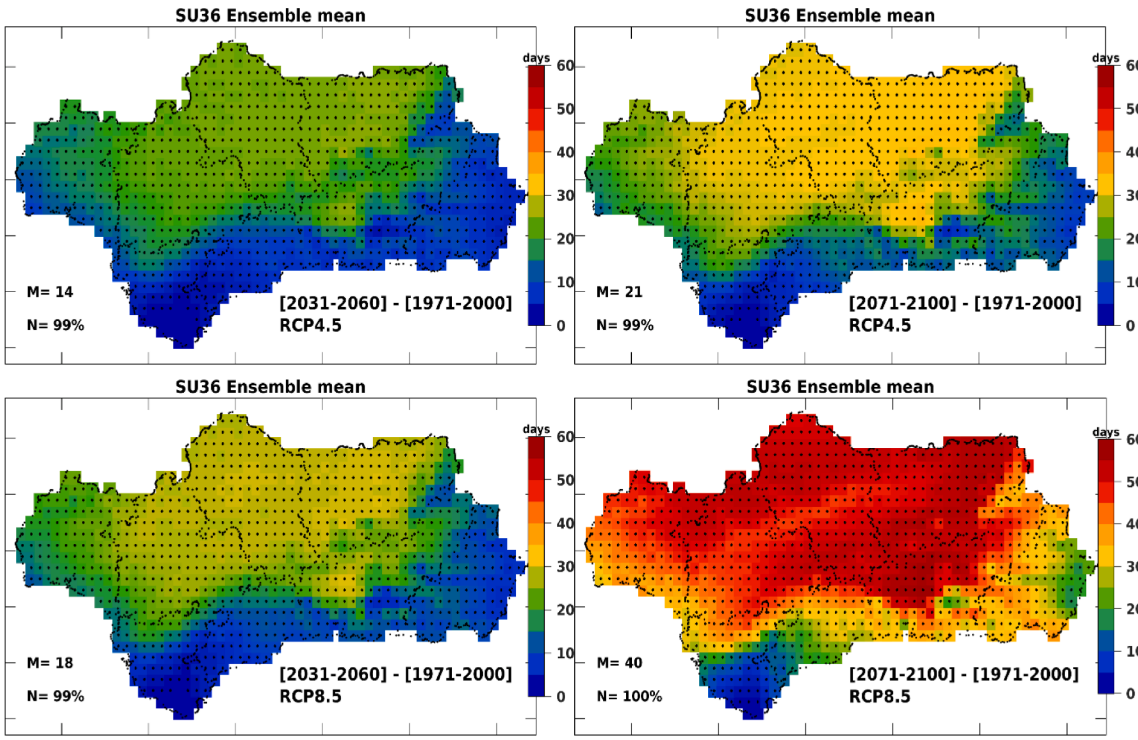

Fig. 10. Mean absolute differences in the number of summer heat days (SU36) for the five member sub-ensemble model between the near (2031–2060) and distant future (2071–2100) and the reference period (1971–2000) under two RCP scenarios (RCP4.5 and RCP8.5). M denotes the spatial average change over all the grid points. All units are absolute values (number of days). Black dots indicate a robust change at the grid point scale while N denotes the percentage of grid points where robust changes are found.

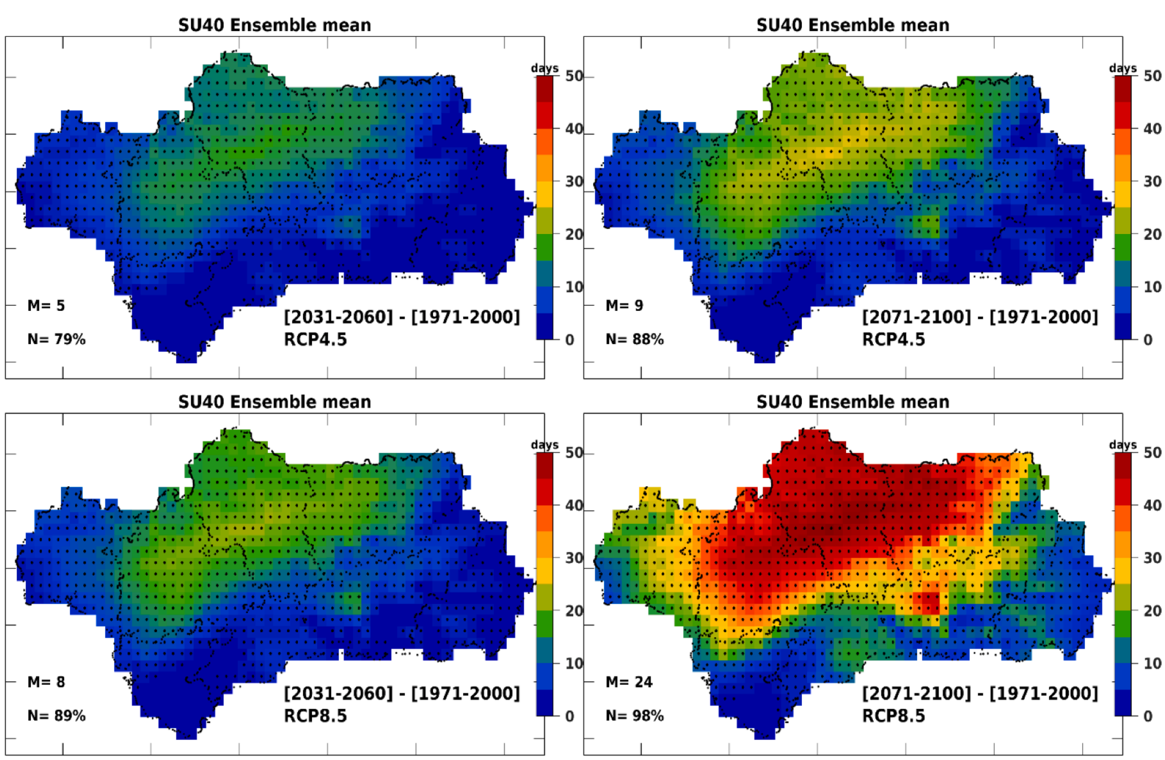

Fig. 11. Mean absolute differences in the number of summer heat days (SU40) for the five member sub-ensemble model between the near (2031–2060) and the distant future (2071–2100) and the reference period (1971–2000) under two RCP scenarios (RCP4.5 and RCP8.5). M denotes the spatial average change over all the grid points. All units are absolute values (number of days). Black dots indicate a robust change at the grid point scale while N denotes the percentage of grid points where robust changes are found.

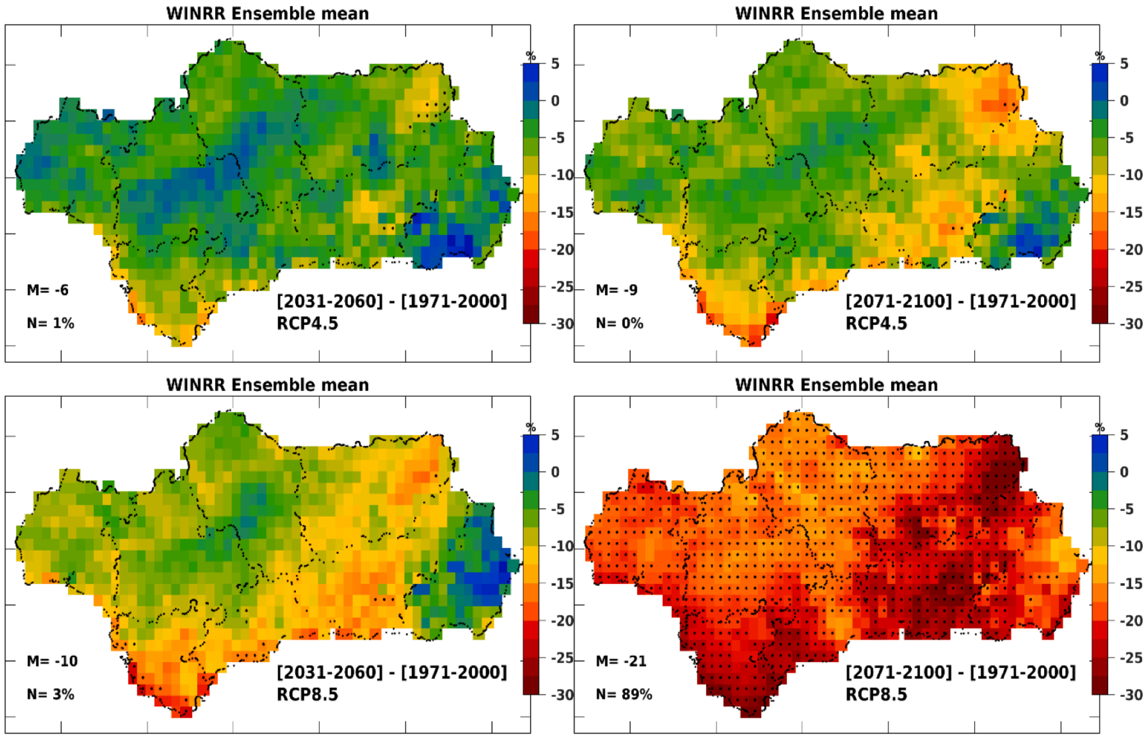

Fig. 12. Mean relative differences for total winter (Oct-May) precipitation (WINRR) for the five member sub-ensemble model between the near (2031–2060) and distant future (2071–2100) and the reference period (1971–2000) under two RCP scenarios (RCP4.5 and RCP8.5). M denotes the spatial average change over all the grid points. All units are %. Black dots indicate a robust change at the grid point scale while N denotes the percentage of grid points where robust changes are found.

for the near future under the RCP4.5 and RCP8.5, respectively. Maximum increases are expected for the central and the northern Andalusia (Seville, Cordoba, Jaen) reaching almost 23 and 28 extra days/year under RCP4.5 and RCP8.5,respectively. For the distant future, the average increase in SU36 reaches almost 21 and 40 extra days/year under RCP4.5 and RCP8.5, respectively. The maximum differences reach almost 55 extra days/year. Even though Andalusia exhibits the highest summer temperatures in Spain (Domínguez et al., 2013) further increase of temperature in the future could overburden farmers with extra irrigation.

3.3.4. SU40

The extreme heat stress, as indicated by the SU40 index, is expected to increase, especially in northern Andalusia (Fig. 11). The average increases for the near future are about 5 and 8 extra days/year under RCP4.5 and RCP8.5, respectively. However, large variability is found between the different provinces; robust increases, higher than 10 extra days/year are projected for the northern Andalusia (Cordoba, Sevilla, Jaen) with the maximum increase reaching 16 and 20 extra days/year of extreme heat stress under RCP4.5 and RCP8.5, respectively. In the distant future, the average projected increases reach about 9 and 24 extra days under RCP4.5 and RCP8.5, respectively. Similarly to what is projected for the near future, the results indicate robust increases in northern Andalusia with the maximum increase reaching 23 and 48 extra days/year under RCP4.5 and RCP8.5, respectively. It has been shown that when midday temperatures rise above 40 °C, heat stress induce a decline in the photosynthetic capacity of the olive plant (Haworth et al., 2018).

3.3.5. WINRR

For the reference period (1971–2000) the accumulated seasonal (Oct-May) precipitation (WINRR index) ranges between 150 and 550 mm/yr; the highest values are found in the mountainous area of Granada. The spatial patterns of the differences of the WINRR index between the reference and the future periods is shown in Fig. 12; WINRR, an index closely related to crop yield, is expected to decrease in both the near and distant future and under both emission scenarios. Similar results have been reported by Fraga et al. (2019), with growing season precipitation projected to decrease in the Iberian Peninsula. In Fig. 12 of our study, blue colour indicates small positive change, while red indicates large negative differences (-10 to -30 %). The spatially averaged relative decrease is 6 % and 10 % in the near future under RCP4.5 and RCP8.5, respectively. However, the changes are not projected to be robust for the majority of the grid points under both scenarios. Similar results are shown for the distant future under RCP4.5. The decrease, however, is accelerated under the RCP8.5 scenario; the highest mean relative decrease for the distant future reaches almost 20 %. The lowest relative decreases in this case (13–15 %) are projected for the grid points around Cordoba, while the highest decreases (>25 %) are projected for the eastern boundaries of Jaen, in Granada and in the southern and coastal boundaries of Cadiz.

4. Summary and conclusions

The long-term climate change impacts on olive crops in Andalusia (South Spain) were examined using specially tailored climatic indicators along with the return period method, which is useful for risk description and quantification. The climatic indices used for this study have been identified in the frame of the Med-Gold Horizon 2020 project as the most appropriate for the olive sector. The return levels of interest for the calculation of the occurrence probabilities were estimated by the upper tail of the reference distribution. Both the climatic indices and the occurrence probabilities of the return period analysis were calculated using an ensemble of high-resolution, bias adjusted RCM-GCM model simulations from the EURO-CORDEX initiative.

Indices analysis. Five indices have been calculated; four temperature (SPRTX, SPR32, SU36, SU40) and one precipitation related (WINRR). The expected future differences in the temperature based indices, which are directly related to early flowering dates in spring (SPRTX, SPR32) and extra irrigation and pest control in summer (SU36, SU40), are positive, while the precipitation related index, which is closely connected to olive yield and soil management, is expected to decrease. Since high summer temperatures favour an earlier ripening of the olives and thus also affects negatively the fruit weight (Garcia-Inza et al., 2014), the increase of SU36 and SU40 may imply the need of extra irrigation, which increases the fruit size and flesh-to-stone ratio (Bartolini et al., 2014). The changes will mostly affect the central and northern Andalusia; the temperature indices will significantly increase in the provinces of Seville, Cordoba and Jaen both in the near and distant future, while for the precipitation index, the most robust decrease is projected for the distant future and under the RCP8.5 emission scenario in the coastal boundaries of Cadiz, eastern Jaen and Granada province. Although olive trees are drought tolerant and are usually grown under rain-fed conditions (Gomez-Rico et al., 2007), the projected changes may imply the need for supplemental irrigation.

Return periods analysis. It is evident that climate change may have important implications for olive crops. Our study highlights the relationship between olive yield and precipitation; although olive trees are drought tolerant, the decreased precipitation projected for the future will affect the olive production. Meteorological, olive yield and olive fly infestation data have been used for showing and validating the relationship -that has already been identified in previous studies – of precipitation with olive yield and of temperature and relative humidity with olive fly attacks; low precipitation during winter lead to decreased yield and a combination of mild summer temperatures and increased relative humidity leads to increased risk of olive fly infestations. As Andalusia is expected to be drier in the future, the return period analysis has revealed that occurrences of bad years in terms of olive yield are subsequently expected to increase; bad years with return periods of below 2 years may increase by about 20 % until the year 2060. The patterns vary considerably among provinces; eastern Andalusia already experiences higher than 0.9 occurrence probabilities and this pattern tends to expand towards the west in the future under both emission scenarios. Regarding olive fly infestations, the number of summer days with maximum temperature >38 °C and relative humidity <45 % was used as a metric of the fly's invasive potential. Climate change is expected to contract the favourable range for olive fly in Andalusia; the occurrence probabilities of bad years due to fly infestations is estimated almost 100 % in central and southern Andalusia in the reference period, while in the future the favourable areas are predicted to contract northward due to increased summer temperature and the high probabilities for fly invasion are confined to the coastal areas. However, this is not a safe conclusion, since the expected higher SPRTX index may advance the flowering stage and therefore allow an early fly attack before the summer heats.

Perhaps the most useful information obtained from the return period maps indicating the future risk of bad years in terms of fly infestations is the identification of high risk areas in need of pest management techniques. Similarly, the return period maps of bad years of olive yield can point towards more sustainable irrigation methods. However, since the water availability is expected to be problematic in the future due to intensified cultivations, the return period maps can be used for better decision making so that more favourable locations for olive orchards can be identified.

Overall, the results highlight the importance to make the olive orchards in Andalusia more resilient to climate risk by encouraging in the same time agricultural practices that do not contribute to increased greenhouse gases emissions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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