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ORIGINAL ARTICLE

# Evaluation of Carob Tree Productivity during a 30-Year Period, in Relation to Precipitation and Air Temperature

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**Abstract** Water availability for irrigation of intensive crops will become a major problem in southern Iberia. One of the tools to sustain land use under water shortage is to choose crops well adapted to those environmental stress conditions featuring low water demand. The aim of this paper is to explore several relationships between climatic variables and the fruit production of carob-tree (yield) in a series of 30 consecutive years (1985–2015) referred to one single orchard. Precipitation and air temperature were the selected variables and regression models were tested. It was not possible to find any relations between yield and temperature, but precipitation during the hydrological year was inversely and significantly related to yield (Model 1- $R^2 = 0.18$). A close analysis indicated that rainfall registered during autumn was particularly effective, since higher yields were obtained in the years with less rainfall registered in the period September + October + November (SON) (Model 2; $R^2 = 0.21$). Although the air temperature effect was not found significant, mean values between 22.0 and 24.5 °C during SON were crucial to flowering and yield. Model 2 was validated using an independent data set considering 3 years, and the calculated yields were overestimated by 18.6% and 4.0% in two consecutive seasons. Moreover, Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios predict a precipitation decrease for SON period in the region, which may create favorable conditions for insect pollination and fruiting success.

## Highlights

- Precipitation and air temperature in a 30-year period are correlated with carob (a dry fruit) production in southern Portugal
- Higher precipitation during September + October + November (SON) is related to lower yield
- Climatic forecast using RCP scenarios indicates a decrease in precipitation during SON for the next decades which may lead to higher yield.

**Keywords** *Ceratonia siliqua* · Climate change · Flowering · Autumn · Yield · Mediterranean

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## 1 Introduction

Mediterranean-climate regions are particularly vulnerable to climate change events, such as drought occurrence and increase in air temperature. In these regions, precipitation, which occurs mainly in winter, presents a very large inter- and intra-annual variation pattern. Most of the climatic models forecast a decrease in precipitation and increase in air temperature by the end of twenty-first century, thus, conditioning the options regarding the adoption of new cropping and farming systems (Del Pozo et al. 2019; Giorgi and Lionello 2008; Ouhamdouch and Bahir 2017; Ouhamdouch et al. 2020). Therefore, crops that cope with water scarcity or extreme climatic events will became essential players in preserving water resources and biodiversity but at the same time, maintaining a significant marketable yield (Galindo et al. 2017; Boumenjel et al. 2020).

In the south of Portugal, natural agroforestry systems are composed of several slow-growing tree species. This region is particularly affected by long dry summers and mild winters with direct consequences on tree productivity and environmental resources (water and soil). The climate is temperate with dry summers (Csa Köppen classification), monthly average temperatures between 12 and 24 °C and total annual rainfall of about 500 mm/year (1971–2000 climate normal). Most of the annual precipitation occurs during the 3-month winter season, while the summer months (June–August) are extremely dry, contributing to only 6% of the annual precipitation (Miranda et al. 2002). As typically observed in southern Iberia, the precipitation in the study area is characterized by large values of inter-annual variability, with large disparities between wet and dry years (Santos and Miranda 2006).

An important tree crop that grows all over the Mediterranean-type ecosystems is the carob-tree (*Ceratonia siliqua* L.), an evergreen species that has the ability to explore heavy textured soils with high percentage of active lime (> 10% of $CaCO_3$) and low content of organic matter. The rooting strategy of this crop allows the uptake of water in deep soil layers, as found by Correia and Martins-Loução (2005). The fruit, carob, is a dry pod with multiple utilizations in pharmaceutical and nutraceutical industry, and is considered a novel functional food (Correia et al. 2018; Goulas et al. 2016; López-Sánchez et al. 2018; Nasar-Abbas et al. 2016).

More than 90% of the mature carob tree orchards are in the southern province of Portugal (Algarve) and most of them are not irrigated and do not receive mineral fertilizers. Therefore, tree growth and yield rely on favorable climatic conditions during the progress of the crop cycle. Climatic requirements of carob-tree (optimal temperature and rainfall) are known at a broad scale (e.g., Tous et al. 2013), but no information is available regarding the impact of climatic variables on long-term tree performance and ultimately, on regional carob production. It is well assumed that 500 mm of precipitation per year is required to obtain significant productions and good vegetative growth, but some branch growth increments (around 4 cm average in a three-month period) were observed for lower amounts (300 mm) of rain (Correia and Martins-Loução 2004). Values of air temperature below 10 °C may cause leaf abscission and death of young tissues, and air temperature is one of the most limiting factors for the success of this crop. The impact of extensive periods of drought or other extreme climatic events on flowering and yield is not known and deserve special attention. As in other fruit tree crop, there are physiological critical periods with direct implications on flowering and yield. In northern hemisphere, flowering season starts in September and extends until the end of November. This a crucial period for pollination, flower fertilization and fruit set (Haselberg and Lüdders 1996). After winter rest (December until February), fruits start to enlarge and attain its maximum weight in June, an important stage for the development of the seeds after fertilization (Warden et al. 1980).

This influence of climate on carob-tree yield is complex since this crop shows a pattern of yield irregularity between years. This pattern is also more pronounced in fertile soils as compared to low fertile soils (Correia and Pestana 2018), but irrespective of the soil type and soil chemistry, the pattern is erratic and difficult to predict on a long-term basis. It seems that there is a role of endogenous factors (for example, hormonal shifts) in this alternate bearing (Haselberg and Lüdders 1996), but there is an important gap of knowledge of the direct impact of climatic variables on flowering and related processes such as pollination effectiveness. Contrary to what occurs in spring, where flowers of other Mediterranean crops are pollinated by bees, in autumn, bees are scarce, and thus, carob flowers are mainly visited by flies and moths and other unspecialized visitors (Retana et al. 1994). Other reports show that high temperatures just before the flowering season may lead to the death of many insects, such as wild bees. Thus, unfavorable environmental conditions during this period limit insect activity, pollen mobility and ultimately, fruit set and production (Al-Ghzawi et al. 2014).

Currently, in southern Portugal, water resources through irrigation are directed towards other high-valuable fast-growing crops (such as Citrus and Avocado), which contribute to a fast and seasonal depletion of available water. Carob-tree shares the same pedo-climatic environment with those crops, but it can grow under rain-fed conditions and co-exist within a mixed agrosystem. Thus, it is important to provide basic and “easy-to-use” information about the response of carob-tree to climate variability and seasonality. This may provide decision tools to select crops particularly suited to cope with environmental constraints. Moreover, if we add the effect of climate change perspectives in southern Iberia (Iglesias and Garrote 2015), which are low precipitation and higher air temperatures, the agronomical implications and farmer’s income are expected to be negatively affected.

In this study, the working hypothesis is that it is reasonable to admit that climatic parameters may be significantly related to carob production analyzing long data series, despite the complex endogenous signaling involved in the reproductive metabolism. The primary objective of this work is to analyze air temperature and precipitation values during specific windows of time and test possible relationships with fruit production considering the yield irregularity characteristic of this crop.

## 2 Materials and Methods

### 2.1 Experimental Data

The selected orchard with a total area of 4.3 ha is located in Castro Marim (37°21’ N 7°48’ W) in the southern part of the province of Algarve. The size of the plot is substantially higher than the average normally found in this region. Soil chemistry of the orchard and cultural practices have been described in Correia and Pestana (2018).

Yield data (fruit production) was provided by the farmer and reports to the period 1985–2015 ($N = 30$ years). The values per tree (kg) were calculated based on the total yield per ha and dividing this value by the number of productive trees per ha, thus, eliminating tree variability within the total area. Tree age is currently >70 years-old. Trees belong to the cultivar “Mulata,” one of the most important cultivars in the country. Male trees are found near the site, and it was assumed that pollen availability was not limited.

The climatic variables under study were maximum and minimum air temperatures and precipitation, and were obtained from the nearest meteorological station (Vila Real St°

António, at 4 km distance). The approach of this study relies on two basic assumptions: (i) air temperature and precipitation at the site, are key variables to influence tree performance, and ultimately, fruit production at harvest. It is assumed that these two parameters are the most important for climatic data analysis and spatial climate assessment (e.g., Daly et al. 2008); and (ii) a significant outcome is achieved by using the equation that maximizes the coefficient of determination ($R^2$) in simple regression (Legendre and Legendre 1998). Total precipitation (P, mm), means of maximum and minimum air temperatures (°C) for each month and for the same period (30 years) were used in this study. Anomalies in precipitation values were calculated considering a mean of 177.2 mm (1971–2000) and under two Representative Concentration Pathways (RCPs) 4.5 and 8.5 scenarios (Vuuren et al. 2011; IPCC 2013).

Several regression models were tested, with yield as the dependent variable and climatic variables (air temperature or precipitation or a mathematical combination of the two) as the independent variables. Statistical analysis was done by using IBM Statistics SPSS version 24.

### 2.2 Validation Orchard

An independent data set was used to verify the output of the selected model. The validation data was obtained from an orchard located at 55 km west in the same province, characterized previously (Correia and Martins-Loução 2004), and refers to a three year-period (1997 to 1999). The trees of this orchard are of the same cultivar and they were not fertilized or irrigated. Precipitation values during September, October and November were used in the model to calculate yield which were compared to the observed values. The relative error was calculated, and expressed as percentage (%).

## 3 Results

Monthly, total precipitation (P) is shown in Fig. 1. In the period under study ($N = 30$ years), the mean value is 486 mm with a maximum of 1078 mm registered in 1989 and a minimum value of 250 mm in 1998. The coefficient of variation (CV) is 36.5%. Figure 2a, b show, respectively, the monthly variation of air temperature and precipitation. The mean of maximum temperature was 22.7 ± 5 °C, with a peak of 34.1 °C in August 2010. As for minimum temperatures, the mean was 13.1 ± 4 °C, and the lowest value was 4.1 °C in February 2012. Thermal amplitude was calculated for each month and the mean was 9.5 ± 2 °C (Fig. 2a). The largest difference between maximum and minimum temperatures was 15.4 °C registered in August 1985.

Yield production (kg of pods per tree) was expressed as yield variation (Fig. 3) calculated as the difference between yield in two consecutive years. This allows identifying the pattern of irregularity (on-off) which characterize this species. Apparently, the alternate bearing phenomenon was slightly attenuated in the period between 1997 and 2007 (second decade).

To assess the effect of climate on fruit production, specific windows of time were plotted against yield (kg) per tree, the independent variable. These windows of time, which may be the entire hydrological year, or a three-month period, were chosen based on what is known about crop physiology and phenology. Therefore, several relationships were tested, and the results are summarized in Table 1. Yield was significantly related to the total amount of precipitation during the hydrological year ($p < 0.05$) but it explained only 18% of variation (Table 1, Fig. 4). Using only the amount of precipitation during the flowering season (September + October +

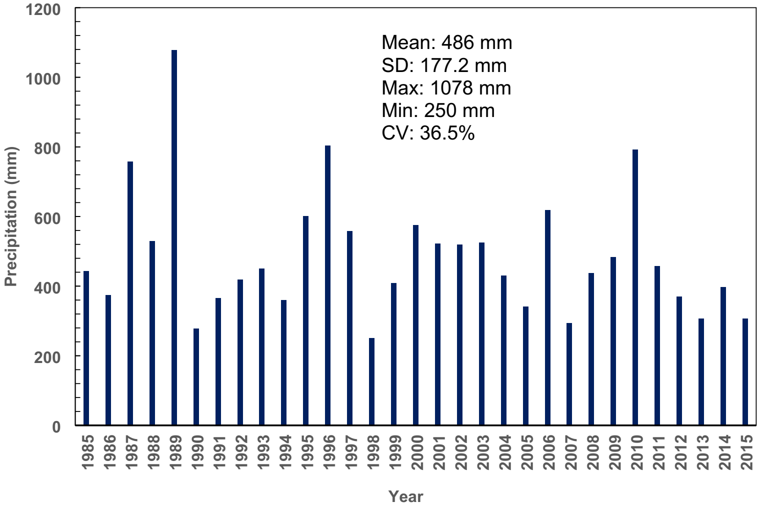

**Fig. 1** Annual precipitation recorded at Vila Real Sto António. Text inside indicate the mean and standard deviation (SD), maximum (Max) and minimum (Min) values, and the coefficient of variation (CV, %), considering the data of the entire experimental period

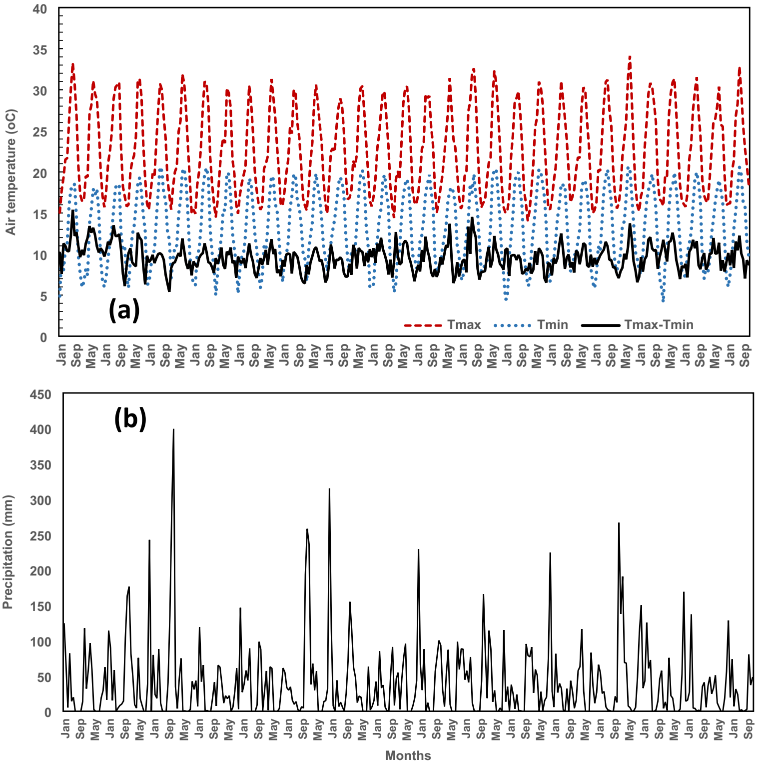

**Fig. 2** Seasonal variation of air temperature (**a**) and precipitation (**b**) between January 1985 and December 2015 at the site. Maximum (Tmax), and minimum (Tmin) values are the means for each month. The thermal amplitude is also shown (Tmax-Tmin)

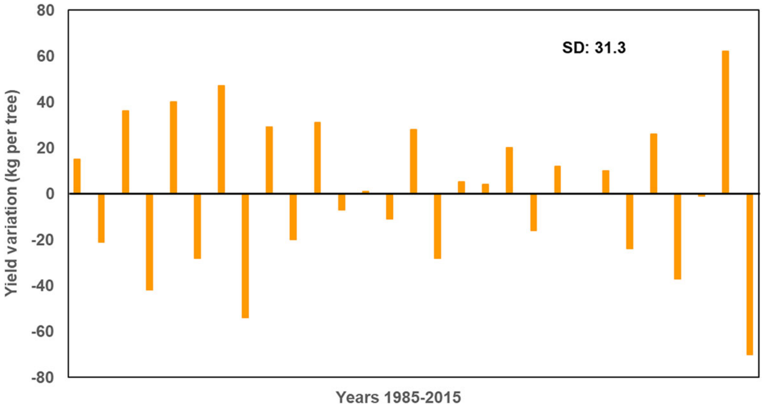

**Fig. 3** Yield variation (kg of pods per tree) from 1985 to 2015. Each bar refers to the difference in kg per tree, of the production registered in two consecutive years (i.e. year 2-year 1; year 3-year 2; year *n* + *1*-year *n*). SD: standard deviation in kg

November; SON) a very similar trend was found (Fig. 5) but with a slightly higher $R^2$ (0.21; $p < 0.05$). Rainfall during spring (April + May + June) had no effect on yield. Interestingly, Figs. 4 and 5 show that higher yields are associated to lower precipitation. Moreover, a close analysis of Fig. 4 indicates that at lower precipitation (ranging from 200 to 400 mm) there is a large variability of yield, where it is possible to find values above 90 kg per tree and less than 20 kg. Contrastingly, if precipitation is between 400 and 550 mm that variability is lower, and there is some consistency of production values.

Air temperature was not found to affect yield. Although several sets of data were tested (data not shown), it was not possible to obtain any significant model (Table 1). Maximum or minimum air temperatures registered in SON, or during vegetative rest, and thermal amplitude were not conclusive. Nevertheless, Fig. 6 shows that the interval ranging from 22 °C to 24 °C (means of maximum temperatures during SON) is apparently important to tree fruit productivity.

To test the best fit (yield and precipitation during SON), a validation independent data set was used (Table 2). Values of precipitation during SON were introduced in the model of Fig. 5 and yield was calculated. As observed in Table 2, yield values were 4% and 18.6% overestimated in relation to the observed values in the validation orchard. Finally, according

**Table 1** Relationships between yield (fruit production per tree) which was the dependent variable, and several climatic parameters (independent variable)

| Independent variable | Model and outcome |
|---|---|
| Hydrological year (P, mm) – Model 1 | Yield = 73.06 $e^{-0.002P}$; $R^2 = 0.18$; $p < 0.05$ |
| Sum of P (mm) during SON – Model 2 | Yield = 56.59 $e^{-0.003P}$; $R^2 = 0.21$; $p < 0.05$ |
| Sum of P during AMJ | No relationship |
| Mean of maximum T during AMJ | No relationship |
| Mean of minimum T during AMJ | No relationship |
| Thermal amplitude during AMJ | No relationship |
| Mean of maximum temperatures during JFM | No relationship |
| Mean of minimum temperatures during JFM | No relationship |

In all cases $N = 30$. T: air temperature; P: precipitation

SON: September + October + November (flowering season); AMJ: April + May + June (floral induction period); JFM: January + February + March (vegetative rest); P: Precipitation (mm); T: Temperature (°C)

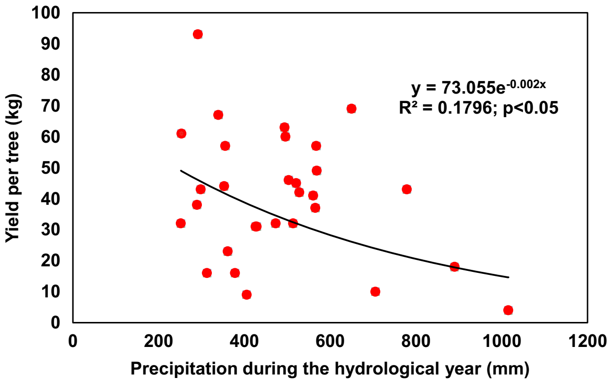

**Fig. 4** Relationship between yield per tree and the precipitation registered during the previous hydrological year

to RCPs 4.5 and 8.5 scenarios, a decrease in precipitation during SON period is expected (Fig. 7) in this region. The means of the precipitation anomalies are −27 mm and − 36 mm, respectively under RCPs 4.5 and 8.5 estimations.

## 4 Discussion

A previous attempt to predict yield in carob-tree was conducted by Correia et al. (2002) by using mature trees submitted to variable water irrigation levels and N mineral inputs for five years. In that study, it was possible to conclude that 92% of yield variation was related to N, P, K, Mn and Fe leaf concentration values, registered in a specific sampling date. However, that study excluded a non-bearing year, which probably explained the high significance of the model obtained and left the effect of an "off-year" as an open and unsolved question. Flower bud induction and floral initiation are key mechanisms to understand the irregularity of fruit production. Environment, hormonal balance and secondary metabolism are involved in rather

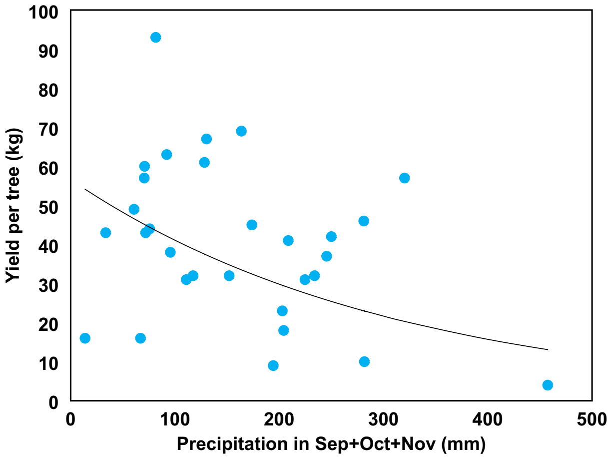

**Fig. 5** Relationship between yield and the sum of precipitation during the flowering season (September + October + November). Each *P* value (X-axis) refers to the sum of the values registered during SON, and refers to the entire period

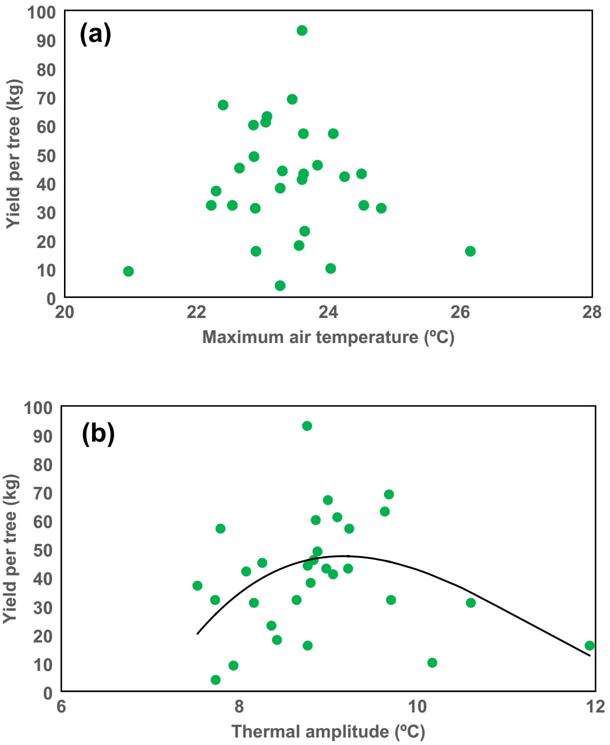

**Fig. 6** Relationship between maximum air temperature during flowering season (**a**) and yield, and between thermal amplitude and yield (**b**). Both models are not significant

complex interaction of alternative pathways (Capovilla et al. 2015; Ionescu et al. 2017; Sofo et al. 2018). In the carob-tree, there are no supporting data to enlighten the physiological events of floral induction, and subsequently, flowering and fruiting. However, there are no doubts regarding the beneficial effects of an adequate soil water content in respect to carbon balance and tree performance (Correia and Martins-Loução 2005; Tous et al. 2013). Due to its deep-rooting strategy, carob-trees rely on a suitable replenishment of deep soil water during autumn and winter to ensure a good canopy development. However, and in terms of water use strategy, vegetative and reproductive output may be inversely related. In a field experiment conducted during three years, Correia and Martins-Loução (2004) observed that a higher number of inflorescences in autumn was inversely related with the sum of precipitation registered in April, May and June, suggesting a possible water stress effect on flowering. Interestingly, in

**Table 2** Validation of the model of Fig. 5

| Years | P (flowering) | $Y_{obs}$ (kg) | $Y_{calc}$ (kg) | RE (%) |
|---|---|---|---|---|
| 1997 | 218.2 mm | | | |
| 1998 | 103.7 mm | 24.8 ± 9 | 29.4 | 18.6 |
| 1999 | | 39.9 ± 13 | 41.5 | 4.0 |

The sum of precipitation (P) during the flowering season of the validation orchard was used to calculate yield per tree ($Y_{calc}$). The values were compared to the observed yield ($Y_{obs}$) and the relative error (RE) was calculated. $Y_{obs}$ is the mean ± standard deviation; $N = 6$ (1998) or 5 (1999)

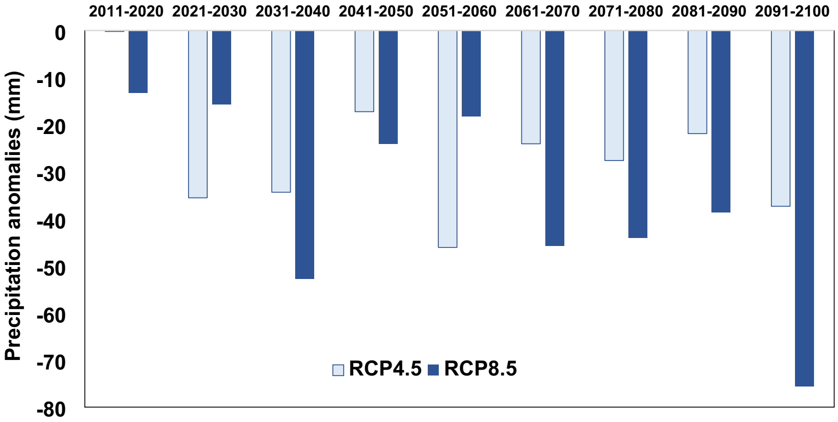

**Fig. 7** Precipitation anomalies (in mm) projected for the region, under two scenarios (RCP's 4.5 and 8.5)

the tropical Star fruit (*A. carambola*) drought stress induces flowering, despite the decrease in leaf water content (Pingping et al. 2017). However, in the present study, and in the absence of inflorescence quantification, it was not possible to establish a similar linkage, although resource trade-off is likely to occur if water supply in a particular season turn out to be highly variable.

In other fruit tree crops grown under rainfed conditions (e.g., Peng et al. 2017), the decrease of water availability in deep soil layers is a major restriction in fruit yield. Paradoxically, in our study, higher values of precipitation during the hydrological year led to lower yields, regardless of the alternate bearing status of the orchard. A refinement of this relationship shows that precipitation during SON triggered a very similar equation but with a slightly higher $R^2$ (0.21, $p < 0.05$) leading to the conclusion that rainfall during the flowering season (autumn) is important. This response is probably explained by the detrimental effect of autumn rainfall during pollination season. In fact, autumn events are particularly important to understand crop phenology alterations and productivity (Gallinat et al. 2015), and crop flowering in this period had received little attention. During autumn, insect migration and mobility is normally driven by temperature and day-length, but it is also affected by rainfall, humidity, and wind (Gallinat et al. 2015). Climatic variables have a strong influence on pollen dispersion. For olives, rainfall events in the autumn lead to lower pollen concentration in the atmosphere (Bonofiglio et al. 2008). Although this parameter is not considered in our study, it is reasonable to postulate the lack of pollination effectiveness due to atmospheric nebulosity. This also includes a deficient pollen transportation by bees and other insects, which are essential players in the flower fertilization of female carobs (Retana et al. 1994). However, the crucial role of insects in flower pollination and fruit set success is directly linked to the pre-existence of inflorescences, which starts to be visible in late summer. In off-years, no inflorescences develop in the previous autumn, suggesting a fail in flower induction and other related events. It is possible to consider the role of specific hormones as flower induction inhibitors (such as abscisic acid), but this hypothesis was not tested. Taking into consideration the work of Haselberg and Lüdders (1996), flowering intensity and yield are strongly influenced by endogenous factors, but the same authors also concluded that early winter rains associated with low temperatures triggered less fruit set, thus, less fruit production.

Visual observation of flowering during SON may provide important information to farmers and to industrial users of carob bean gum by giving a rough estimation of predicted yield. By incorporating the values of precipitation and eventually other climatic variables, yield projections in the following summer may be more reliable. Unfortunately, no relationships were found to sustain a diagnostic based on climatic patterns during winter or spring at the site under study. It seems, however, that air temperatures may also play an important role during SON. For example, in European beech, in the absence of water and nutrient limitation, temperature is a dominant factor controlling specific phenological events such as leaf senescence (Fu et al. 2017). Warmer temperatures during autumn, may led to faster insect developmental rates, added generations and delayed migration and diapause but there are threshold limits that must be accomplished for pollination success. It is known that if air temperature rises above 30 °C, bees normally change their preference to cooler flowers (Shrestha et al. 2018), and in olive high temperatures can cause growth inhibition of the ovary pollen tube (Bonofiglio et al. 2008). Increasing ambient temperature during the flowering season may cause phenological mismatches between woody crops and the incidence of its natural pollinators (Ollas et al. 2019). Our results show that there is an interval of thermal amplitude during SON, which may be considered favorable for flowering and insect pollination (Fig. 6b). Values between 22 and 24.5 °C (Fig. 6 a) were found to be optimal for fruit production (regardless of the values obtained) which are similar to optimum ambient temperature for the foraging flights of *Bombus terrestris*, one of the most important pollinators in cultivated crops (Roman and Szczesna 2008).

Interestingly, it seems that under low precipitation during hydrological year (200–400 mm, Fig. 4) the yield per tree is highly variable. This is in contrast with the years where precipitation varies between 400 and 600 mm (Fig. 4). Although this is a rough and qualitative assessment, we may speculate that under a scenario of precipitation decrease in the Mediterranean basin, an erratic yield pattern may occur which may present a potential loss of economic revenue for the regional gum industry and for the farmers.

While precipitation values in SON explain only 21% of yield variation, the model is useful to estimate yield of a different orchard. Calculated values are overestimated but the relative error of the estimations was 4% and 18.6%, in two consecutive seasons. Nevertheless, the interpretation of validation data should be done with caution since only three years (two seasons) and a maximum of six trees were used to test the outcome of the model. According to Miranda et al. (2002), regional and national forecast models project a drier climate in the southern regions of the country. In autumn, a decrease in precipitation is predicted by both RCP scenarios (Fig. 7). Based on the results presented here, we may not exclude these unfavorable climatic conditions for the success of the pollination events in this crop (less precipitation and warmer temperatures). Although with focus on a different perspective, López-Tirado and Hidalgo (2018) predict an increase in areas of *Quercus ilex* and *Pinus halepensis* stands, in a context of changing environment in southern Europe.

Air temperature and rainfall are of outmost importance to characterize the impacts of climate change in plant production and farming. This is particularly true in semi-arid regions (Ouhamdouch and Bahir 2017; Sun and Wenpeng 2017) where the interactions between climatic variables and plant productivity are rather complex. In this study, we must take into consideration the high variability of precipitation values in this 30 year-period (CV = 36.5%) which led to unpredictable outcomes in terms of soil water availability and fruit production. In a scenario of dry farming agriculture and climate change, this represents an additional problem for crop management. In southern Iberia, rainfed crops may coexist with high yielding and fast-growing fruit tree species. As pointed by Altieri et al. (2015), traditional farming systems are key players in future agroecological measures that strengthen the resilience of farmers, and may help modern and intensive agriculture systems to be more adapted to climatic extremes.

## 5 Conclusions

In our study, temperature effects were not clear factors affecting carob yields, whereas precipitation values were, especially during the flowering season September + October + November (SON). The best model obtained in this study reveals that 21% of yield variation is attributed to precipitation in this particular season (SON). It is probable that rainfall during autumn interferes with insect activity and flower pollination, and future research must link climatic parameters to insect activity and pollen availability. Nevertheless, under low precipitation during the hydrological year, the reproductive outcome (i.e., fruit production) is highly variable, which is a disadvantage to industrial crop processing, ultimately affecting regional competitiveness in Southern Iberia.

**Data Availability** Not applicable.

## Compliance with Ethical Standards

**Conflict of Interest** Not applicable.

**Ethics Approvals** Not applicable.

**Consent to Participate** Not applicable.

**Consent for Publication** Not applicable.

**Code Availability** Not applicable.

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