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ESCUELA TÉCNICA SUPERIOR DE INGENIEROS AGRÓNOMOS

DEPARTAMENTO DE PRODUCCIÓN AGRARIA

Response of maize and olive to climate change under the semi-arid conditions of southern Spain

Tesis doctoral

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TESIS DOCTORAL

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LOS VOCALES

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ABBREVIATIONS

ADAT	Anthesis date
ADPS	Adaptation selected
AEMET	Spanish meteorological agency
A _n	Argentine experiment <i>n</i>
AOC	Atlantic ocean coast
B	Baseline period
C	Control plots
CV	Coefficient of variation
DAS	Days after sowing
DJF	Winter (December, January, February)
DOY	Day of the year
DSSAT	Decision Support System for Agrotechnology Transfer
DT _{max}	Mean increment of maximum temperatures
DT _{min}	Mean increment of minimum temperatures
EDO	End of dormancy
ENS-EOBS	12 RCMs from the ENSEMBLES project with a bias correction in temperature and precipitation with respect to the E-OBS gridded observational dataset
ENS-Spain02	12 RCMs from the ENSEMBLES project with a bias correction in temperature and precipitation with respect to the Spain02 gridded observational dataset
E-OBS	Gridded observational dataset (Haylock et al. 2008)
EPP	Effective pollination period
ET _c	Crop evapotranspiration
FAO	Food and Agriculture Organization
fdmg _n	Simulated attainable yield normalized by the maximum value
FF	Far Future
fHS	Fractional stress intensity index
Fobs-Forg	Difference between flowering dates observed and estimated
FRTDM	Fraction of aboveground biomass to be translocated to seeds
G2	Maximum possible number of kernels per plant
G3	Kernel filling rate during the linear grain-filling stage and under optimum conditions
GCM	Global climate model
GDD	Growing degree days
GDP	Gross domestic product
GH	Greenhouse

GS _n	Growing stage <i>n</i>
GV	Guadalquivir Valley
H	Heated plots
hs1d	Heat stress events of one day above threshold
hs3d	Heat stress events of three consecutive days above threshold
HSF	Heat stress during flowering
IP	Iberian Peninsula
IPCC	Intergovernmental Panel on Climate Change
IRR	Irrigation requirements
IWP	Irrigation water productivity
JJA	Summer (June, July, August)
LAD	Leaf area duration
LAI	Leaf area index
MAM	Spring (May, April, May)
MBE	Mean bias error
MDAT	Maturity date
N	North
NE	Northeast
NF	Near future
NW	Northwest
O _i	Observed value
OU	Outdoors
p	Dimensionless penalty constant
P1	Thermal time from seedling emergence to the end of the juvenile phase
P2	Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate
P5	Thermal time from silking to physiological maturity
PAR	Photosynthetically active radiation
PAR _i	Intercepted PAR
PHINT	Phylochron interval
PostS	Post-silking treatment
Precip	Precipitation
PreS	Pre-silking treatment
RAEA	Red Andaluza de Experimentación Agraria
RCM	Regional climate model
RCP	Representative concentration pathways
RedHS	Heat stress reduction factor
RGR _{LAI}	Maximum relative increase in LAI
RIA	Agroclimatic Information Network of Andalusia

RMSE	Root mean square error
RTMCO	Correction factor for RUE
RUE	Radiation use efficiency
S_i	Simulated value
S	South
SE	Southeast
SIMPLACE <Lintul5,HS,Tc>	Combined model SIMPLACE<Lintul5, DRUNIR, CanopyT, HeatStressHourly>
SLA	Specific leaf area
S_n	Spanish experiment n
SON	Autumn (September, October, November)
Spain02	Gridded observational dataset (Herrera et al., 2012)
SRAD	Solar radiation
SRES	Special Report on Emission Scenarios
T_{air}	Air temperature
T_{air_ear}	Air temperature at ear level
T_{air_tas}	Air temperature at tassel level
T_b	Base temperature
T_{can}	Canopy temperature
$T_{can,lower}$	T_{can} lower limit
$T_{can,upper}$	T_{can} upper limit
T_{crit}	Critical temperature
Tday	Daytime
T_h	Hourly temperature
Tlim	Limit temperature for chilling accumulation
Tmax	Maximum temperature
Tmean	Mean temperature
Tmin	Minimum temperature
T_o	Optimal temperature
TSUM1	Thermal time from emergence to anthesis
TSUM2	Thermal time from anthesis to maturity
TT	Thermal time
TT_{hs}	Hourly stress thermal time
TTorg	Thermal time (from De Melo-Abreu et al., 2004)
TU	Total chilling units
TUE	Transpiration use efficiency
TUmax	Maximum value chilling units
TUmean	Mean value chilling units
TUmin	Minimum value chilling units

TUorg	Chilling units (from De Melo-Abreu et al., 2004)
TWP	Total water productivity
Tx	Breakpoint temperature
Y	Maize grain yield
Y _n	Normalized Y

SUMMARY

Global climate projections indicate an increase in atmospheric CO₂ concentration causing for Mediterranean regions an increase in both mean and maximum temperatures, an average decrease in precipitation and an increase in the temporal and spatial variability of extreme events related with rainfall, such as droughts. All these changes in many areas within Andalusia region (southern Spain) would have a direct impact on the agriculture, a critical sector with great social and economic importance.

This Thesis is a further step in the knowledge of the impact assessment that climate projections may have on agriculture in the region. To achieve this purpose, two ensembles of regional climate models (ENS-EOBS and ENS-Spain02) with a bias correction in temperature and precipitation were used in order to reduce the uncertainty linked to the use of climate models. Crop development, growth and yield under these climate conditions were simulated using crop models previously site-specific calibrated and validated. The assessment of these impacts aims to be useful for decision-making, allowing exploring the potential of adaptation measures to maintain or even increase the yield under future climate conditions.

In this Thesis the impacts of climate change on two crops of great importance in Mediterranean regions were evaluated. On the one hand, the maize crop, a reference irrigated crop under semi-arid conditions, which was analyzed in the first two chapters of the Thesis. On the other hand, the olive, crop extensively cultivated in Andalusia, the main olive oil producer region in the World, that was analyzed in Chapter 3.

Chapter 1 describes the impacts and adaptation to climate change for maize cultivated in five locations of Andalusia. For this purpose experimental data obtained from irrigated maize (FAO-700 cycle) under not limiting conditions of water and nutrients were considered. With these data CERES-Maize model under the DSSAT platform was calibrated and validated. For the consideration of climate data several sources were used; for the observed climate, data from the Agro-climatic Information

Network of Andalusia (RIA) was used and for the simulated climate, data from an ensemble of twelve regional models (ENS-EOBS) with a bias correction in temperature and precipitation over the original European project ENSEMBLES was used.

The results for the end of the 21st century project a reduction in the maize crop cycle length causing a decrease in the duration of the grain filling period and then, a decrease in yield maize and irrigation requirements. In addition, the stomatal closure caused by the increase in CO₂ concentration, could lead to an increase in the water use efficiency. To reduce the negative impacts on maize crop, in this Thesis some adaptation measures were evaluated. Thus, some proposed adaptations were to advance the sowing date 30 days earlier than current and to change the maize cultivar seeking to increase the grain filling period and its efficiency. These adaptations offset the yield losses and even in some cases, the projected yield was increased. The impacts and the adaptation strategies effect were also evaluated from the point of view of the incidence of extreme temperature events at flowering, showing an increase in the number of extreme events as well as in the production damage at the end of the 21st century. The proposed adaptation strategies previously described resulted in an overall reduction of crop damage by extreme maximum temperatures at all locations with the exception of specific locations such as Granada, where losses were limited to 8 %.

With this precedent, the Chapter 2 deals with the modelling of heat stress events on maize yield. A heat stress response function was developed and evaluated into the modeling framework SIMPLACE, within the Lintul5 crop model and the canopy temperature model (CanopyT). For this task, experimental data from Pergamino (Argentina) considering a maize temperate hybrid, and from Lleida (Spain), with a maize cultivar FAO-700 cycle, were used. In both experiments the maize plants were subjected to high temperature conditions around flowering by placing polyethylene tents. Argentine data were used to obtain a yield reduction factor in relation with thermal time under a critical temperature of 34 °C during the flowering period. On the other hand, the Spanish data were divided into two sets, one of them under control

conditions to calibrate the model, and the other set to validate it using the reduction factor obtained from the Argentina data. The model evaluated consider canopy temperature (T_{can}) or air temperature (T_{air}) for the simulation of impact of heat events on maize yield, obtaining better model performance using T_{can} when the critical temperature was set to 34 °C. However, when critical temperature for T_{air} was increased to 39 °C, the results were similar for both temperatures (canopy and air) indicating that for irrigated and high radiation conditions the air temperature could be used as input in the model without the need to simulate the canopy temperature.

The Chapter 3 evaluates the impacts of climate change on olive flowering for current and future climate conditions at southern Spain. For this purpose an experiment located at Cordoba from 1st October 2013 to the end of May 2014 was set to evaluate ten olive genotypes under two different climate conditions, one outdoors (OU) and the other inside of a greenhouse (GH). The aim of the experiments carried out in GH was to identify the impacts of the increase in temperatures on olive phenology, reproducing the mean increment of maximum and minimum temperatures (DTmax, DTmin) projected at the end of the 21st century. To quantify these increases, data from an ensemble of twelve regional climate models (ENS-Spain02), with a bias correction in temperature and precipitation from the original climate models of the ENSEMBLES European project were used. Once the foreseen climate conditions were reproduced in GH, olive flowering dates were evaluated under both climate conditions using previous flowering models, obtaining good results under OU conditions, but not for GH. Based on these results, a new model was proposed and evaluated taken into account on one hand the chilling hour accumulation and on the other hand obtaining the flowering dates achieved after heating accumulation. Once the new model was developed, flowering dates were evaluated for the whole region of Andalusia, obtaining a mean advance in the flowering date of 17 days for all the genotypes for the climate conditions foreseen at the end of the 21st century. A spatial analysis of the results was carried out, identifying the highest advance in flowering date in the mountainous area of Jaen and Granada provinces and the lowest in the Atlantic Ocean Coast area. Finally, a spatial analysis evaluating the vulnerable and suitable areas for

olive cultivation in Andalusia at the end of the 21st century was held. Thus, several areas were vulnerable due to high temperatures in flowering (North and Northeast regions) or to lack of chilling hour accumulation in winter (Atlantic Ocean and the Southeast coast). Equally, potential new areas for olive cultivation were detected as the southern area of Andalusia.

RESUMEN

Las proyecciones climáticas globales indican un aumento en la concentración de CO₂ atmosférico que, para las regiones mediterráneas, implican un aumento tanto en las temperaturas medias como en las máximas, una disminución promedio de las precipitaciones y un aumento de la variabilidad temporal y espacial de los fenómenos extremos relacionados tanto con la lluvia como con las sequías. Todos estos cambios tendrían un impacto directo en la agricultura de muchas áreas de la región de Andalucía (sur de España), sector crítico de gran importancia social y económica.

Esta tesis es un paso más en el conocimiento de la evaluación de impactos que las proyecciones climáticas pueden tener sobre la agricultura en la región. Para lograr este propósito, se han utilizado dos conjuntos de modelos climáticos regionales (ENS-EOBS y ENS-Spain02) con una corrección del sesgo de la temperatura y la precipitación con el fin de reducir la incertidumbre relacionada con el uso de modelos climáticos. El desarrollo del cultivo, crecimiento y rendimiento en estas condiciones climáticas se han simulado utilizando modelos de cultivos previamente calibrados y validados localmente. La evaluación de estos impactos pretende ser útil para la toma de decisiones, lo que permite explorar el potencial de las medidas de adaptación para mantener o incluso aumentar el rendimiento bajo condiciones climáticas futuras.

En esta Tesis han evaluado los efectos del cambio climático en dos cultivos de gran importancia en las regiones mediterráneas. Por un lado, el maíz, un cultivo en regadío de referencia en condiciones semiáridas, analizado en los dos primeros capítulos de la tesis. Por otro lado, el olivo, ampliamente cultivado en Andalucía, siendo la principal región productora de aceite de oliva a nivel mundial; este cultivo se analiza en el Capítulo 3.

El Capítulo 1 se describe los impactos y adaptaciones al cambio climático para el maíz cultivado en cinco localizaciones de Andalucía. Para este fin se han utilizado datos experimentales obtenidos a partir de maíz en regadío (ciclo FAO-700) bajo condiciones no limitantes de agua y nutrientes. Con estos datos el modelo CERES-Maize bajo la

plataforma DSSAT se ha calibrado y validado. Los datos climáticos considerados en este estudio proceden de varias fuentes; para el clima observado, se han utilizado los datos de la Red de Información Agro-climáticas de Andalucía (RIA), y para el clima simulado, los datos de un conjunto de doce modelos regionales (ENS-EOBS) con una corrección del sesgo en la temperatura y la precipitación sobre los modelos originales del proyecto Europeo ENSEMBLES.

Los resultados obtenidos para el final del siglo XXI proyectan una reducción en la longitud del ciclo del maíz causando una disminución en la duración del periodo de llenado de grano y, por tanto, una disminución del rendimiento del maíz y de las necesidades de riego. Además, el cierre estomático causado por el aumento de la concentración de CO₂, podría conducir a un aumento en la eficiencia del uso del agua. Para reducir los impactos negativos sobre el cultivo de maíz, en esta Tesis se evalúan algunas medidas de adaptación. De este modo, algunas adaptaciones propuestas son el adelanto de la fecha de siembra 30 días antes de la fecha actual y el cambio de la variedad de maíz buscando aumentar la eficiencia y período de llenado del grano.. Estas adaptaciones compensan las pérdidas de rendimiento e incluso en algunos casos, las proyecciones indican un aumento del rendimiento. Los impactos y el efecto estrategias de adaptación también se han evaluado desde el punto de vista de la incidencia de eventos extremos de temperatura en la floración, mostrando un aumento en el número de eventos extremos, así como en el daño en la producción a finales del siglo XXI. Las estrategias de adaptación propuestas descritas anteriormente dieron lugar a una reducción en los daños por temperaturas máximas extremas en todos los lugares, con la excepción de zonas específicas, como Granada, donde las pérdidas se limitan al 8 %.

Una vez identificado el problema en el Capítulo 1, una vía de solución se plantea en el Capítulo 2, que trata la modelización de eventos de estrés térmico en el rendimiento del maíz. Una función de respuesta al estrés térmico fue desarrollado y evaluado en el marco de modelado SIMPLACE, dentro del modelo de cultivo Lintul5 y de un modelo de temperatura de la cubierta (CanopyT). Para este cometido se han utilizado datos experimentales de Pergamino (Argentina) considerando un híbrido templado maíz, y de Lleida (España), con un ciclo de cultivo de maíz FAO-700. En ambos

experimentos las plantas de maíz fueron sometidas a condiciones de alta temperatura alrededor de la floración mediante la colocación de tiendas de polietileno. Los datos de Argentina se han utilizado para obtener un factor de reducción de rendimiento en relación con el tiempo térmico durante el periodo de floración considerando una temperatura crítica de 34 °C. Por otra parte, los datos de España se dividieron en dos grupos, uno de ellos en condiciones de control para calibrar el modelo, y el otro conjunto para validarlo usando el factor de reducción obtenido a partir de los datos de Argentina. El modelo evaluado considera la temperatura de cubierta (T_{can}) o la temperatura del aire (T_{air}) para la simulación del impacto de los eventos de calor sobre el rendimiento del maíz, obteniendo un mejor resultado utilizando T_{can} cuando la temperatura crítica se fijó en 34 °C. Sin embargo, cuando la temperatura crítica para T_{air} se aumentó a 39 °C, los resultados fueron similares para ambas temperaturas (cubierta y aire) que indican que para las condiciones de riego y alta radiación la temperatura del aire se podría utilizar como dato de entrada en el modelo sin necesidad de simular la temperatura de la cubierta.

El Capítulo 3 evalúa los impactos del cambio climático en la floración del olivo para las condiciones climáticas actuales y futuras en el sur de España. Para este propósito se ha llevado a cabo un experimento en la localidad de Córdoba desde el 1 de Octubre 2013 hasta finales de Mayo 2014 en el que se han evaluado diez genotipos de olivo en dos condiciones climáticas diferentes, uno en el exterior (OU) y el otro en el interior de un invernadero (GH). El objetivo de los experimentos llevados a cabo en GH fue identificar los impactos del aumento de las temperaturas en la fenología del olivo, reproduciendo el incremento medio de las temperaturas máximas y mínimas (DTmax, DTmin) proyectados al final del siglo XXI. Para cuantificar estos aumentos, se han utilizado los datos de un conjunto de doce modelos climáticos regionales (ENS-Spain02), con una corrección en el sesgo de la temperatura y la precipitación de los modelos climáticos sobre los originales del proyecto Europeo ENSEMBLES. Una vez que las condiciones climáticas previstas fueron reproducidas en GH, las fechas de floración del olivo han sido evaluadas bajo las dos condiciones climáticas usando modelos de floración anteriores, obteniendo buenos resultados en condiciones OU, pero no para GH. Basándose en estos resultados, se ha propuesto y evaluado un nuevo modelo

teniendo cuenta por un lado la acumulación frío y por otra parte el cálculo de las fechas de floración después de un periodo de acumulación por calor. Una vez desarrollado el nuevo modelo, se han evaluado las fechas de floración para toda la región de Andalucía, obteniendo un adelanto medio en la fecha de floración de 17 días para todos los genotipos bajo las condiciones climatológicas previstas al final del siglo XXI. Finalmente se realizó un análisis espacial de los resultados, identificando el mayor adelanto en la fecha de floración en las zonas montañosas de las provincias de Jaén y Granada y la menor en la costa del océano Atlántico. Igualmente, se ha realizado un análisis espacial evaluando las áreas vulnerables y adecuadas para el cultivo del olivo en Andalucía a finales del siglo XXI. De este modo, varias zonas muestran vulnerables a las altas temperaturas en floración (regiones Norte y Nordeste) o por falta de acumulación de frío en invierno (costa del Océano Atlántico y la costa sureste). Igualmente, se han identificado nuevas áreas potenciales para el cultivo del olivo como la zona sur de Andalucía.

INTRODUCTION

Agriculture is one of the most important social and economic activity at global scale, and directly dependent on the climate and edaphic conditions, making this activity high vulnerable to climate change effects (Olesen and Bindi, 2002; Easterling et al., 2007; Tubiello and Fischer, 2007). This Thesis has been developed in Andalusia, located in the South of Spain, and is focused on the impact of climate change in two representative crops of the region: maize (*Zea mays*) and olive (*Olea europaea*). Maize is a summer crop that is the world's most widely grown cereal in terms of grain production, although wheat and rice are the most important for direct human consumption and cultivated area (Steduto et al., 2012). Maize crop is cultivated in a wide range of climate and soil conditions, and can be considered as a reference herbaceous irrigated crop of the Andalusian cropping systems. In Andalusia, maize is irrigated and accounted for a mean cultivated area of around 34.000 ha and 11.000 kg ha⁻¹ production for the period 2010-2013 (RAEA, 2015). Olive is a traditional Mediterranean crop, being Spain the first olive oil producer in the world with around 40 % of the total production (FAOSTAT, 2016). The southern Spanish region of Andalusia represents the first national olive oil producer with 80% of the national production (1.1M tons; CAPDR, 2016a, covering 1.4 Mha which around 33 % correspond to irrigated olives (MAGRAMA, 2015). Olive is recognized by its social role as this crop generates a high rate of employment per surface unit and currently provides around 32 % of total agriculture employees in Andalusia region (CAPDR, 2008).

According to the World Meteorological Organization (WMO), climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Furthermore, the United Nations Framework Convention on Climate Change (UNFCCC) provides another definition, where the "climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods". Therefore, both definitions are different, as the anthropic attribution of the change is not part of the WMO definition.

Historical observational atmospheric data until date show a significant increase in the greenhouse gases concentration (Fig I.1). This trend is projected to continue, causing an increase in global temperature at the end of the 21st century (Intergovernmental Panel on Climate Change, IPCC, 2014). The changes in mean precipitation will not be uniform: an increase is projected in the high latitudes, mid-latitudes wet regions and equatorial Pacific while in many mid latitude as southern Europe and subtropical dry regions precipitation will likely decrease (IPCC, 2014).

Figure I.1. Past atmospheric concentrations of the greenhouse gases carbon dioxide (CO₂, green), methane (CH₄, orange) and nitrous oxide (N₂O, red) determined from ice core data (dots) and from direct atmospheric measurements (lines). Concentration units are parts per million (ppm) or parts per billion (ppb) (source: IPCC, 2014)

In order to simulate the foreseen changes in the climate conditions and based on the current information, the generation of climate projections implies a successive decision steps. One of these steps is the selection of emission scenarios, for instance among the SRES scenarios (Special Report on Emission Scenarios, Nakićenović et al., 2000), which describe the driving forces of future emissions. SRES scenarios follow four storylines grouped into four scenario families: A1, A2, B1 and B2. Group A1 describes a world in development with rapid economic growth and a reduction of regional differences. This group is disaggregated in three scenarios according to the base of the technological development: fossil fuels (A1F), non-fossil (A1T) or balanced (A1B). Scenario A2 describes a very heterogeneous world, determined by self-reliance and preservation of local identities, while the B1 describes a convergent world population that reaches a maximum and then decreases. Finally the B2 scenario describes a world with an increased concern for environmental and social sustainability compared to the A2 scenario. Until recently, climate projections have been given only using these

emission scenarios; however, there are currently a new generation of proposed scenarios, the Representative Concentration Pathways (RCPs; Moss et al., 2010), taking into account also the system resilience and mitigation and adaptation strategies. These RCPs have been considered in the last IPCC report (IPCC, 2014).

Simulated climate under climate scenarios is produced by Global Climate Models (GCMs). These models cover the entire globe with a resolution ranging from 150 x 150 km to 300 x 300 km and describe the climate behavior by integrating different ocean-atmospheric dynamics with mathematical equations to generate climate projections. There are two main downscaling techniques for the generation of climate projections at regional level providing climate information on a scale compatible with the regional and local impact studies, the dynamic and the statistical methods. The dynamic downscaling approach reduces the scale of the GCM outputs through the Regional Climate Model (RCM) maintaining their boundary conditions; therefore the generated RCM are numerical models run in a limited area nested in a GCM (Castro et al., 2005). The current RCMs provide a resolution between 50 x 50 km and 5 x 5 km. In the other hand, statistical downscaling techniques use transfer functions to represent the observed, historical relationships between large-scale atmospheric variables with those observed locally (Wilby et al., 1998).

This Thesis uses the first approach based on RCMs. RCMs consider the altitudinal variation by including the topographic forcing in the atmospheric variability (Castro et al., 2005), which is essential in the evaluation of climate change impacts on agriculture in heterogeneous regions as Andalusia (Guereña et al., 2001). In spite of the use of RCMs with high spatial resolution, climate projections contain multiple sources of uncertainty such as the selection of emission scenarios, the driver GCM or the inherent uncertainty to the climate model, as the different physical parameterization of models and their resolution (Olesen et al., 2007; Ruiz-Ramos and Mínguez, 2010; Osborne et al., 2013). Furthermore, RCMs simulations may present large biases when compared to observations (Dosio and Paruolo, 2011; Ceglar and Kajfež-Bogataj, 2012) that can limit their application at local and regional scale. For example, several studies indicate that the simulated summer temperature at southern Europe of recent decades is overestimated by RCMs (Christensen et al., 2008; Dosio et al., 2012). Another example is given by Ceglar and Kajfež-Bogataj (2012), who showed that the use of raw simulations

from RCMs into a crop model produces unrealistic maize yield estimations due to the underestimation of the intensity of daily precipitation. This uncertainty could be reduced with the bias correction of climate projections (Dosio et al., 2012; Ruiz-Ramos et al., 2015). But it is noteworthy that the uncertainties in regional climate projections can be better characterized and reduced when an ensemble of simulations exploring all the relevant uncertainty dimensions is considered (Giorgi et al., 2009). For that reason, in this Thesis an ensemble of climate projections from one of the major projects that has generated regional projections for Europe, ENSEMBLES (www.ensembles-eu.org, Van der Linden and Mitchell 2009), is used. The ENSEMBLES projections were still referred to SRES scenarios and do not consider RCPs.

Most of the climate projections obtained with these climate models foresee a global increase in mean temperature around 1 to 4 °C considering the range of RCPs emissions scenarios by the end of the 21st century (IPCC, 2014), similar to the increase provided by the previous IPCC report (IPCC, 2007). Temperature projections over Europe (A1B scenario) show increases in the mean annual temperature, this increase being higher in the summer months. Regarding precipitation, increases in northern Europe (up to 16 %) and decreases in the South (from -4 to -24 %) are projected with high uncertainty (Christensen et al., 2007; Bindi and Olesen, 2011) (Fig.I.2). Climate change will also strongly impact on the frequency and intensity of extreme events (Easterling et al., 2000; Sánchez et al., 2004; Beniston et al., 2007), this has been already observed, as in the summer heat wave of 2003 and 2010 (Schär and Jendritzky, 2004; Barriopedro et al., 2011). Extreme maximum temperature events (Meehl and Tebaldi, 2004; Hertig et al., 2010) are projected to become more frequent in the future (Beniston, 2004; Schär and Jendritzky, 2004; Tebaldi et al., 2006; Beniston et al., 2007; van der Velde et al., 2012).

Figure I.2 Temperature and precipitation changes over Europe for the A1B scenario. Top row, Annual mean, DJF and JJA temperature change between 1980 and 1999 and 2080 to 2099, averaged over 21 models. Bottom row, same as top, but for percentage of change in precipitation (from Christensen et al., 2007 and Bindi and Olesen, 2011).

The Mediterranean region is expected to be one of the most affected areas by climate change (Giorgi and Lionello, 2008). In Spain, some temperature projections from GCMs indicate an increase of around 4 °C during the warmest months considering both A2 and B2 scenarios (Giannakopoulos et al., 2009). These results are in agreement with Gosling et al. (2011) through the Met Office report for Spain, which projects an increase in annual temperature up to around 4 °C for A1B scenario. Within the CMIP3 multi-model ensemble of GCMs, made up of 21 members, the highest agreement between models was found in the southern Spain when comparing the increase of the mean annual temperature by 2100 with regard to the baseline climate (1960-1990). Also, these authors report projections of rainfall decrease for the Southwest of Spain over 20 %, and between 10 and 20 % over other rest of the country. Van der Linden and Mitchel (2009) in the ENSEMBLES European project (A1B scenario), report projections of increase in temperatures for southern of Spain from 2 °C in winter months to up to 5 °C in summer months, with a decrease in precipitation from 15 % in winter months to 30 % in summer months. In general, regional projections for ENSEMBLES project for A1B scenario showed the same trends that those of the former project PRUDENCE for A2, B2 scenarios (Christensen and Christensen, 2007) but the magnitudes of projected changes are larger.

Future projections of the impact of climate change on crops are usually obtained through crop models combined with climate change scenarios. Crop models simulate crop growth, phenology, development and production once calibrated and validated, using mathematical representations of the main processes involved with different degree of complexity and biophysical understanding. Crop models are commonly classified into empirical or mechanistic (Dent and Blackie, 1979; Connolly, 1998; Thornley and France, 2007). In one hand, empirical models apply functions fitted to data without considering true simulations of the physiological processes involved in growth (Fourcaud et al., 2008). In the other hand, the mechanistic models represent the physiological responses of the crops to environmental variables and management to estimate crop development, growth and yield.

Other way to classify the crop models is attending the way that the model estimates the daily biomass accumulation under potential conditions; for instance the carbon driven group, when the model is based on the carbon assimilation by leaves through the photosynthesis process. Simulated growth processes and phenological development are regulated by temperature, radiation, and atmospheric CO₂ concentration and are limited by water availability (Todorovic et al., 2009); within this kind of crop models we can find the WOFOST (Diepen et al., 1989; Boogaard et al., 1998) and CROPGRO (Boote et al., 1998) models. The second group is the radiation driven models, which simulate the biomass through the intercepted radiation using the radiation use efficiency (RUE), as the models used in this Thesis: CERES-Maize (Jones and Kiniry, 1986) and SIMPLACE (Gaiser et al., 2013). Finally, the third group, the water driven models, uses the transpiration use efficiency (TUE) to calculate the biomass as proportional to transpired water, as for instance, AQUACROP model (Raes et al., 2009; Steduto et al., 2012).

Specifically for the crops addressed in this Thesis, maize growth and development have been modeled through different procedures and several approaches have been considered to achieve maize yield assessment. Thus, empirical functions applied to grain yield, as GAEZ model (Fischer et al., 2002) or GLAM (Challinor et al., 2004, 2005); considering daily increment in harvest index, as AQUACROP (Raes et al., 2009; Steduto et al., 2012) or CROPSYST (Stockle et al., 2003; Moriondo et al., 2011); or

determining grain number, as CERES-Maize (Jones and Kiniry, 1986) or APSIM maize (Carberry et al., 1989).

The olive crop modelling has lower development than the maize one. To evaluate the olive flowering dates, different models have been published based on the pollen density (Galan et al., 2005; Bonofiglio et al., 2008; Oteros et al., 2014) or in phenological observations (Orlandi et al., 2005). There are some models that calculate different processes of the olive productivity, as the photosynthesis, transpiration or water use efficiency (Diaz-Espejo et al., 2002, 2006; Connor and Fereres, 2005). Other models calculate the biomass production based on annual radiation (Villalobos et al. 2006), the functional approach based on the relation between yield and potential evapotranspiration (Viola et al., 2012) or calculates the potential olive oil production based on a three-dimensional model of canopy photosynthesis and respiration and the dynamic distribution of assimilates among organs (Morales et al., 2016). However, there is a need to improve the olive crop models under elevated both temperatures and CO₂ concentrations (Moriondo et al., 2015).

To evaluate the impact of climate change on crops is essential to analyze each component that affects crop growth, development and yield. Thus, components as phenology, transpiration efficiency or harvest index play a critical role in the response to crops to climate change. Phenology has been defined as the timing of recurring biological events regarding to biotic (genetic background) and abiotic (environmental and management) forces, and the interrelation among them (Lieth, 1974; Slafer et al., 2009). It is noteworthy that the phenological phases are largely controlled by temperature and day length (Sadras and Calderini, 2009). During the phenological period of flowering, high temperatures affect the number of flowers per plant, limit the pollen release and diminish the pollen viability, flower fertility and therefore the viable seeds (Prasad et al., 2000, 2006; Wheeler et al., 2000; Moriondo et al., 2011; Vuletin Selak et al., 2013). On the other hand, crop growth has been defined as an increase in the size of an individual or organ with time and depends on the capture of resources including CO₂, radiation, water, N and other nutrients (Sugiyama, 1995; Sadras and Calderini, 2009).

Experiments under elevated CO₂ concentration have shown that the carbon uptake, growth and above-ground production increase, while specific leaf area and stomatal conductance decrease (Ainsworth and Long, 2005) under these conditions.

Those changes could benefit plants and especially C3 plants (olive), and both C3 and C4 under water stress conditions, due to the increase in water use efficiency (Vu and Allen, 2009; Allen et al., 2011). For herbaceous species, the C3 present more positive effect than C4 species (maize) (Warrick et al., 1986). The trees are more responsive than herbaceous species to elevated CO₂ (Ainsworth and Long, 2005). There are few studies dealing with olive trees under CO₂ elevated concentrations, but the existing ones have shown a positive response of the photosynthetic rate and a decreased stomatal conductance, leading to greater water use efficiency with no effect on biomass accumulation rate (Sebastiani et al., 2002; Tognetti et al., 2002). Therefore, in addition to the effects of temperature and rainfall it is important to evaluate the effect of the projected CO₂ increase.

Maize grain yield is determined by the number of grains and its weight, being largely dependent on the climate conditions during the critical period of flowering (Fischer and Palmer, 1984; Kiniry and Ritchie, 1985; Grant et al., 1989; Lizaso et al., 2007). During this period the grain number is determined (Fischer and Palmer, 1984; Otegui and Bonhomme, 1998). Under high temperatures, the source capacity is reduced; both the photosynthetic rate causing a reduction in the carbohydrates synthesis (Barnabás et al., 2008) and the respiration rate (Wahid et al., 2007) are reduced. When these net assimilation reductions occur during the critical period of flowering a reduction in grain yield was observed (Andrade et al., 1999, 2002). Furthermore, the sink capacity could be reduced under high temperatures due to low pollen viability (Herrero and Johnson, 1980), grain abortion (Rattalino Edreira et al., 2011; Ordóñez et al., 2015) or the synchrony disruption between anthesis and silking (Cicchino et al., 2010); this reduction in sink capacity makes the losses of grain number irreversible. Large-scale observational studies analyzing maize yields and temperature records indicate that large yield losses are associated with even brief periods of high temperature when crop-specific thresholds are surpassed (Schlenker and Roberts, 2009; Gourdji et al., 2013).

Regarding olive trees, pollen concentration studies have shown that the elevated temperatures could generate an advance in the flowering date (Osborne et al., 2000; Galán et al., 2005; Avolio et al., 2008; Orlandi et al., 2010), being this advancement an indicator of the climate warming in the Mediterranean area (Osborne et al., 2000; Moriondo et al., 2013). These higher temperatures and the heat stress events during

flowering may cause damages such as ovarian abortion (Rallo, 1994), vegetative damage (Mancuso and Azzarello, 2002) and pollen germination damage (Cuevas et al., 1994; Koubouris et al., 2009), with the subsequent decrease in yield. Another important factor to take into account is the projected water shortage. Thus, in spite of the olive drought resistance (Connor and Fereres, 2005), the olive under water stress reduces the photosynthetic rate due to the stomata closure (Fereres, 1984; Angelopoulos et al., 1996). Another effect that can reduce yield appears when water stress during flowering affect the fertilization, as the flowers remain closed (Rapoport et al., 2012). Also, between the period from floral development to fruit development water stress has a direct effect on fruit tissues (Rapoport et al., 2004; Gucci et al., 2009).

Observed phenological trends across Europe (1971-2000) for 542 plant species indicate a mean advance 2.5 days per decade in leafing, flowering and fruiting records (Menzel et al., 2006). Data since 1986 showed an advancement in foliation, flowering and fruit ripening more evident in arboreal species (Olive, vine, *Quercus spp.*) than in herbaceous ones, showing that the major factor in the earlier foliation, flowering and fruit ripening was the increase in temperature (García-Mozo et al., 2010). In Cordoba, a province located at southern Spain in Andalusia, an increase in mean temperature of 1 °C during March–April–May induced an advance in olive flowering of 7.6 days during the 1982-2007 (Orlandi et al., 2010).

Concerning the crop yield, French maize yields observed over the past 50-years were found to decrease; this decrease has been related with an increase in the number of days with maximum air temperature above 32 °C (Hawkins et al., 2013). Likewise, a panel analysis for this species in the US determined that yields decreased with cumulative degree days above 29 °C (Schlenker and Roberts, 2009). Furthermore, Lobell et al., (2011) detected maize yield losses across Sub-Saharan Africa ranging from 1 to 1.7 % (depending on water availability) per each degree day above 30 °C.

Under climate change conditions, projected phenological trend across Europe implies an advancement of the flowering and maturity dates of spring cereals of 1 to 3 weeks by 2040 (Olesen et al., 2012), partially explained by an advancement of sowing dates. The projected rising temperatures in the spring and summer in the South of the Iberian Peninsula would lead to a shortening of the cereal phenological cycles (Guereña

et al., 2001), and in the case of the olive trees, a general advance of the crop cycle from 1 to 3 weeks could be expected at the end of the 21st century (Galan et al., 2005).

The projected effects on crop yield in Europe have been studied both at the continental level (Olesen and Bindi, 2002, 2004; Bindi and Olesen, 2011), and at regional level as well. In Mediterranean Europe, yield decreases are expected for spring-sown crops, as maize, sunflower or soybeans (Audsley et al., 2006; Giannakopoulos et al., 2009; Moriondo et al., 2010). For autumn-sown crops as winter and spring wheat, the impact would be more geographically variable, with projections of yield decrease in the most southern areas and of yield increase in the northern areas of the Mediterranean region, as the North of Spain and Portugal (Mínguez et al., 2007; Olesen et al., 2007; Giannakopoulos et al., 2009; Moriondo et al., 2010).

For the Iberian Peninsula, the published studies describe that rising temperatures, changes in rainfall patterns and the interaction of these two changes with increasing in CO₂ levels would cause widely varying effects on crops, depending on their location, growing season, management and variety. The decrease in maize biomass and yield due to the increase of future temperatures in the Iberian Peninsula has been projected (Iglesias and Mínguez, 1995; Guereña et al., 2001; Mínguez et al., 2007; Garrido et al., 2011). Yield decrease was projected with high degree of coincidence between climate models for irrigated maize (Ruiz-Ramos and Mínguez, 2010). Rey et al. (2011) project a maize yield decrease for the Iberian Peninsula in the future period (2071-2100) between 8 % to 20-25 % depending of the region. Nevertheless, not all projections are negative; for example in the case of rainfed spring wheat sowing in autumn, a yield increase is projected in some areas of current low production (Mínguez et al, 2007; Olesen et al., 2007; Ruiz-Ramos and Mínguez, 2010). In addition, results to date on yield projections present different uncertainty degrees linked to the studied crop and the water management regime (rainfed or irrigated), being determinant the water availability related to the inter-annual variability of precipitation and its uncertainty (Ruiz-Ramos and Mínguez, 2010). This uncertainty is smaller for southern than for northern regions due to the consistent occurrence of water stress through the 30 year simulations. Regarding the impact on olive oil yield, studies under future climate conditions for Andalusia region have shown that climate change may not be a large

threat and even suggest a slightly increase in oil yield (Iglesias et al., 2010; Morales et al., 2016) due to the increase of the photosynthesis rate per unit of absorbed PAR.

For some crops and under certain conditions, the benefits of increased CO₂ could offset the projected yield decrease under future climate (Long et al., 2006). However other studies have showed that the shortening of the phenological cycle in herbaceous species due to the higher projected temperatures under climate change will not be compensated by the increase in the photosynthetic rate caused by increased CO₂ (Boote et al., 2005; Christensen et al., 2007; Ferrise et al., 2011; Garrido et al., 2011).

Additionally to the described impacts, the increase in the frequency and intensity of extreme events (that for the Mediterranean area mainly related with heat stress and drought), together with the projected increase in mean temperature are expected to cause negative impacts on crop yield (Seneviratne et al., 2012; Gourdjji et al., 2013; Lobell et al., 2013). For most crops and regions, the intensity, frequency and relative production damage due to heat stress are projected to increase from the baseline to the A1B scenario (Teixeira et al., 2013). In the Iberian Peninsula, the heat extreme events represent a threat to summer-grown but not to winter-grown crops (Ruiz-Ramos et al., 2011). The term “heat stress” on plants under these extreme temperature events has been used to refer to brief episodes of high temperature lying outside of the range typically experienced (Porter and Gawith, 1999; Luo, 2011; Moriondo et al., 2011).

To cope with the impacts of climate change on agriculture, adaptation strategies could be used, depending of the crop, climate scenario or location. Adaptation strategies evaluated could be earlier sowing dates to avoid the warmer periods, longer grain-filling period or decreasing irrigation intervals in order to decrease canopy temperature especially at anthesis day (Giannakopoulos et al., 2009; Moriondo et al., 2010; Moradi et al., 2013; Trnka et al., 2014). These adaptations singly or in combination have substantial potential to offset negative climate change impacts (Howden et al., 2007). In the olive trees case the adaptation strategies are designed to reduce the air temperature, using cover crops and soil management practices to modify the albedo (Davin et al. 2014), or the consideration of supplementary irrigation to reduce the olive canopy temperature (Doughty et al., 2011; Andrade et al., 2012).

A recently approach developed by FAO (Food and Agriculture Organization of the United Nations), the Climate-smart agriculture (CSA) (<http://www.fao.org/climate->

smart-agriculture/en/) includes these adaptation strategies that could reduce or even increase the actual and projected yield under climate change conditions. The CSA approach looks forward to transform and reorient the agricultural systems, supporting the development and ensuring the food security under a changing climate.

In spite of the previous studies, important knowledge gaps remain for both maize and olive crops in key process as flowering under water and heat stress conditions. The only way to determine accurate functions defining these processes that fill this knowledge gap is the development of field experimentation that could lead to an uncertainty reduction based on the correct calibration and validation of the crop models under local conditions, as well as under forced climate conditions. This aspect is partially addressed also in this Thesis.

OBJECTIVES

The general objective of this Thesis is to evaluate the impacts of climate change and extreme events on maize and olive crops under the semi-arid conditions of Andalusia, located at southern Spain, and to propose adaptation strategies. For this purpose, the impact of climate change on phenology, water requirements and yield as well as key aspects of model improvement for both crops, are undertaken. Finally, an evaluation of adaptation strategies to limit the impact of climate change on these crops in the Mediterranean region will be proposed.

For this purpose, the specific objectives are:

- To evaluate different adaptation strategies for irrigated maize in five locations of Andalusia under future climate conditions, considering maximum temperature events during flowering, by using CERES-Maize crop model calibrated and validated with local experimental data.
- To develop, parameterize and evaluate the performance of a canopy heat stress method to account for the negative impacts of extreme high temperatures on maize grain yield at field scale.
- To evaluate olive flowering at southern Spain at the end of 21st century by developing a phenological model based on experimental data obtained under current and forced climate conditions, assessing the vulnerable and suitable areas within Andalusia for olive cultivation considering chilling requirements and heat stress during flowering.

THESIS STRUCTURE

The present Thesis is structured as described in the Figure I.3. In this scheme the three chapters are related. Firstly we evaluate the impact and adaptation strategies on two reference crops, for one side, Maize and for the other side Olive. The usefulness of the current tools has been evaluated, assessing the impact and adaptation in maize and considering the extreme events on flowering, using a method external to the crop model. For the olive some of the current olive flowering methods were evaluated. Once evaluated the current tools, some points to improve as the heat or water stress and the phenology dates estimation have been addressed: The Chapter 2 proposes a model improvement to capture the effect of heat stress during flowering on maize, and in the Chapter 3 a model to estimate the flowering date under current and forced climate conditions was proposed and evaluated.

Figure I.3 Schematic representation of the Thesis structure.

CHAPTER 1. STRATEGIES FOR ADAPTING MAIZE TO CLIMATE CHANGE AND EXTREME TEMPERATURES IN ANDALUSIA, SPAIN

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ABSTRACT

Climate projections indicate that rising temperatures will affect summer crops in the southern Iberian Peninsula. The aim of this study was to obtain projections of the impacts of rising temperatures, and of higher frequency of extreme events on irrigated maize, and to evaluate some adaptation strategies. The study was conducted at several locations in Andalusia using the CERES Maize crop model, previously calibrated/validated with local experimental datasets. The simulated climate consisted of projections from regional climate models from the ENSEMBLES project; these were corrected for daily temperature and precipitation with regard to the E-OBS observational dataset. These bias-corrected projections were used with the CERES-Maize model to generate future impacts. Crop model results showed a decrease in maize yield by the end of the 21st century from 6 to 20 %, a decrease of up to 25 % in irrigation water requirements, and an increase in irrigation water productivity of up to 22 %, due to earlier maturity dates and stomatal closure caused by CO₂ increase. When adaptation strategies combining earlier sowing dates and cultivar changes were considered, impacts were compensated, and maize yield increased up to 14 %, compared with the baseline period (1981–2010), with similar reductions in crop irrigation water requirements. Effects of extreme maximum temperatures rose to 40 % at the end of the 21st century, compared with the baseline. Adaptation resulted in an overall reduction in extreme Tmax damages in all locations, with the exception of Granada, where losses were limited to 8 %.

1.1. INTRODUCTION

The effects of climate change on agriculture in Europe have been studied at both continental (Olesen and Bindi, 2002; Bindi and Olesen, 2011; Christensen et al., 2012) and regional scales, focusing on e.g. the Mediterranean basin or the Iberian Peninsula (IP) (Mínguez et al., 2007; Ruiz-Ramos and Mínguez, 2010; Garrido et al., 2011). The projected increase in temperature, the changes in the pattern of rainfall, and their interactions with increasing CO₂ concentrations would cause variable effects on harvests depending on location, growing season, crop, and variety. For example, projections for southern Spain show a higher rise of spring and summer temperatures, compared with other seasons and regions of IP (Christensen and Christensen, 2007; López de la Franca et al., 2013). This should cause a shortening of the phenological cycle that would offset the enhanced photosynthetic rates under increased CO₂. The final result of these counteracting effects would be a decrease in yield and biomass for irrigated summer crops in southern Spain (Guereña et al., 2001; Mínguez et al., 2007; Giannakopoulos et al., 2009; Garrido et al., 2011).

Most impact assessment studies in agriculture use crop models in combination with climate scenarios (Meza et al., 2008; Moriondo et al., 2010; Vučetić 2011). The climate scenarios are usually provided by general climate models (GCMs) downscaled by either statistical (Wilby et al., 1998) or dynamical (Castro et al., 2005) techniques, or by a combination of both (Førland et al., 2011). Dynamical downscaling is done by using regional climate models (RCMs) that generate projections (Giorgi et al., 2001) at a compatible resolution with the assessment of regional and local impacts. RCMs are especially useful in regions of complex orography, as is the case for IP (Guereña et al., 2001).

Climate projections contain multiple sources of uncertainty, such as selection of emission scenarios and model-dependent uncertainty, e.g. parameterization and resolution (Olesen et al., 2007; Ruiz-Ramos and Mínguez, 2010; Osborne et al., 2013). RCM simulations may present large biases when compared to observations (Dosio and Paruolo, 2011; Ceglar and Kajfež- Bogataj, 2012), which can limit their application for local/regional assessment. For that reason, the current methodology includes the use of

CHAPTER 1. Strategies for adapting maize to climate change and extreme temperatures in Andalusia, Spain

ensembles of climate projections (Christensen et al., 2009; Semenov and Stratonovitch 2010), and evaluation using local climate data.

Climate change will strongly increase the frequency and intensity of extreme events (Easterling et al., 2000; Sánchez et al., 2004; Beniston et al., 2007), similar to the case of extreme maximum temperature (T_{max}) events (Beniston 2004; Meehl and Tebaldi, 2004; Schär and Jendritzky, 2004; Tebaldi et al., 2006; Beniston et al., 2007; Hertig et al., 2010). These episodes have a direct influence on crops and therefore should be considered in a comprehensive impact assessment (García-López et al., 2014). For example, T_{max} events have been reported as the most hazardous events for maize under irrigated conditions in Andalusia, since high temperatures during flowering and grain-filling are expected to result in lower grain yield (Herrero and Johnson, 1980; Ruiz-Ramos et al., 2011).

Although some studies address the adaptation of irrigated crops to climate change (Garrido et al., 2011; Olesen et al., 2011; Moradi et al., 2013), or the effect of extreme events (Ruiz-Ramos et al., 2011), few have evaluated adaptations in relation to those extreme events (Travis and Huisenga, 2013; Trnka et al., 2014). In fact, the current ecophysiological crop models do not simulate the whole extent of weather extremes on critical crop phases such as pollination or grain-filling (García-López et al., 2014), in turn introducing an important additional source of uncertainty in the context of climate change impact. Furthermore, crop modeling also incorporates uncertainty, due to both the model mechanisms to describe the processes, which is partially addressed by the use of several crop models, i.e. an ensemble of impact models, and the lack of local calibration (Palosuo et al., 2011; Rötter et al., 2011). For that reason, the crop model has to be calibrated with field data at the relevant spatial scale for the study to improve its application (Boote et al., 2013). Then, for a specific crop in a regional cropping system, as is the case for maize in Andalusia, an ecophysiological crop model with site-specific calibration and validation must be considered.

In Andalusia, agriculture and livestock account for 4.3 % of regional gross domestic product (GDP; MAGRAMA 2015). Irrigated agriculture represents around 64 % of total agricultural income, although only 32 % of the area is irrigated (CAPDR 2011). Maize is a traditional irrigated summer crop in this region, with 81.9 % (32000 ha) of the

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cultivated area located in the Guadalquivir Valley (RAEA 2012). Due to the foreseen increase in temperature and reference evapotranspiration (Espadafor et al., 2011), water requirements for maize could increase in the future in this region (Mínguez et al., 2005) if adaptation strategies are not used.

Considering the importance of irrigated agriculture in Mediterranean environments, the objective of this study is to determine the effect of adaptation strategies for irrigated maize in Andalusia in terms of yield and water requirements. The adaptation strategies proposed are evaluated in relation to the impact of Tmax as one of the most relevant extreme events for irrigated maize in Andalusia

1.2. MATERIAL AND METHODS

1.2.1. Location

We selected 5 locations (Fig. 1.1) according to field experimental data availability, representing different areas of maize cultivation in Andalusia: 2 in Seville province (Alcalá del Río and Lora del Río), 2 in Córdoba province (Palma del Río and Córdoba), and 1 in Granada. The Seville and Córdoba locations are in the Guadalquivir River basin, ranging from 11 to 117 m above sea level. Granada has a greater altitude (630 m), and is close to the Sierra Nevada Mountains. The climate is Mediterranean type, with dry summers, at all locations, according to the Köppen classification (Essenwanger 2001). For the locations along the Guadalquivir basin, annual mean precipitation is ca. 600 mm, concentrated mainly from autumn to spring; annual mean temperature is ca. 18 °C, with a Tmax during the maize-growing season (March–August) of ca. 30 °C (Table 1.1). Conditions are drier and cooler in Granada, with a Tmax during the growing season (March–August) around 28 °C (Table 1.1).

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Figure 1.1. Study locations, corresponding to sites with maize field experiments

Table 1.1. Location, soil type (Soil Survey Staff 1999), annual mean temperature (Tmean) and accumulated precipitation (Precip) from the nearest weather stations from each location, years with experimental data from Red Andaluza de Experimentación Agraria (RAEA), and mean observed sowing date for the 5 sites. All locations have a Mediterranean climate according to Essenwanger's (2001) classification

Location	Coordinates	Soil type	Tmean (°C)	Precip (mm)	RAEA Data Years	Sowing date
Alcalá del Río	37.51N 5.96W	Xerofluvent	18.3	597	2003,2005, 2006,2007	17-march
Lora del Río	37.64N 5.52W	Xerofluvent	18.2	663	2003	20-march
Palma del Río	37.7N 5.28W	Xerofluvent	18.2	634	2003,2007	21-march
Córdoba	37.86N 4.79W	Xerofluvent	17.9	661	2005,2006,2007, 2008,2009,2011	21-march
Granada	37.17N 3.63W	Xerorthent	15	385	2005,2006,2007, 2008,2009,2010	23-april

1.2.2. Climate data

Daily observed and simulated climate data of Tmax and Tmin, solar radiation, and precipitation were used. For observed climate, climate data from the Agroclimatic Information Network of Andalusia (Red de Información Agroclimática de Andalucía, RIA in Spanish; Gavilán et al., 2006) from 2001– 2010 were used (www.juntadeandalucia.es/agriculturaypesca/ifapa/ria).

For simulated climate, data from a subset of 12 RCMs from the ENSEMBLES project (www.ensembles-eu.org) at 25 km horizontal resolution with a bias correction in temperature and precipitation (Dosio and Paruolo, 2011; Dosio et al., 2012) were used.

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The correction was done with respect to the E-OBS gridded observational database (Haylock et al., 2008). The bias-corrected ensemble is hereafter named ENS-EOBS. Before using the simulated database as input for the crop model, it was tested for Tmax, Tmin, and seasonal rainfall (March–August; Table 1.2) against observed weather station data (from RIA). The bias correction could not be done for solar radiation (SRAD), because E-OBS does not include radiation data. The SRAD bias was small, and it ranged between $0 \text{ MJ m}^{-2} \text{ d}^{-1}$ (at Córdoba in spring) and $-1.8 \text{ MJ m}^{-2} \text{ d}^{-1}$ (at Palma del Río in July). The consequences of SRAD bias on simulated yield were evaluated, and resulted in a mean error of maximum yield change, averaged over locations, of 4.3 % (results not shown).

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Table 1.2. Climate data during maize growing cycle: monthly maximum (Tmax) and minimum (Tmin) temperatures and accumulated precipitation for Agroclimatic Information Network of Andalusia (RIA) station data (2001–2010), and difference between mean values from these data and those from the ensemble mean (12 regional climate models) from the bias-corrected ensemble ENS-EOBS, for the baseline period 1981–2010

		Tmax (°C)						Tmin (°C)						Precipitation (mm month ⁻¹)					
		March	April	May	June	July	August	March	April	May	June	July	August	March	April	May	June	July	August
Alcalá del Río	RIA	20.7	23.4	27.1	32.4	35.4	35.2	8.3	10.2	12.8	16.5	17.6	17.9	62	59	31	5	0	7
	ENS-EOBS	-0.2	-0.4	0.0	-0.6	0.3	0.4	0.1	0.1	0.4	0.3	1.6	1.4	-14	-15	-6	6	2	-3
Lora del Río	RIA	20.6	23.6	27.5	33.3	36.3	36.0	7.8	9.6	12.4	16.5	17.8	18.3	66	63	43	4	1	2
	ENS-EOBS	-0.4	-0.8	-0.4	-1.3	-0.4	-0.1	0.2	0.4	0.7	0.3	1.4	1.1	-15	-17	-17	7	2	1
Palma del Río	RIA	20.0	23.1	27.2	33.2	36.3	36.0	8.0	10.0	12.9	17.0	18.8	19.1	70	56	49	7	0	5
	ENS-EOBS	0.0	-0.3	-0.1	-1.2	-0.3	-0.1	-0.3	-0.2	0.0	-0.3	0.4	0.2	-18	-8	-23	4	3	-3
Córdoba	RIA	19.7	22.5	26.6	32.8	36.4	36.1	7.5	9.3	12.1	16.6	18.5	19.2	89	58	40	10	3	6
	ENS-EOBS	0.1	0.1	0.4	-0.8	-0.2	-0.1	-0.2	0.1	0.5	-0.1	0.6	0.1	-39	-11	-13	-1	1	-3
Granada	RIA	18.5	21.0	25.3	32.2	35.4	34.8	4.7	6.5	9.7	14.3	16.1	16.1	50	38	31	4	0	3
	ENS-EOBS	-1.4	-1.3	-1.0	-2.3	-0.9	-0.6	1.1	1.4	1.6	1.1	2.4	2.6	0	5	2	17	10	4

1.2.3. Crop modelling

We used the CERES-Maize crop model (Jones and Kiniry, 1986) in the DSSAT v. 4.5 platform (Decision Support System for Agrotechnology Transfer; Jones et al., 2003; Hoogenboom et al., 2010). This is an ecophysiological model which simulates crop growth and development, and can be used with climate projections and elevated CO₂ conditions. The CERES-Maize model uses radiation use efficiency (RUE) to calculate biomass from intercepted photosynthetically active radiation (PAR) by the crop canopy. Photoassimilate partitioning and remobilization to grains determine the crop yield. Duration of phenophases, e.g. days from emergence to end of the juvenile phase, or grain-filling duration, are estimated by growing degree days (GDD; °Cd), which is the accumulated exposure to average daily temperature above a threshold (8 °C) below which there is no development, and a maximum of 34 °C above which the rate of development remains constant. Phenophase duration, in days, correlates to average temperature, except for the duration of flower induction, which is controlled by day length (Kiniry 1991). CO₂ enrichment affects dry matter production and transpiration. Potential growth rate is affected by a multiplicative coefficient, increasing the daily dry matter production at optimum temperature, water, and nitrogen supply (Kimball 1983; Cure and Acock, 1986). This coefficient is 1.17 for C3 crops and 1.05 for C4 crops when [CO₂] is 550 mg l⁻¹. Also, transpiration rate is affected by stomatal resistance, which increases with CO₂ concentration (Hoogenboom et al., 1995).

Model inputs include 6 cultivar-specific parameters, daily meteorological variables (maximum and minimum temperatures, solar radiation, precipitation, wind run, and relative humidity), soil features (depth, texture by layers, water holding capacity), and crop management (sowing date, population density, fertilization, and irrigation, among others). Cultivar parameters, controlling phenology, growth, and grain yield, have to be set during the calibration process.

Soil and crop experimental data for crop model calibration and validation were taken from the Andalusia Network of Agricultural Trials (Red Andaluza de Experimentación Agraria, or RAEA; www.juntadeandalucia.es/agriculturaypesca/ifapa/web/ifapa/productos/transferencia).

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The data corresponded to field experiments with the HELEN cultivar (FAO 700), from 2003 to 2011 (Table 1.1). Omitted years were due to insufficient weather data or agronomic causes not simulated by the crop model, such as pests and diseases preventing adequate crop growth. Sowing dates were in March for sites in the Guadalquivir basin, and in April for Granada (Table 1.1). Target population densities of 10 plants m⁻² were sown in rows 0.75 m apart, and arranged in a randomized block design. Fertilizer and irrigation management was always set to avoid nutrient and water limitations.

Crop measurements included sowing, emergence, silking, and harvest dates, plant population at emergence, grain weight, and yield. Maturity dates were estimated from Iglesias and Mínguez (1995). The experiments used for calibration were from Granada (years 2005, 2006, and 2007), while the other locations were used for validation, as were some years from Granada (2008, 2009, and 2010). Calibration and validation were evaluated in terms of root mean square error (RMSE) and mean bias error (MBE) between observed and simulated data:

$$RMSE = \sqrt{\frac{\sum_i^n (S_i - O_i)^2}{n}} \quad (1)$$

$$MBE = n^{-1} \sum_{i=1}^N (S_i - O_i) \quad (2)$$

where S and O are the simulated and observed data, and n is the number of observations.

Once the crop model was calibrated and validated, impact assessment in terms of crop yield and water requirements were calculated for the near future (2021–2050) and far future (2071–2100) in comparison to the baseline period (1981–2010), hereafter called NF, FF, and B, respectively. Then a set of autonomous adaptation strategies (i.e. farmers' adaptations; Garrido et al., 2011) were tested to avoid or reduce the negative biophysical impacts found. Adaptations were compared to un-adapted baseline and future projections in terms of crop yield and water requirements. The adaptations included earlier sowing dates, up to 60 d in advance, at 15 d intervals, and cultivar changes through the modification of cultivar phenology. This latter was implemented

through the change of the CERES cultivar coefficients controlling the duration of grain-filling (P5) and the grain-filling growth rate (G3). The P5 coefficient was changed, seeking a longer but feasible grain-filling from 800 to 850 GDD, while the grain-filling rate was increased by modifying the G3 coefficient from 8 to 9 mg d⁻¹; the objective was to test changes within the scope of current breeding research. These adaptations were simulated individually and in combination.

Water requirements were evaluated in terms of crop evapotranspiration (ET_c; mm) estimated by the CERES-Maize crop model. Equally, this model was used for the determination of irrigation requirements (IRR; mm), and water use efficiency in terms of water productivity (TWP; kg m⁻³) and irrigation water productivity (IWP; kg m⁻³).

1.2.4. Extreme events

Impacts of extreme Tmax events on maize were quantified by the method of Teixeira et al., (2013). Briefly, this approach considers (1) critical and limiting temperatures, which are the thresholds above which yield damage increases until a limit when total production fails; these limits are set to 35 and 45 °C, respectively; (2) calculation of the stress intensity index (fHS, fractional) based on the Tmax during the sensitive period to temperature (30 d centered in the mid-point of the reproductive phase); it represents the intensity and number of stress events that may affect the crop during flowering; the mentioned period is considered as the only one sensitive to heat stress; and (3) the production damage index, calculated from the simulated attainable yield normalized by the maximum value for each period and location (fdmg_n); this index quantifies the impact on yield.

Similar to previous modifications (Hawkins et al., 2013), two changes to the method were made: (1) the use of daily Tmax during 30 d after silking instead of the daytime Tday, given that current cultivars are adapted to the high temperature regime of the study area; and (2) the use of potential yield data from the CERES-Maize simulations instead of attainable yield, as simulations without nitrogen and water stresses were considered.

Both fHS and fdmg_n were calculated and evaluated for the 5 locations (Fig. 1.1) and for the 3 periods (B, NF, and FF), with and without adaptation strategies.

1.3. RESULTS

1.3.1. Crop model calibration and validation

The combination of cultivar-specific coefficients that present agronomic coherence and the lowest RMSE and MBE between observed and simulated silking dates and yield data for the HELEN cultivar was determined (Table 1.3). RMSE for the silking date simulation (expressed in days after sowing, DAS) was 3.1 and 5.6 d for calibration and validation, respectively, with MBE values equal to -1 and 3 d, respectively. RMSE errors for yield assessment were 344 and 1457 kg ha⁻¹ for calibration and validation, respectively, and MBE errors were -138 and 224 kg ha⁻¹, respectively.

Table 1.3. Cultivar-specific parameters calibrated in the CERES-Maize crop model for the HELEN cultivar (FAO 700) using measured data from Red Andaluza de Experimentación Agraria (RAEA) experiments. P1: thermal time from seedling emergence to the end of the juvenile phase (expressed in degree days above a base temperature of 8 °C) during which the plant does not response to changes in photoperiod; P2: extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h); P5: thermal time from silking to physiological maturity (expressed in degree days above a base temperature of 8 °C); G2: maximum possible number of kernels per plant; G3: kernel filling rate during the linear grain-filling stage and under optimum conditions (mg d⁻¹); PHINT: phylochron interval, the interval in thermal time (degree days, °Cd) between successive leaf tip appearances

P1	P2	P5	G2	G3	PHINT
245	0	800	1100	8	45

1.3.2. Evaluation under the present climate

The ENS-EOBS ensemble mean of climate variables for the grain-filling period (June–August) showed small biases related to measured data by RIA (Table 1.2); all locations showed a small bias or no difference with respect to the RIA dataset for monthly Tmax, Tmin (except for Granada), and precipitation (Table 1.2). Precipitation biases were not considered important in this study because crops were well irrigated.

The evaluation of ENS-EOBS was extended to its performance on impact assessment comparing yield simulations done by CERES-Maize with RIA and ENS-EOBS

climate datasets for the baseline period (Table 1.4). The yield difference ranged from –6.1 % (for Granada) to 0.6 % (for Palma del Río; Table 1.4). Both simulated time series showed similar interannual variability (coefficient of variation, CV_{time}), with the greatest difference in Granada (Table 1.4).

Table 1.4. Simulated yield run with observed Agroclimatic Information Network of Andalusia (RIA) data (2001–2010), and interannual variability (coefficient of variation, CV_{time}). Difference (% of yield) regarding RIA-derived simulations and those conducted with the bias-corrected ensemble ENS-EOBS for the baseline period (1981–2010), and CV_{time} for these simulations

Location	Climate data used in the crop simulations			
	RIA		ENS-EOBS (%) vs RIA	
	Yield (kg ha ⁻¹)	CV_{time}	Yield difference (%)	CV_{time}
Alcalá del Río	16177	8.7 %	1.9	7.3 %
Lora del Río	16055	10.8 %	1.1	7.7 %
Palma del Río	16094	10.8 %	0.6	7.4 %
Córdoba	15961	7.5 %	1.0	7.7 %
Granada	16966	4.5 %	-6.1	8.6 %

1.3.3. Impact and adaptation projections

Simulated phenological dates for Palma del Río (representative of Guadalquivir locations) and Granada are shown in Fig. 1.2 for B, NF, and FF periods. As GDD accumulated faster in future climate, both silking (anthesis date, ADAT) and maturity (MDAT) dates occurred earlier compared to the baseline simulations when sowing date was not changed, leading to a shorter grain-filling duration (MDAT – ADAT), especially in the FF period (ca. 17 d for the Guadalquivir locations and 20 d for Granada).

The simulated yield impact for irrigated maize, considering an optimal irrigation schedule for the ENS-EOBS ensemble mean, is shown in Table 1.5 for the B, NF, and FF periods and for the 5 locations. The results show a decrease in maize yield, greater in FF, when yield decrease was ca. 6–7 % at Guadalquivir locations and ca. 20 % in Granada. However, these effects when compared to the B period were only statistically significant in Córdoba and Granada (Table 1.5).

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Interannual variability (CV_{time} in % for the 30 yr period) in the future (NF and FF) was ca. 8 % for all Guadalquivir locations, similar to that of the baseline simulations (Table 1.5). Granada showed a higher increase in variability, especially in the FF (ca. 15 %). The spread or uncertainty related to the differences among the 12 RCM projections that form ENS-EOBS was measured by the coefficient of variation among them (CV_{ensemble} , %). This spread was similar for all locations (CV_{ensemble} : 7–8 %), decreasing slightly in the FF, except for Granada, where it increased up to ca. 12 % (Table 1.5).

These results show that recovering the baseline yields, particularly in Granada, requires adaptation measures. The first adaptation proposed consisted of earlier sowing dates (Fig. 1.3a,b).

Figure 1.2. Simulated phenology for the baseline period (1981–2010), near future (2021–2050), and far future (2071–2100): (a) anthesis date (ADAT), (b) maturity date (MDAT), and (c) grain-filling duration (MDAT – ADAT). DOY: day of the year

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Table 1.5. Simulated yield obtained with the bias-corrected ensemble ENS-EOBS for the baseline period (1981–2010), near future (2021–2050), and far future (2071–2100). Difference (% of yield) between future and baseline periods is indicated in brackets. a,b Significant differences ($p < 0.05$). Interannual variability is expressed as coefficient of variation from year to year (CV_{time}); spread of the ENS-EOBS-derived ensemble of impacts is expressed as coefficient of variation among the 12 projections ($CV_{ensemble}$)

Location	1981 – 2010			2021 – 2050			2071 – 2100		
	Yield (kg ha ⁻¹)	CV_{time} (%)	$CV_{ensemble}$ (%)	Yield (kg ha ⁻¹)	CV_{time} (%)	$CV_{ensemble}$ (%)	Yield (kg ha ⁻¹)	CV_{time} (%)	$CV_{ensemble}$ (%)
Alcalá del Río	16491 ^a	7.3	6.9	16272 ^a (-1.3 %)	7.9	7.4	15410 ^a (-6.5 %)	8.0	6.9
Lora del Río	16238 ^a	7.7	7.0	16016 ^a (-1.3 %)	7.9	7.0	15127 ^a (-6.8 %)	8.1	7.2
Palma del Río	16194 ^a	7.4	6.9	16012 ^a (-1.1 %)	7.7	6.4	15126 ^a (-6.5 %)	8.1	7.0
Córdoba	16118 ^a	7.7	6.6	15885 ^{ab} (-1.4 %)	7.7	6.3	15006 ^b (-6.8 %)	8.5	6.9
Granada	15924 ^a	8.6	6.2	15061 ^a (-5.3 %)	9.2	4.4	12665 ^b (-20.6 %)	15.0	12.3

Analyzing Fig. 1.3a, sowing dates 30 d earlier allowed for recovering the baseline yield in NF, although the option that minimized the impact was sowing 45 d earlier for all locations in FF (Fig. 1.3b). Results indicate a different behavior for Granada than for the rest of the locations. In Granada, even with earlier sowing dates, future yield was 9 to 11 % lower than that for the B period, while in the other locations, yield was consistently around 3 % lower than for the B period.

The second adaptation proposed in this study was the modification of the cultivar, adapting the grain-filling duration (P5 in Table 1.3) and grain-filling rate (G3 in Table 1.3) (Fig. 1.3c). For the NF period, modifying grain-filling duration was enough to recover the baseline yield (results not shown). However, for the FF period, baseline yields were recovered for all locations except for Granada, which still had lower yields than in the B period. Similar behavior was found when grain-filling rate was increased. The combination of both changes in the cultivar exceeded the B yields by up to 10 % at all locations except Granada, where the yield remained ca. 10 % lower than that of the B simulations.

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Figure 1.3. Projections of crop yield, impacts, and adaptations for the 12 regional climate model (RCM) projections of the bias-corrected ensemble ENS-EOBS at each location. The y-axis shows the simulated yield; x-axis specifies the simulation: yield for 1981–2010 (baseline), yield without adaptation for 2051–2071 or near future (NF), for 2071–2100 or far future (FF), and adaptations for NF (NF; adaptation) and FF (FF; adaptation). Adaptations are as follows: (a) sowing date advanced 15, 30, 45, and 60 d in the NF; (b) sowing date advanced 15, 30, 45, and 60 d in the FF; (c) increase in the CERES cultivar coefficients for duration of grain-filling (P5) and grain-filling rate (G3), and increase in both P5 and G3, in the FF; (d) combination of sowing 30 d earlier and increased P5, sowing 30 d earlier and increased G3, and sowing 30 d earlier and increased P5 and G3, in the FF. Boxplots show the distribution of the 12 RCM-derived results: box: 2nd and 3rd quartiles; line in the middle: median; point in the middle: mean; whiskers: maximum and minimum

The advance in sowing dates and the changes in crop phenology were combined in several ways, to improve Granada's result, and to explore the potential of these combinations for the Guadalquivir locations (Fig. 1.3d for FF). When the sowing date was advanced by 30 d and the cultivar-specific coefficients were set to $P5 = 850 \text{ GDD}$ and $G3 = 9 \text{ mg d}^{-1}$, the B yields were recovered at Granada (0.2 % of change). The same phenology, but with a sowing date 45 d earlier, showed an even higher yield for Granada (4.5 % of change). However, the 30 d option was the adaptation selected (hereafter called ADPS), valid for all locations to minimize disruption of the current cropping system, as large shifts in sowing dates may imply changes in crop rotations.

An average reduction of ET_c of 10 and 25 % was found for the NF and FF, respectively (Table 1.6). The baseline ET_c values were lower for Granada than for the Guadalquivir locations. IRR ranged from 668 mm for Granada to 726 mm for the Guadalquivir Valley. As a consequence of the ET_c reductions, IRR showed decreases of around 9% in all locations for the NF period, which were slightly higher for the Guadalquivir locations (ca. 25 %) compared to Granada (ca. 16%) by the end of the 21st century. These reductions in ET_c and IRR values were accompanied by an increase in water productivity (Table 1.6); both TWP and IWP were higher for all locations in NF and FF compared with baseline values.

In the ADPS simulations for Guadalquivir locations, ET_c values increased around 3.5 % compared with the results obtained without adaptation strategies. This increase was around 9.5 % for Granada. The IRR results showed limited changes for the Guadalquivir locations (0.4 and -1.1 %) and an increase for Granada (7 and 6 %) for NF and FF periods, respectively, compared with the same period

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Table 1.6 Mean values of crop cycle duration, maturity date (MDAT), total season evapotranspiration (ET_c), total irrigation requirements (IRR), water productivity (TWP), and irrigation water productivity (IWP), with the 12 regional climate models of the bias-corrected ensemble ENS-EOBS, for the baseline period (1981–2010), near future (2021–2050), and far future (2071–2100), with (ADPS) and without ('Impact') adaptation. ADPS: Adaptation selected (sowing date 30 d earlier, $P5 = 850$ GDD and $G3 = 9$ mg d^{-1}),, DOY: day of the year

Location	Result	1981–2010	2021–2050		2071–2100	
		Baseline	Impact	ADPS	Impact	ADPS
Alcala del Río	Crop cycle (d)	138	132	154	121	143
	MDAT (DOY)	200	194	187	183	175
	ET_c (mm)	722	650	673	543	555
	IRR (mm)	729	659	658	554	543
	TWP ($kg\ m^{-3}$)	3.1	3.5	4.2	4.1	4.9
	IWP ($kg\ m^{-3}$)	2.3	2.5	3.1	2.8	3.5
Lora del Río	Crop cycle (d)	137	131	153	120	141
	MDAT (DOY)	202	196	189	185	177
	ET_c (mm)	705	635	665	532	550
	IRR (mm)	699	631	633	531	527
	TWP ($kg\ m^{-3}$)	3.1	3.5	4.1	4.0	4.8
	IWP ($kg\ m^{-3}$)	2.3	2.6	3.1	2.9	3.5
Palma del Río	Crop cycle (d)	137	130	154	121	143
	MDAT (DOY)	203	196	190	186	179
	ET_c (mm)	730	658	682	555	566
	IRR (mm)	768	697	697	592	580
	TWP ($kg\ m^{-3}$)	3.1	3.5	4.2	4.0	4.9
	IWP ($kg\ m^{-3}$)	2.1	2.3	2.9	2.6	3.2
Córdoba	Crop cycle (d)	138	131	154	121	143
	MDAT (DOY)	204	197	191	187	180
	ET_c (mm)	713	643	673	539	562
	IRR (mm)	710	645	653	542	544
	TWP ($kg\ m^{-3}$)	3.1	3.5	4.1	4.0	4.8
	IWP ($kg\ m^{-3}$)	2.3	2.5	3.0	2.8	3.4
Granada	Crop cycle (d)	126	119	142	108	129
	MDAT (DOY)	225	217	211	205	198
	ET_c (mm)	688	623	684	525	575
	IRR (mm)	668	608	649	527	560
	TWP ($kg\ m^{-3}$)	3.2	3.4	3.9	3.4	4.1
	IWP ($kg\ m^{-3}$)	2.4	2.5	2.8	2.5	2.9

1.3.4. Extreme events

The fHS parameter increased for all locations and for both NF and FF periods (Fig. 1.4). The increase for the future periods compared with the B period was lower in the Guadalquivir Valley locations than for Granada. The implementation of ADPS in NF resulted in a slight decrease of fHS in the Guadalquivir locations, and in a minor increase in FF. In Granada, the compensation was lower, increasing in both NF and FF compared with the B period.

Figure 1.4 Heat stress index (fHS) for the baseline period (1981–2010), for the near future (2021–2050) without adaptation ('impact') and with the adaptation selected (ADPS, sowing date 30 d earlier, $P5 = 850$ GDD and $G3 = 9 \text{ mg d}^{-1}$), and for the far future (2071–2100) without adaptation ('impact') and with the ADPS, for all locations (top to bottom: Alcalá del Río, Lora del Río, Palma del Río, Córdoba, Granada). Lower part of the box: first quartile; line in the middle: second quartile or median; upper part of the box: third quartile; point in the middle: mean; vertical lines (whiskers): maximum and minimum

The fdmg_n parameter showed an increase in all locations for the future periods (Fig. 1.5), as expected due to the fHS results. This increase was more evident in Granada than in the Guadalquivir locations at the end of the 21st century. This index was also evaluated with the ADPS adaptation for the future periods, compared with the B period without ADPS (Fig. 1.5), showing a decrease in production damage for NF at the Guadalquivir locations equal to 26 %, and a slight increase in Granada (5 %). This trend

continued into the FF, with a decrease in production damage in the Guadalquivir locations of 8 % and an increase in Granada (8 %) compared to B.

The uncertainty of the $fdmg_n$ projections was evaluated in terms of the ensemble spread: Granada showed the highest ensemble spread for the FF period, with differences between maximum and minimum $fdmg_n$ values of 0.7, compared with 0.4 for the Guadalquivir locations. Equally, FF was the period with higher spread among the projections when adaptation was simulated, for all locations (Fig. 1.5).

Figure 1.5. Same as for Fig. 1.4, but for normalized production damage index ($fdmg_n$)

1.4. DISCUSSION

1.4.1. Impacts

The model parameterization and the errors of model calibration and validation were similar to those determined in previous studies (Meza et al., 2008; Vučetić 2011; Angulo et al., 2013; Moradi et al., 2013).

Granada presented different results than the other locations. Granada station is not well represented by the E-OBS grid cell. The complex orography of the Granada area has a lower altitude (633 m), compared to the mean grid altitude of 1034 m for both E-OBS and ENS-E OBS. This could explain the higher bias in temperatures, which was not

improved by bias correction. Also, this could explain why yield simulation could not be improved and why there was high uncertainty of crop projections at Granada.

In the Guadalquivir locations, yield decrease in the FF period was moderate and smaller than indicated by previous projections for the Guadalquivir basin (Guereña et al., 2001; Garrido et al., 2011; Rey et al., 2011). However, yield impacts in Granada were in agreement with those previous studies. This response at Granada could be explained because the grain-filling duration projected for the FF period decreased more than at the other locations.

The overall uncertainty of these projections is low compared to other studies (Ruiz-Ramos and Mínguez, 2010). This is a consequence of (1) conducting simulations under an optimum irrigation supply, excluding uncertainty linked to precipitation, which is usually high for the IP (Sánchez and Miguez-Macho, 2010); and (2) the use of the bias-corrected ensemble ENS-OBS. Furthermore, the variability of climate conditions in the selected locations adds value to the study and increases the representativeness of the result.

1.4.2. Agronomic adaptations

Earlier sowing dates showed positive effects in agreement with previous studies (Tubiello et al., 2000; Moriondo et al., 2011). In Andalusia, the optimum sowing date is determined by matching the crop cycle to a period of temperatures warm enough to not limit maize growth, but cool enough to allow for a long crop cycle, and especially a long grain-filling period. Our results are relevant for adaptation studies, which usually use static sowing dates through the adaptation simulation for simplicity (e.g. Moriondo et al., 2011). A simple rule for computing the sowing date as a function of the year or decade could be more realistic and easy to implement.

Ideotypes taking advantage of the changed conditions with a longer and more efficient grain-filling period would be feasible, and breeders are currently investigating increasing leaf area duration (LAD), stay-green trait (Chen et al., 2013; Ning et al., 2013), and extending the duration of grain-filling (Tollenaar and Lee, 2011). The 2 coefficients affecting the targeted variables were modified within a feasible range, taking as reference their values from previously calibrated cultivars. The simulations confirmed

that these changes are promising, although in Granada, further adaptations would be needed.

The combination of both strategies confirms that their effects are not additive. The objective of recovering the potential baseline yield in Granada was accomplished with the combined adaptation ADPS. Future farming will exhibit a yield gap (Cassman et al., 2003; van Ittersum et al., 2013) compared to our simulations. The crop model does not simulate some processes, such as pests and diseases that could be enhanced by longer crop cycles, together with elevated temperatures. Also, the current model description of some processes might not be robust enough under future conditions (Prasad et al., 2006). Therefore, the actual yields should be lower than our projections (ca. 36 %; see MAGRAMA 2013 for current yields).

For crop irrigation requirements (IRR), Mínguez et al., (2005) determined increases in crop water requirements; however, Yano et al., (2007) reported an IRR reduction of 25 % in 2079 for Turkey, and Guereña et al., (2001) showed a reduction of 16 % for maize in Spain in 2050, due to the CO₂ concentration increase. In our study, the observed decrease in estimated IRR for future periods without adaptation strategies agrees with these studies, and could be explained by: (1) reduction of the crop cycle duration due to warmer temperatures, avoiding the crop cycle going into the summer; and (2) the ET_c reduction due to decreased stomatal conductance as an effect of future CO₂ concentrations (Cure and Acock, 1986; Ainsworth and Long, 2005).

IRR values under the ADPS simulations were lower for the NF and FF periods than for the B period. This reduction could be due to the earlier maturity dates, avoiding the driest and hottest period for the maize crop.

The increased water productivity (TWP) in the future periods could be related to reduced stomatal conductance (Leakey et al., 2006; Vanuytrecht et al., 2012). When the adaptations were implemented, TWP and IWP increased because yield increased more than crop transpiration and irrigation water requirements, respectively.

1.4.3. Extreme Tmax events

In this study, we considered daily Tmax instead day-time Tday: (1) to take into account that cultivars used in the Mediterranean region could have more heat tolerance than those of colder latitudes; and (2) to test another possible adaptation consisting of developing cultivars with further tolerance to high temperatures.

The increase in projected heat stress index resulted in an increase in production damages at the end of the 21st century, in agreement with previous results (Beniston et al., 2007, Ruiz-Ramos et al., 2011). The adaptation strategies tested here, such as the crop cycle change and the consideration of new cultivars, diminish negative impacts at field, regional, and European levels (Olesen et al., 2011). However, our results emphasize that the adaptations for these events must be local, due to differences in the spatial pattern of extreme events (Teixeira et al., 2013).

1.5. CONCLUSIONS

The CERES-Maize crop model was calibrated and validated using experimental data for 5 semi-arid locations, spanning an overall time period of 9 yr, obtaining a locally tailored approach for yield and irrigation needs estimation. Analysis of how extreme events can enhance or reduce the impacts, and the effect of adaptation strategies, is essential. The methodological improvement obtained with bias correction increased the quality of the climate data inputs.

A negative impact of climate change on irrigated maize yield was simulated due to (1) the shorter crop cycle, and (2) an increase in the frequency of events generating heat stress. The implementation of adaptation strategies consisting of a combination of earlier sowing dates and cultivars with a more efficient grain-filling period could compensate both effects, and even increase the maize yield in southern Spain. In parallel, irrigation requirements were reduced around 25 % for future periods compared with the baseline period, both with and without adaptation strategies, due to the reduction in ET_c and higher water use efficiency.

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CHAPTER 2. MODELLING THE IMPACT OF HEAT STRESS ON MAIZE YIELD FORMATION

This Chapter is the result of a stay at University of Bonn from 01/02/2015 to 30/03/2015, being Dr. Thomas Gaiser the supervisor of the stay.

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ABSTRACT

The frequency and intensity of extreme high temperature events is expected to increase with climate change. Higher temperatures near anthesis have a large and negative effect on maize (*Zea mays*, L.) grain yield. While crop growth models are commonly used to assess climate change impacts on maize and other crops, it is only recently that they have accounted for such heat stress effects, despite limited field data availability for model evaluation. There is also increasing awareness but limited testing about the importance of canopy temperature as compared to air temperature for heat stress impact simulations. In this study, four independent irrigated field trials with controlled heating imposed with polyethylene tents were used to develop and evaluate a heat stress response function in the crop modeling framework SIMPLACE, in which the Lintul5 crop model was combined with a canopy temperature model. A dataset from Argentina with the temperate hybrid Nidera AX 842 MG (RM 119) were used to develop a yield reduction function based on accumulated hourly stress thermal time above a critical temperature of 34 °C. A second dataset from Spain with a FAO-700 cultivar was used to evaluate the model with daily climate inputs in two sets of simulations. The first was used to calibrate SIMPLACE for conditions with no heat stress, and the second was used to evaluate SIMPLACE under conditions of heat stress using the reduction factor obtained with the Argentine dataset. Both sets of simulations were conducted twice; the heat stress function was alternatively driven with air and simulated canopy temperature. Grain yield simulated under heat stress conditions improved when using canopy temperature instead of air temperature (RMSE equal to 175 and 309 g m⁻², respectively). For the irrigated and high radiative conditions, raising the critical threshold temperature for heat stress to 39 °C improved yield simulation using air temperature (RMSE: 221 g m⁻²) without the need to simulate canopy temperature (RMSE: 175 g m⁻²). However, this approach of adjusting thresholds is only likely to work in environments where climatic variables and the level of soil water deficit are constant, such as irrigated conditions and are not appropriate for rainfed production conditions.

KEYWORDS: Heat stress; Maize; *Zea mays* (L); Crop models.

2.1. INTRODUCTION

The frequency of extreme temperature (Alexander et al., 2006; IPCC, 2007; Orlowsky and Seneviratne, 2012) and drought (Alexander et al., 2006) events has increased across many world regions in the past 60 years, and is expected to further increase (Beniston et al., 2007; Seneviratne et al., 2012). Together with higher mean temperatures, these extreme events are expected to cause negative impacts on crop growth (Seneviratne et al., 2012; Gourdji et al., 2013). Large-scale observational studies analyzing maize yield and temperature records indicate that large yield losses are associated with even brief periods of high temperatures when crop-specific high temperature thresholds are surpassed. French maize yields over the past 50-years were found to have decreased as the number of days with maximum air temperature above 32 °C increased (Hawkins et al., 2013). Likewise, a panel analysis of maize yields in the US, determined that yield decreased with cumulative degree days above 29 °C (Schlenker and Roberts, 2009). Similarly, Lobell et al. (2011) detected maize yield losses across Sub-Saharan Africa ranging from 1 to 1.7 % (depending on water availability) per each degree day above 30 °C.

Maize yield is largely determined during a rather narrow window of time of four to five weeks bracketing silking (Fischer and Palmer, 1984; Otegui and Bonhomme, 1998). It is during this time that crop growth rates strongly determine the number of grains set (Otegui and Bonhomme, 1998), a key determinant of final grain yield (Fischer and Palmer, 1984). This is why this period is referred to as “critical” for maize yield determination with a high sensitivity to abiotic stress (Fischer and Palmer, 1984; Kiniry and Ritchie, 1985; Grant et al., 1989; Lizaso et al., 2007). The mechanisms of yield reduction with high temperatures are associated with reductions in both source and sink capacity. Equally crop development rate, photosynthesis and respiration rates also respond non-linearly to high temperatures (Lobell et al., 2011), but the reducing effects on these processes are reversed when temperatures return to optimal ranges (Rattalino Edreira and Otegui, 2012; Ordóñez et al., 2015). Nevertheless, reductions in net assimilation (photosynthesis plus respiration) that produce a marked decrease in plant growth rate can result in large yield reductions if they occur during the critical period for kernel number determination (Andrade et al., 1999, 2002). The reduction in sink

capacity can be caused by direct high temperature effects on flowering dynamics, ovary fertilization or grain abortion, with resulting losses in grain number being irreversible (Herrero and Johnson, 1980; Rattalino Edreira et al., 2011; Ordóñez et al., 2015).

Evidence from field trials has demonstrated that when heating was performed during the critical period, reductions in maize yield were very large (Cicchino et al., 2010; Rattalino Edreira and Otegui, 2012; Ordóñez et al., 2015). These reductions were independent of the negative effects of heat on pollen viability (Rattalino Edreira et al., 2011; Ordóñez et al., 2015), and were predominantly driven by reduced ovary fertilization of pollinated spikelets exposed to temperatures above 35 °C (Dupuis and Dumas, 1990). The reduction in grain number due to kernel abortion was the main effect of high temperatures during flowering in other work (Rattalino Edreira and Otegui, 2013; Ordóñez et al., 2015).

Various studies have identified a threshold optimum temperature of about 30 (Gilmore and Rogers, 1958; Tollenaar et al., 1979) to 35 °C (Jones and Kiniry, 1986) for maize. In field trials with controlled heating, Cicchino et al. (2010b) determined the critical optimum temperature at flowering in two years as 35.5 ± 1.3 °C and 32.2 ± 1.1 °C with a temperate hybrid. Porter and Semenov (2005) reported that temperatures above 36 °C reduced pollen viability in this species. Finally, Sánchez et al. (2014) reported 37.3 and 36 °C for the flowering and grain filling period, respectively, as the threshold optimum temperature.

Some evidence suggests that the crop canopy temperature better explains yield reductions associated with surpassing high temperature thresholds better than air temperature (Craufurd et al., 2013; Siebert et al., 2014; Webber et al., 2016). The differences between air temperature and the temperature of the canopy surface can differ significantly depending on the irrigation conditions, as the irrigation have a cooling effect on the ambient that could reduce the canopy temperatures (Lobell et al., 2008) by as much as 10° C (Kimball et al., 2015) . However under rainfed conditions when soil water is limiting, or when transpiration rates are low due to low vapor pressure deficit, crop canopy temperature can increase above air temperature leading to yield loss from high crop temperatures (Lobell et al., 2015). The difference between air and crop canopy temperature is thought to be critical for heat stress responses as the difference of 1 - 2

°C can lead to large over or underestimation of yield loss from heat stress (Webber et al., 2016). While temperature gradients exist within the vertical plant profile (Rattalino Edreira et al., 2012), it may be sufficient to capture the difference between the canopy surface and air temperature for simulations at the field and larger scales.

Currently, only a few published crop models include the effects of heat stress on maize yield and its physiological determinants, such as GLAM (Challinor et al., 2005, 2004), Aquacrop (Raes et al., 2009; Steduto et al., 2012), a modified Cropsyst (Moriondo et al., 2011) or APSIM maize (Lobell et al., 2015). Additionally, other research groups are currently developing heat stress modules specific for maize such as Lizaso et al. (2016). However, no published studies have evaluated model performance under heat stress using field trials with controlled heating. Consequently, heat stress model development and testing has been limited by a lack of data from field experiments with the application of high temperatures compared to a non-heated control. This applies even more so for modelling the effect of canopy temperature as compared to air temperature. Without such data, correct attribution of heat stress is difficult to distinguish from other growth limiting factors.

This study makes use of two independent datasets collected at Argentina and Spain in which controlled heating was applied to field grown maize crops. These datasets are used to parametrize and evaluate the performance of a canopy heat stress approach to account for the negative effects of extreme high temperatures on maize grain yield. The model performance is evaluated using both air and simulated canopy temperature as inputs to the heat stress module. These functions are included in crop models to be applied at field and larger scales.

2.2. MATERIAL AND METHODS

2.2.1. Experimental data

2.2.1.1. Argentine experiments

To develop a relationship with high temperatures, two experimental datasets obtained at Pergamino (33°56' S, 60°34' W), Argentina, were used. Crops were cultivated under field conditions, but with controlled heat stress. These two experiments were carried out during two growing seasons (Table 2.1), in 2006/2007 (A1) and 2007/2008 (A2). Details of crop husbandry can be found in Cicchino et al. (2010a, 2010b). Briefly, the cultivar used was the temperate hybrid Nidera AX 842 MG, classified as 119 for relative maturity (Peterson et al., 1973). The experiments were fully fertilized and irrigation was supplied to avoid water stress. Crop management ensured minimal weed, pest and disease pressure. Two temperature regimes were applied (C: control plots; H: heated plots). The timing of heating was applied was an experimental treatment with two levels: GS1 heating between the appearance of the 11th leaf (V11 of Ritchie and Hanway, 1982) and tasseling and GS2 with heating from tasseling to 15 days after silking. In A1, only GS1 has applied, whereas in A2, heating was applied for each of GS1 and GS2. The duration of heating periods in GS1 and GS2 (ca. 15-20 days) was based on dates of VT and silking of control plots. Shoot biomass was estimated based on plants tagged before heating. Yield (Y) and yield components (kernel number per plant and individual kernel weight) were determined by harvesting ears with grains of each tagged plant, oven dried until constant weight and then weighed.

Temperature regime treatments were obtained by placing polyethylene shelters over two consecutive central rows of plots to increase the temperature via the greenhouse effect created by the shelters. In the heated treatments (H), the shelters reached close to the ground surface, except for one side that remained open to approximately 15 cm above ground level. For the control treatments (C), the South facing side remained open up to 1.4 m above the soil surface. The purpose of the open shelters in the C treatment was to avoid differences in solar radiation between treatments. Hourly records of air temperature in C and H plots were obtained by means

of sensors (TC1047, Microchip Technologies, Chandler, AZ) installed at ear height and connected to dataloggers (Temp-Logger, Cavadevices, Buenos Aires, Argentina). Solar radiation, wind speed and relative humidity data were collected from a weather station 500 m from the experimental site. The Argentine experiments were used for determination of the heat stress reduction factor, but not used for simulations with the canopy heat stress model, as only the air temperature at ear level ($T_{\text{air\_ear}}$) was recorded in these experiments.

2.2.1.2. Spanish experiments

Datasets from two field experiments with controlled heating were used in the model evaluation. These two experiments were arranged into two studies, S1 and S2, each replicated for two consecutive growing seasons. The first year (2009) was conducted in Menarguens (41°43'48"N, 0°44'24"E) and the following three years (2010, 2011, 2012) in Algerri (41°48'36"N, 0°38'24"E), both in Lleida, Spain (Table 2.1). Study S1 was carried out in 2009 (S1.1) and 2010 (S1.2) and S2 in 2011 (S2.1) and 2012 (S2.2). The cultivar Pioneer 31N28 (FAO-700) was used in S1.1, S1.2 and S2.1. For S2.2, Pioneer 33Y72 (FAO700) was used. PR33Y72 is similar to PR31N28 in all traits considered. Biomass was estimated by above-ground dry weight through oven drying the samples collected in each plot at maturity. Yield and its components were measured on these same samples. Additional details are reported in Ordoñez et al. (2015). Similar to the Argentine experiments, crop management ensured that there was minimal water, nitrogen or biotic stresses during the cropping season. The temperature regimes for S1 were (i) C: a control with no imposed heating, (ii) S1_Pre: heating imposed from 15 days before silking (Silk-15d) to maturity, and (iii) S1_Post: heating imposed from 15 days after silking (Silk+15d) to maturity. Heating periods were about 76 days in S1. The temperature regimes for S2 were (i) C, as described above, (ii) S2_Pre: heating imposed from 7 days before silking (Silk-7d) to 9 days after silking (Silk+9d), and (iii) S2_Post: heating imposed from 14 days after silking (Silk+14d) to 32 days after silking (Silk+32d). Heated treatments were established by means of polyethylene shelters mounted on structures of 3–3.5 m height (leaving the bottom 0.3 m open). As in the experiments from Argentina, elevated temperatures were obtained due to the greenhouse effect of

CHAPTER 2. Modelling the impact of heat stress on maize yield formation

the shelters. Air temperature inside the shelters was measured at tassel ($T_{\text{air\_tas}}$) and ear levels ($T_{\text{air\_ear}}$).

Tabla 2.1 Details of experiments used in the study

Location	Experiment	Harvest Year	Heating treatment code	Heating treatment period	Air temperature measurement level
Argentina	A1	2007	A1_GS1 ^a	V11 to VT	Ear
	A2	2008	A2_GS1	V11 to VT	Ear
		2008	A2_GS2	VT to Silk+15d	Ear
Spain	S1.1	2009	S1_PreS	Silk-15d to Mat	Ear and tassel
			S1_PostS	Silk+15d to Mat	Ear and tassel
	S1.2	2010	S1_PreS	Silk-15d to Mat	Ear and tassel
			S1_PostS	Silk+15d to Mat	Ear and tassel
	S2.1	2011	S2_PreS	Silk-7d to Silk+9d	Ear and tassel
			S2_PostS	Silk+14d to Silk+32	Ear and tassel
	S2.2	2012	S2_PreS	Silk-7d to Silk+9d	Ear and tassel
			S2_PostS	Silk+14 to Silk+32d	Ear and tassel

^a Abbreviations: d, days; GS, Growing stage; Mat, Maturity; PostS, Post silking heating; PreS, Pre silking heating; Silk, Silking; VT, tasseling.

2.2.2. Model description

The maize heat stress model was developed and tested in SIMPLACE (Scientific Impact assessment and Modeling PLatform for Advanced Crop and Ecosystem management) modeling framework (Gaiser et al., 2013) together with the Lintul5 model (Wolf, 2012), the DRUNIR water balance model (Spitters and Schapendonk, 1990; Van Oijen and Leffelaar, 2008) and the CanopyT model (Webber et al., 2016). The combined model is SIMPLACE<Lintul5, DRUNIR, CanopyT, HeatStressHourly>, further referred to as SIMPLACE <Lintul5,HS,Tc>. The Lintul5 model is radiation use efficiency (RUE) based, that accounts for water and nutrient limitation. Crop development rates are a function of 24-h mean temperature above a base temperature, variety-specific parameters, and

photoperiod sensitivity. Two parameters (TSUM1 and TSUM2) account for the thermal time required from emergence to anthesis and anthesis to maturity, respectively. Biomass growth is determined as the product of RUE and the amount of photosynthetically active radiation (PAR) that is intercepted by the crop (PARi). PARi is determined using Beer's Law as a function of the leaf area index (LAI). LAI growth is exponential, early determined by biomass accumulation and a time-varying specific leaf area (SLA). RUE also varies as a function of the crop development stage, and is reduced as a function of water stress. Water stress occurs when the crop transpiration is lower than the rate of potential transpiration. Partitioning of biomass to roots, stems, leaves and grains varies with the crop development stage, with partitioning to roots increasing under water stress. Lintul5 also has a RUE correction factor (RTMCO) that reduces RUE when daily mean temperature rises above 35 °C throughout the entire growing season.

Consideration of canopy temperature (T_{can}) allows accounting for the feedback between crop water status and crop temperature. The CanopyT model calculates hourly T_{can} using daily climate data with an energy balance approach correcting for atmospheric stability conditions using the Monin-Obukhov Similarity Theory (Webber et al., 2016). The model makes simplifications about the canopy resistance term to avoid the need to calculate stomatal conductance. It is assumed that the upper (warm) temperature limit ($T_{can,upper}$) for particular weather conditions is reached when the crop does not transpire, as occurs under conditions of high water stress. Likewise, the lower (cool) temperature limit ($T_{can,lower}$) is reached when the crop is transpiring at its maximum potential rate, as occurs under non-water limiting conditions. Actual T_{can} is determined by interpolating between these two extremes as a function of crop water stress. This simplification renders it suitable for application in crop models aimed at field, regional and larger scales. The evaluated model approach compared very well to other approaches used to simulate T_{can} (Webber et al., 2015).

The heat stress module developed here, HeatStressHourly, is based on an approach implemented in the APSIM crop model (Lobell et al., 2015), modified for hourly time steps with the possibility to use either simulated canopy (T_{can}) or air temperature (T_{air}). Daily minimum and maximum values of T_{air} are converted to hourly values using a sinusoidal function as in Goudriaan and van Laar (1994) and Nguyen et al.

(2014). The module developed here reduces yield (Y) as a function of the hourly stress thermal time (TT_{hs} , in °Ch) (Blumenthal et al., 1991) accumulated above a critical high temperature threshold (T_{crit}) during the critical period for kernel number determination (between 300 °Cd before and 200 °Cd after silking, ca. 30 days bracketing silking).

2.2.3. Simulation steps

Model development and testing consisted of three main steps: (i) heat stress yield reduction factor determination, (ii) crop model calibration, and (iii) model validation (see Fig. 2.1). Broadly speaking, the Argentine experiments were used in Step 1 to establish the yield reduction heat stress factor (RedHS), by comparing the control and heated treatments. The Spanish dataset was used in Steps 2 and 3, for calibration (using the experiments without heat stress) and validation of the combined model SIMPLACE <Lintul5,HS,Tc> with the heat stress experiments, respectively. Simulations were conducted twice using two different estimates of hourly temperature (T_h) to calculate hourly stress thermal time (TT_{hs}) (Eq. 1); first using hourly $T_h = T_{air}$, and secondly with hourly $T_h = T_{can}$, as input:

$$TT_{hs,i} = T_{h,i} - T_{crit} \quad \text{Eq. [1]}$$

Step 1: To determine RedHS based with a specified critical temperature threshold; air temperature at ear level (T_{ear}) was used, as it can be considered the actual temperature experienced by the ear. RedHS was calculated as the reduction in Y per TT_{hs} , with $T_{crit} = 34$ °C as obtained by Cicchino et al. (2010b) with the same set of experiments. Y was normalized (Eq. 2) with the Y obtained in the control treatment at each experiment, considering the Y in the control as the maximum Y that can be achieved in a particular year and site under the given conditions.

$$Y_{n,i} = \frac{Y_{oi}}{Y_{mi}} \quad \text{Eq. [2]}$$

Where, $Y_{n,i}$ is normalized Y, Y_{oi} is the observed Y from the heated treatment and Y_{mi} is the maximum Y observed in the control experiment, and i representing the experiment.

With $TT_{hs,i}$ and Y_{ni} had been calculated, the RedHS was calculated as

$$RedHS = \frac{\sum_{i=1}^N \left(\frac{\Delta Y_{n,i}}{\Delta TT_{hs,i}} \right)}{N} \quad \text{Eq. [3]}$$

Where, ΔY_n is the difference between the $Y_{n,i}$ for the control (equal to 1) and $Y_{n,i}$ for the heated treatment for each experiment, and $\Delta TT_{hs,i}$ the difference between the hourly stress thermal time for the control treatment and the heated treatment. The index i indicates the experiment/treatment combination (e.g. 1= A1_GS1, 2= A2_GS1 and 3= A2_GS2) and N the total number of experiment/treatments combinations.

Step 2: SIMPLACE <Lintul5,HS,Tc> was calibrated for conditions of no heat stress using the control treatments in the Spanish dataset following the procedure shown in Fig. 2.1. The first step was to calibrate the phenology routine (anthesis and maturity dates) with the parameters TSUM1 and TSUM2. Then the biomass data were used to calibrate RUE, SLA and RGRLAI (maximum relative increase in LAI). In a final step, Y was used to calibrate FRTDM (fraction of aboveground biomass to be translocated to seeds). Final Y was first simulated using the same T_{crit} for both T_{can} and T_{air} , and later increasing the T_{crit} for T_{air} based on the difference in temperatures within the maize canopy (Rattalino Edreira et al., 2012).

Step 3: Validation of calibrated SIMPLACE <Lintul5,HS,Tc> was performed with the heated treatments from the Spanish datasets, considering the RedHS factor obtained in Step 1 and the crop parameters calibrated in Step 2.

Steps 1 to 3 were conducted with each T_{air} and T_{can} , and results compared. Additionally, simulated T_{can} for the Spanish experiments were compared with observed ear temperature values.

Figure 2.1. Flowchart illustrating heat stress reduction function development and evaluation procedure. The heat stress reduction factor determination (Step 1) is shown on the left, model calibration (Step 2) on the right, and model evaluation (Step 3) in the bottom. The experiment/treatment combinations considered in each step are shown in parentheses of the grey boxes.

To estimate errors in the calibration process, root mean square error (RMSE), and mean bias error (MBE) were determined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (S_i - O_i)^2}{n}} \quad \text{Eq. [4]}$$

$$MBE = \frac{\sum_{i=1}^n (S_i - O_i)}{n} \quad \text{Eq. [5]}$$

where S_i is the simulated value and O_i the observed value, and i representing the experiment.

2.3. RESULTS

2.3.1. Step1: Determination of yield reduction heat stress factor

$TT_{hs,i}$ calculated with T_{ear} from A1_GS and A2_GS experiments (Table 2.1) and T_{crit} set at 34 °C showed a negative relationship with Y (Table 2.2). The Y reductions resulting from heating were larger for A2_GS1 than for A1_GS1, with a mean reduction in Y due to heating of 683 g m⁻² (59.3 % reduction in Y_n). Y reduction for A2_GS2 was intermediate between these values. The relative Y loss per unit TT_{hs} between the three experiment/treatment combinations was A1_GS1 > A2_GS2 > A1_GS2. The mean Y decrease per unit TT_{hs} during the critical period, i.e. RedHS, was -0.0025 °Ch⁻¹ (Table 2.2).

Table 2.2. Relationship between hourly stress thermal time (TT_{hs}) based on ear temperature and normalized maize grain yield (Y_n) for the Argentine experiments with a critical threshold temperature of 34 °C. The reduction heat stress factor (RedHS) represents the relationship between Y_n and TT_{hs} .

		TT_{hs} (°Ch)	Y (g m ⁻²)	Y_n	RedHS (°Ch ⁻¹)
A1_GS1	control	13.6	1015.5	1	-0.0030
	heated	186.8	480.3	0.473	
A2_GS1	control	194.5	1254	1	-0.0019
	heated	540.4	439.7	0.351	
A2_GS2	control	17.1	1161.6	1	-0.0025
	heated	261.2	461.6	0.397	
Mean					-0.0025

2.3.2. Step 2. Model calibration

The crop parameters resulting in the lowest values of RMSE and MBE for simulation of the control treatments with SIMPLACE are presented in Table 2.3. The RUE parameter value from emergence to anthesis was 2.7 g MJ⁻¹, and then decreased linearly from 2.7 g MJ⁻¹ to 2.5 g MJ⁻¹ around mid-grain filling, to 1.3 g MJ⁻¹ at maturity. The other parameters were kept constant throughout the crop cycle.

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Table 2.3. Crop parameters for cultivar FAO-700. TSUM1: thermal time from emergence to anthesis, TSUM2: thermal time from anthesis to maturity, SLA: specific leaf area, RUE: Radiation use efficiency for biomass production, RGRLAI: Maximum Relative increase in LAI and FRTDM: fraction of aboveground biomass to be translocated to seeds.

	TSUM1 (°Cd)	TSUM2 (°Cd)	SLA (m ² g ⁻¹),	RUE* (g MJ ⁻¹)	RGRLAI (m ² m ⁻² d ⁻¹)	FRTDM
FAO-700	850	1100	0.014	2.7 - 2.5 - 1.3	0.014	0.01

* Different values corresponding to different crop development stages: 2.7 g MJ⁻¹ from emergence to anthesis; 2.7 to 2.5 g MJ⁻¹ from anthesis to mid grain filling; 2.5 g MJ⁻¹ to 1.3 g MJ⁻¹ from mid grain filling to maturity

Phenological dates from the Spanish experiments were well simulated with SIMPLACE <Lintul5,HS,Tc> using the TSUM1 and TSUM2 parameters (Table 2.4). RMSE results for the anthesis and maturity date calibration were ca. 5 and 3 days, respectively.

Table 2.4. Performance of SIMPLACE <Lintul5,HS,Tc> to simulate phenological dates showing simulated (sim) and observed (obs) anthesis and maturity in days after sowing (DAS) for each treatment. The root mean square error (RMSE) and mean bias error (MBE) for each cultivar are shown.

Cultivar	Year	Treatment	Anthesis (DAS)				Maturity (DAS)			
			sim	obs	RMSE	MBE	sim	obs	RMSE	MBE
FAO 700	2010	C	87	83	4.7	1.0	159	161	2.8	0.00
	2011		89	84			159	155		
	2012		102	98			167	169		
	2009	S1_PreS	63	71	4.7	1.0	--	--	2.8	0.00
	2009	S1_PostS	63	70			--	--		
	2010	S1_PreS	85	85			--	--		
	2010	S1_PostS	87	83	4.7	1.0	--	--	2.8	0.00
	2011	S2_PreS	88	85			--	--		
	2011	S2_PostS	89	84			--	--		
	2012	S2_PreS	100	103	4.7	1.0	--	--	2.8	0.00
	2012	S2_PostS	102	98			--	--		

After phenology calibration, the relationships between $T_{\text{air-tas}}$, $T_{\text{air-ear}}$, and simulated T_{can} were evaluated using S1_PreS, S1_PostS, S2_PreS and S2_PostS experiments. Simulated T_{can} at 14.00h from the Spanish experiments was similar to observed daily maximum $T_{\text{air-ear}}$ (Fig.2.2a). During periods with heating, which did not

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entirely correspond with the critical period, the mean difference between simulated T_{can} and observed $T_{air-ear}$ was 0.1 °C. Both T_{can} and $T_{air-ear}$ were lower than air temperature at tassel height (Fig.2.2b), with a mean difference between $T_{air-ear}$ and $T_{air-tas}$ of approximately 8.8 °C.

Figure 2.2. Comparison of temperatures: a) Correlation between maximum observed air temperature at ear level ($obs\ T_{air-ear}$) and simulated canopy temperature ($sim\ T_{can}$). b) Correlation between maximum observed daily air temperature at tassel height ($obs\ T_{air-tas}$) and maximum observed temperature at ear level ($obs\ T_{air-ear}$) as well as simulated canopy temperature ($sim\ T_{can}$).

Simulated hourly $T_{air-tas}$ for 14:00 h (from daily measured temperature at tassel height) and simulated T_{can} at 14:00h were compared for three different periods: (1) the entire growing season, (2) the critical period (-300 +200 °Cd around silking), and (3) the times when temperatures were above 34 °C within the critical period. Mean differences of around 5 °C were obtained between simulated T_{can} and $T_{air-tas}$ for the heated treatments (S1_PreS/PostS and S2_PreS/PostS) during the critical period (Table 2.5). This difference increased to around 5.7 °C when the temperatures exceeded 34 °C (Table 2.5).

Table 2.5. Differences between simulated 14.00 h T_{air} (from daily measured data) and simulated 14.00 h T_{can} with SIMPLACE <Lintul5,HS,Tc> for the entire growing season, the critical period (from -300 to +200 °Cd around silking) and times when T_{air} was above 34 °C in the critical period. Standard deviation is in parenthesis.

Treatment period	Year	Difference between T_{air} and simulated T_{can}		
		Growing season	Critical period	Critical period with $T_{air} > 34$ °C
		----- °C -----		
S1_PreS	2009	-5.7 (2.6)	-4.5 (2.3)	-5.8 (2.1)
S1_PosS	2009	-5.2 (2.6)	-3.7 (1.6)	-4.3 (1.4)
S1_PreS	2010	-5.6 (3.7)	-7.6 (2.4)	-8.6 (0.7)
S1_PosS	2010	-4.9 (3.6)	-4.1 (2.6)	-5.5 (1.6)
S2_PreS	2011	-2.7 (2.1)	-5.0 (3.3)	-8.2 (0.9)
S2_PosS	2011	-2.8 (1.9)	-2.7 (1.5)	-5.4 (1.9)
S2_PreS	2012	-2.9 (2.1)	-5.2 (3.2)	-8.1 (1.3)
S2_PosS	2012	-3.0 (2.3)	-2.5 (1.2)	-4.0 (1.5)
Mean		-4.1	-4.4	-6.3

After crop parameters calibration (Table 2.3), there was no difference in the model performance for simulating biomass and Y of control treatments with or without use of RedHS with T_{can} . Thus, both models exhibited similar RMSE values for biomass with the critical threshold temperatures of $T_{crit} = 34$ °C (Table 2.6, Fig. 2.3). However, a larger RMSE was determined when RedHS was used with T_{air} as input (394 vs. 373 g m⁻² for biomass and 260 vs. 234 g m⁻² for Y). Nevertheless, the RMSE for all biomass and Y estimations did not vary when T_{crit} for T_{air} was increase to= 39 °C. This increase was due to the best match and the difference in temperature between T_{air} and T_{can} obtained during the critical period (Table 2.5).

Table 2.6. Root mean square error (RMSE) and mean bias error (MBE) for calibrations based on measurements performed on control treatments. Values were obtained excluding (no RedHS) or including the heat stress module (RedHS with both T_{can} and T_{air}).

Trait	Error term	no RedHS	With RedHS and T_{can}	With RedHS and T_{air}	
			$T_{crit} = 34$ °C	$T_{crit} = 34$ °C	$T_{crit} = 39$ °C
		----- g m ⁻² -----			
Biomass	RMSE	373	373	394	373
	MBE	-3	-3	110	-3
Grain yield	RMSE	234	234	260	234
	MBE	25	25	-88	25

Figure 2.3. Observed and simulated values of above ground biomass and grain yield (Y) for the control treatments using the model (i) without the heat stress module (no RedHS) (a and b), and (ii) with heat stress module (RedHS) including or T_{air} (c and d). Upper figures with $T_{crit} = 34^{\circ}\text{C}$, and lower figures with T_{crit} for T_{air} up to 39°C and T_{crit} for T_{can} equal to 34°C . The line in each figure represents the 1:1 relationship.

2.3.3. Step 3. Model evaluation

The model evaluation with the treatments with heat stress from the Spanish dataset generated an overestimation of crop biomass when the heat stress module was not included in the analysis (no RedHS), with greater error for S_{PreS} than for S_{PostS} . This bias was reduced when the heat stress module was added (RMSE declined from 497

to 416 g m^{-2}). With the inclusion of the heat stress reduction module, biomass in both treatments (S_{PreS} and S_{PostS}) was slightly underestimated. Using the same T_{crit} (34°C) for T_{air} and T_{can} , the error obtained using T_{air} as an input was higher than using T_{can} (RMSE: 557 vs 395 g m^{-2}); however, when increasing the T_{crit} for T_{air} up to 39°C the error was reduced though still slightly greater than that obtained with T_{can} using $T_{\text{crit}} = 34^\circ\text{C}$ (RMSE: 420 vs 395 g m^{-2}) (Fig. 2.4, Table 2.7).

Figure 2.4 Observed and simulated values of Biomass for pre-silking heating), and post-silking heating using the model (i) without the heat stress module (no RedHS) (a and b) and (ii) with heat stress module (RedHS) including T_{can} or T_{air} (c and d). Upper figures with T_{crit} for T_{air} and T_{can} equal to 34°C , and lower figures with T_{crit} for T_{air} up to 39°C and T_{crit} for T_{can} equal to 34°C . The line in each figure represents the 1:1 relationship.

Results for Y showed a similar trend to those for biomass, with the highest errors reported when the model without the RedHS module was used (Table 2.7). Inclusion of RedHS with T_{can} as the input temperature reduced errors for both heated periods (S_PreS and S_PostS), with a greater improvement in the S_PostS treatment than in the S_PreS. When T_{crit} with T_{air} was increased to 39 °C, the errors were (i) lower compared to the model without RedHS, and (ii) slightly higher than using RedHS with T_{can} (Fig. 2.5, Table 2.7).

Figure 2.5. Observed and simulated values of grain yield (Y) with pre-silking heating and post-silking heating using the model (i) without the heat stress module (no RedHS) (a and b) and (ii) with heat stress module (RedHS) including T_{can} or T_{air} (c and d).. Upper figures with T_{crit} for T_{air} and T_{can} equal to 34 °C, lower figures with T_{crit} for T_{air} at 39 °C and T_{crit} for T_{can} equal to 34 °C.

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Table 2.7. Root mean square error (RMSE) of simulated biomass and grain yield for treatments heated during the pre-silking (S_PreS) or the post-silking (S_PosS) periods, obtained with the model excluding (no RedHS) and including the heat stress module (RedHS). For the latter, results based on canopy (T_{can}) or air (T_{air}) temperatures are present, considering T_{crit} for T_{air} and T_{can} equal to 34°C, and T_{crit} for T_{air} up to 39 °C and T_{crit} for T_{can} equal to 34 °C. Data correspond to the heated treatments.

RMSE	Treatment period	no RedHS	RedHS using T_{can}		RedHS using T_{air}	
			$T_{crit} = 34\text{ }^{\circ}\text{C}$		$T_{crit} = 34\text{ }^{\circ}\text{C}$	$T_{crit} = 39\text{ }^{\circ}\text{C}$
----- g m^{-2} -----						
Biomass	S_PreS	606	557	685	579	
	S_PosS	387	233	428	260	
	Mean	497	395	557	420	
Grain yield	S_PreS	917	235	258	235	
	S_PosS	257	116	361	207	
	Mean	587	175	309	221	

In addition to the action of RedHS reducing Y on hours when the respective T_{crit} was exceeded, a reduction factor acting on RUE in response to daily mean temperatures above 35 °C (RTMCO) may also additionally reduce new biomass production and resultant partitioning to yield due to heat stress. The relationship between these two sources of reduction in Y is shown in Fig. 2.6. Results showed equal reductions due to reductions in RUE (RTMCO) and the action of the RedHS response in most of the experiments. However, for the S_PreS of the years (2010, 2011 and 2012) when the critical and heating periods matched, yield reductions were more relevant (approximately 40 % higher) due to the heat stress (RedHS) than for RTMCO (Fig.2.6).

Figure 2.6 Variation of the heat stress reduction factor (RedHS, in normalized units) across heat stress treatments, and its response to the introduction of a correction factor applied to the radiation use efficiency values during critical phase in LINTUL5 (RTMCO, normalized) for (a) T_{can} and (b) T_{air} .

2.4. DISCUSSION

There is growing consensus that the frequency and magnitude of high temperature events will increase with climate change (Tebaldi et al., 2006; Field et al., 2012) and that these high temperature events will likely lead to increased incidence of heat stress for crops (Schlenker and Roberts, 2009; Lobell et al., 2013; Trnka et al., 2014). It has been emphasized that crop models must be improved to consider the effects of heat stress for both large (Ewert et al., 2015; Rezaei et al., 2015) and local (García-López et al., 2014; Gabaldón et al., 2015) scale assessments of climate change impacts on cropping systems. A challenge for model improvement is often the lack of field experiments with control trials to test model responses, in this case, of imposing high temperatures. A related challenge for simulating heat stress under field conditions and at larger scales is to account for the interaction between water and heat stresses that cannot be accounted for by considering only air temperature (Webber et al., 2016). This is the first study we are aware of in which a heat stress response in a maize crop growth model has been tested with field data from two different datasets from two contrasting world regions, Argentina's Rolling Pampas (isohygrous) and the NE-E Spain (Mediterranean regime).

The goal of the study was to develop and evaluate a model suitable for application in large scale climate change and adaptation impact assessments. The results showed that the model tested in this study (SIMPLACE <Lintul5,HS,Tc>) was able to reproduce maize biomass growth and yield of maize grown under high temperature conditions near flowering. The model reduced yield as a function of accumulated stress thermal time during the critical period for Y formation bracketing silking. In the model, the direct heat stress effects on grain was accounted for in a heat stress reduction function, parameterized with the data from Argentina, and validated with the experimental data from Spain. Additionally, RUE is reduced when daily mean temperature is greater than 35 °C. The evaluation showed that the model performs well with a slight underestimation of the effects of heat stress in the Spanish experiments (Fig. 2.4 and 5). However, different cultivars used in the Argentine and Spanish experiments though neither the RedHS factor nor T_{crit} were not re-calibrated between experiments. Therefore these parameters may be considered to have general validity for

long cycle maize varieties and be appropriate for use under climate change conditions, due to the higher temperatures projected at the end of the 21st century.

The heat stress reduction factor using T_{can} performed better than that using T_{air} when the critical threshold temperature determined in Cicchino et al. (2010a) was used. This critical threshold is also close to values reported in other studies on the sensitivity of maize yield formation to high temperature (Herrero and Johnson 1980; Dupuis and Dumas, 1990). However, in the conditions of the Spanish validation experiments, evaporative cooling was high due to irrigation combined with high radiation and a high vapor pressure deficit, similar to the conditions of Arizona reported in Kimball et al. (2015). As a result, the crop was consistently several degrees cooler than the ambient air, such that T_{crit} used in RedHS with air temperature could be increased to 39 °C to account for this cooling. In this case, yield simulations had a similar performance as compared to using $T_{crit}= 34$ °C in RedHS with canopy temperature, with only slightly larger error. Therefore, under irrigated conditions and environmental conditions like those tested in the Spanish conditions (Webber et al., 2016), if estimation of T_{can} is not possible, it may be reasonable to increase T_{crit} when air temperature is used to determine heat stress effects. This approach is not expected to be valid under rainfed conditions when both water availability and the atmospheric demand are more variable. Collectively, using air temperature to simulate heat stress effects, T_{crit} would need to be increased after rainfall events on clear, dry days, but decreased on hot humid days, or when soil water was limiting. This uncertainty in the response highlights the need to increase the number of field experiments combining heat stress with water availability in order to obtain an accurate approach valid for any climate conditions and crop water status.

The aim of the study was to develop a heat stress response function together with a canopy temperature model for application in regional climate change impact and adaptation assessment studies, rather than to explicitly simulate the detailed mechanism of heat stress. However, a reflection on the main processes causing large yield losses in field trials with controlled heating is compared to processes captured in the model in response to high temperature. Rattalino Edreira et al. (2011, 2012, 2013) indicated that reduction in yield is explained by both a reduction in RUE (-3 to 33 % of

final biomass) as well as a failure of reproductive processes such as ovary pollination and fertilization together with an increased kernel abortion, all conducive to a reduction in kernel numbers of ca. 60 %. We are potentially double counting some of the effects of high temperature with the heat stress reduction function RedHS as it is calculated based on the reduction in yield in the heated treatments as a function of the accumulation of TT_{hs} above T_{crit} in the experiments from Argentina, in which Y losses were due to both a failure of reproductive processes and a reduction in RUE. A next step in our model development is to examine how the response of RUE to temperatures greater than 35 °C correlates with TT_{hs} and reduces the RedHS factor in proportion to the amount of heat stress that is already accounted for in RTMCO. However, this relationship between the high temperature dependence of RTMCO and RedHS is expected to vary with the environment depending on the magnitude of diurnal temperature variation.

Another aspect of crop growth and development known to be affected by high temperatures is phenology. Thus, there is evidence to suggest that high temperatures delay flowering (Cicchino et al., 2010a). The error of 5 days in the date of anthesis demonstrates that the model presented here does not contain a response of development rate to extreme high temperatures. This fact should be included in future model improvements in order to obtain an improved yield simulation, as specification of the critical period depends on accurate simulation of the flowering.

Beyond the processes captured in the model, there are two limitations of the study. Firstly, the model was only tested using irrigated trials. Using our canopy temperature model, we hypothesized to be able to account for interaction between crop temperature and levels of soil water stress, though this has not been tested to date for either the canopy temperature model, nor for the heat stress module. Further model testing and experimental datasets are critical for extending the model to these conditions, as many world regions with the largest food security challenges (e.g. Sub-Saharan Africa) rely on rainfed production, and high temperatures and drought events are likely to coincide. A related limitation is that the trials were conducted under non-nutrient limiting conditions, which are not the case for many rainfed maize systems, particularly in tropical regions. A second limitation is related to the data used for model development and model testing. While these experiments are unique for maize in

imposing controlled heat stress under field grown conditions, they did present challenges for model testing. The reduction in incident solar radiation due to the polyethylene film was not a severe artefact, but reduced wind speed and increased relative humidity may represent an important bias from many natural conditions. To some extent these variables were measured in the experiments, and reliable estimates generated when required. Ideally for modeling studies, weather stations would be installed for each heat treatment. This raises the more general need for increasing collaboration between modelers and experimentalists – from physiologist to agronomists and engineers. Such collaboration can inform and support model development, as well as support experimental design such that datasets are more fully useful and valid for model improvement. The synergistic relationship extends beyond the sharing of data for model improvement to enabling better science by bringing both sets of knowledge together and systemizing what is known about crop response to climatic factors. This collaboration should be strengthened and facilitated, particularly in joint proposals and experiment planning.

2.5. CONCLUSION

Climate change will bring higher temperatures and increased risk of heat stress in cereal crops. Despite crop models being widely used to assess climate change impacts on crops, models have only recently included heat stress responses. This study presented a model to simulate the impacts of high temperatures on maize yield. The model estimated grain yield reductions based on accumulated hourly stress thermal time above a critical threshold temperature in the critical period around flowering. The model was developed and tested with six experiments that used controlled heating conditions in Argentina and Spain. The model performance was better when simulated canopy temperature was used as an input to heat stress function. For satisfactory performance with air temperature, the critical threshold for heat stress was increased from 34 °C, which is a physiologically meaningful threshold, to 39 °C, as the crops were considerably cooler than the air due to ambient cooling caused by irrigation. Increasing the critical temperature is an alternative option to the use of air temperature with the heat stress reduction function in irrigated conditions, but is not expected to be suitable

under rainfed conditions. This study has reinforced the potential for greater collaboration between modelers and experimentalists.

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CHAPTER 3. IMPACT OF CHANGES IN MEAN AND EXTREME TEMPERATURES CAUSED BY CLIMATE CHANGE ON OLIVE FLOWERING AT SOUTHERN SPAIN

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ABSTRACT

Due to the severe increase in the foreseen temperatures in the future and the great economic and social importance of olive growing for vast agricultural areas in the Mediterranean Basin, accurate climate change impact assessment on olive orchards is required. The aim of this study was to assess the flowering date and the impact of mean and extreme temperature events on olive flowering at southern Spain under baseline and forced climate conditions. For such a purpose, experimental data were obtained from ten olive genotypes: six well-known olive cultivars in the region, one cultivar, 'Chiquitita', obtained from conventional breeding, and three wild olives from Canary Islands. A site-specific model calibration was conducted, obtaining a satisfactory performance with average error for flowering date estimation equal to 2 days for baseline and future climate conditions. The outputs from twelve climate regional models from the ENSEMBLES European project with a bias correction in temperature and precipitation were used. An advance in the olive flowering dates of about 17 days at the end of the 21st century compared with baseline period (1981-2010), and an increase in the frequency of extreme events around flowering were found. A spatial analysis of results allowed determining those areas at southern Spain with higher vulnerability to climate change impact caused by the lack of chilling hours accumulation (areas located at Atlantic Ocean coast and the South-East coast) and by the occurrence of high temperatures during flowering (areas located at North and Northern-East of Andalusia region).

KEYWORDS: olive trees, climate change, southern Spain, ENSEMBLES projections, flowering date

3.1. INTRODUCTION

Olive (*Olea europaea* L.) has been cultivated in the Iberian Peninsula since second century BC (International Olive Council, 2014). Currently, Spain is the leading world olive oil producer with around 40 % of the global production (FAOSTAT, 2016). The southern Spanish region of Andalusia represents the first national olive oil producer with 80% of the national production (1.1M tons; CAPDR, 2016a). Olive cultivation in Andalusia plays an important social role as it generates a high rate of employment per surface unit and provides around 32 % of total agriculture employees in the region (CAPDR, 2008). Due to this economic and social importance of olive crop in Andalusia, a detailed analysis of the impacts of climate change on Mediterranean olive orchards at mid- and long-term is required.

Climate projections provided by the last Intergovernmental Panel on Climate Change AR5 (IPCC, 2014) foresee a global increase in mean temperature around 2 °C by the end of the 21st century. However, the projections of temperature increase are around 4 °C for Andalusia region during the warmest months (Giorgi and Lionello, 2008; Giannakopoulos et al., 2009). In addition, although high degree of uncertainty due to the difference in model projections has been reported as consequence of the errors for estimating the annual and seasonal variations and across seasons for the region, the climate projections indicate a likely rainfall decrease (CEDEX, 2011) and some authors coincide to forecast an increase in the inter-annual rainfall variability for the Iberian Peninsula (Vicente-Serrano et al., 2011).

Considering the foreseen future climate conditions, some studies have evaluated the impact of climate change on olive yield, projecting a yield decrease at the end of 21st century due to the combined effect of increased mean and extreme temperatures, reduced precipitation (Koubouris et al., 2009; Viola et al., 2013), and increased net irrigation requirements (Rodríguez Díaz et al., 2007; Tanasijevic et al., 2014). However, to understand the impacts of climate change on crop yield is essential the analysis of the effects of such change, especially the temperature and daylength changes, on its phenology (Lieth, 1974; Schwartz, 1999; Sadras and Calderini, 2009). Numerous studies focused specially on temperature have been carried out for a wide range of agricultural species. These studies have demonstrated variations in the phenological phases

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associated to changes in air temperature (Bradley et al., 1999; Schwartz, 1999) and then, warm springs cause advances in the beginning of the growing period (Menzel, 2000; Chmielewski and Rötzer, 2001; Ahas et al., 2002). Similarly, an advancement of the pollen season is strongly correlated with higher temperatures (van Vliet et al., 2002). Furthermore, in the recent past a decrease in the accumulated chilling units for several crop trees around the world has been observed, as for example for olive trees in California over the last 50 years (Baldocchi and Wong, 2008).

For olive, as for many others crops, the flowering is a key phenological stage due to the sensitivity to extreme events related with heat and water stress during this period affecting significantly to the final oil yield (Ayerza and Sibbett., 2001; Rapoport et al., 2012). Traditionally, olive flowering date estimation has been carried out by pollen capturing (Galán et al., 2005; Bonofiglio et al., 2008; Avolio et al., 2012; Orlandi et al., 2013) or by simulation models based on phenological observations (Orlandi et al., 2005a). For flowering date simulation, different approaches have been considered, such as taking in to account both the chilling and heating requirements (Garcia-Mozo et al., 2000; De Melo-Abreu et al., 2004; Galán et al., 2005; Aguilera et al., 2014), or simpler approaches uniquely considering heating requirements with a fixed starting spring date (Orlandi et al., 2010a, 2010b).

Two main procedures have been considered for the estimation of olive chilling requirements. One is based on the methodology described by Richardson et al. (1974) that considers an upper temperature threshold for penalty of chilling accumulation. This threshold for olive varied in a wide range (from 12 to 20.7 °C) according to De Melo-Abreu et al. (2004), Orlandi et al. (2006) and Aguilera et al. (2014). In the second approach (Aron, 1983) the chilling hours are accumulated without any penalty when temperatures are below a threshold. This threshold for olive ranges from 7 to 7.2 °C according to De Melo-Abreu et al. (2004) and Galán et al. (2005). Other authors such as Fornaciari et al. (1998) and El Yaacoubi et al. (2014) suggest that olive has not consistent chilling requirements and then, flowering is highly dependent to heat accumulation. For heat accumulation, the most widely used method considers the Growing Degree Days (GDD), in which heat units are accumulated when the mean daily temperature exceeds a threshold. Very different values of this threshold have been reported for olive on several

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studies carried out in the Mediterranean area ranging from 5 to 23 °C, depending of the cultivar and location (De Melo-Abreu et al. 2004, Galán et al. 2005, Orlandi et al. 2005a, 2010a; Aguilera et al. 2014).

Future flowering dates could be estimated through the mentioned phenological models together with future climate projections data provided by Global Climate Models (GCMs) or Regional Climate Models (RCMs). RCMs simulate spatial climate at higher resolution than the GCMs, being their added value more evident in orographically complex areas such as the Iberian Peninsula (Guereña et al., 2001). However, projections from these climate models present biases regarding local observations (Déqué et al., 2007) that increase the uncertainty of the impact projections (Olesen et al., 2007; Carter, 2010; Ruiz-Ramos and Mínguez, 2010). Considering these RCMs changes in the crop phenology have been reported. Thus, a decrease in chilling unit accumulation has been foreseen for a range of tree crops such as olive, peach, vineyard and apple in Spain under future climate conditions (Pérez-López et al., 2012). This reduction could generate lack of fulfilment of the chilling accumulation requirements that could lead to a failed or poor flowering stage (Hartmann and Porlingis, 1957). Additional changes in phenology for olive have been reported, even when chilling requirements are met, detecting an advance of around one week in olive flowering date per 1 °C of mean temperature increase (Orlandi et al., 2010c; Avolio et al., 2012), which would result in an advance of 2 weeks of the flowering date at the end of 21st century under Southern Spain climate conditions (Galán et al., 2005).

Due to the wide ranges reported in the calibration of key phenological parameters and for some contradictory results related with the chill accumulation requirements previously described, the modelling of the flowering date for olive is affected by a huge uncertainty. The present work aims to mitigate these inaccuracies by generating reduced uncertainty projections of flowering date and of occurrence of extreme events during the flowering stage for olive at southern Spain at the end of 21st century. To achieve this objective, results and conclusions are based on experimental data obtained under baseline and forced climate conditions and on phenological modelling. In addition, a spatial analysis for determining the vulnerability of current olive

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growing areas and for identifying those potential suitable areas for olive cultivation under the future foreseen climate conditions was carried out.

3.2. MATERIAL AND METHODS

3.2.1. Study area

Andalusia region is located at southern Spain (Fig. 3.1) and presents a wide range of climatic and orographic conditions. Average annual precipitation for the period 1971-2000 ranged between 200 to more 1500 mm, being the mayor part of Andalusia around 500-750 mm. For the same period, annual mean temperatures ranged between 8-10 °C in the mountainous area located at Eastern of Andalusia to up to 20 °C in the South-East Coast, with average mean temperatures around 18 °C in the Guadalquivir Valley (Agroclimatic Information Network of Andalusia, RIA). Equally, orography varied significantly, from flat areas within the Guadalquivir Valley to mountainous areas, mainly located at the North and East of the region (Supplement Fig A.1).

Olive area in Andalusia covers around 1.4 Mha and is concentrated mainly at the mid- and upper section of the Guadalquivir Valley (Fig. 3.1). In order to evaluate the olive phenology and the occurrence of extreme events under different climate conditions, eight representative locations were selected to summarize the results obtained in the study: Osuna, Antequera, Cordoba, Baena, Martos and Baeza located in the main olive cultivated areas, and Jerez and Seville located outside of them (Fig. 3.1).

Figure 3.1. Common grid from ENSEMBLES project and ENS-Spain02 dataset over Andalusia including olive cultivated area and some representative locations considered in the study.

3.2.2. Experimental design and measurements

An experimental study for the evaluation and calibration of models for the assessment of olive flowering date described in Section 3.2.4 was conducted in the facilities of IFAPA-Alameda del Obispo, located in Córdoba (Andalusia), southern Spain (37.85°N, 4.8°W), at an altitude of 110 m a.s.l. (Fig. 3.1). The area is characterized by a Mediterranean climate with an annual mean temperature of 17.6 °C and 536 mm of accumulated rainfall (Spanish Meteorological Agency, AEMET). Ten olive genotypes were considered in the study. Six of them are traditional cultivars originating in southern Spain ('Hojiblanca' and 'Picual'), north-eastern Spain ('Arbequina' and 'Arbosana'), Greece ('Koroneiki') and Italy ('Frantoio'). In addition, a new cultivar ('Chiquitita') obtained by systematic breeding from the cross 'Picual' x 'Arbequina' (Rallo et al., 2008) was also evaluated. The remaining three genotypes ('FV18', 'GM22' and 'GM25') are wild olives that belong to *Olea europaea* subsp. *guanchica* and originating at Canary Islands. These wild olive trees are adapted to the subtropical climate of the Islands with annual mean temperatures of 20 °C, and a limited annual oscillation between maximum and minimum temperatures of around 6 °C.

Thirty-two trees per genotype two-years-old and with a mean height of 1.5 m were grown in five litter pots filled of peat. The trees were split in two groups in separate environments that reproduced baseline and future climate conditions, respectively. One group with 16 trees (four blocks with four repetitions per cultivar) was located outdoors (OU); the other group with 16 trees was maintained inside a greenhouse (GH) under controlled climate conditions from 1st of October 2013. The OU experiment represented baseline climate conditions, while the GH experiment was set to reproduce the projected temperature increase at the end of 21st century. Temperature control in the GH was regulated by a heating and cooling system, windows and a moving thermal blanket. OU and GH temperature and humidity were measured and collected every 10 minutes by two data-logger with build-it sensors (Tinitag Ultra 2 TGU-4500) located at 2 m above the ground (ca. 0.5 m above the plants). Both OU and GH experiments were irrigated at optimal rate to consider as much as possible uniquely the effect of temperature on phenology.

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The monthly Tmax differences between GH and OU, DTmax (GH-OU), ranged from 3.4 °C in March to 8.8 °C in November (Fig. 3.2), while differences in monthly Tmin, DTmin (GH-OU), ranged between 1.7 °C in December and 3.3 °C in May. Considering ENS-Spain02 database and comparing far future (FF) and baseline (B) periods, the DTmax (FF-B) ranged from 2.7 °C in December to 5.6 °C in May and for DTmin (FF-B) from 2.1 °C in March to 4.1 °C in May. For all the months, the difference between DTmax (GH-OU) and DTmax (FF-B) was below 0.5 °C, except for the months May, October and November. Equally, the difference between DTmin (GH-OU) and DTmin (FF-B) was below 0.6 °C for all the months (Fig 3.2). Daily maximum and minimum temperatures for both experimental conditions are shown in the Fig A.1 (Supplement).

Figure 3.2. Monthly differences for maximum temperature (DTmax) and minimum temperature (DTmin) (°C) obtained with the ENS-Spain02 for the baseline period (1981-2010) and far future (2071-2100) periods, and those obtained between the temperatures outdoors (OU) and inside greenhouse (GH).

The full bloom phase was defined according to De Andrés (1974), and was established as the date when at least 50 % of the flowers were opened, and was identified by visual observation in repeated field visits (Orlandi et al., 2002, 2005a, 2005c; Oteros et al., 2013) carried out during the flowering period.

3.2.3. Baseline and projected climate for southern Spain

Simulated daily climate data for Andalusia under baseline and future conditions were obtained from the ENS-Spain02 ensemble of climate models (Ruiz-Ramos et al., 2015), which consist of bias-corrected projections from twelve RCMs from the ENSEMBLES European project (www.ensembles-eu.org) corresponding to the SRES A1B scenario (Nakićenović et al., 2000). For ENS-Spain02, temperature and precipitation bias

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of RCM outputs were corrected following Dosio and Paruolo (2011), using transfer functions with regard to the observational gridded dataset Spain02 (Herrera et al., 2012). Spain02 is developed for continental Spain and the Balearic Islands with 2756 quality-controlled stations, covering the period from 1950 to 2007, with a spatial resolution of 25 km. ENS-Spain2 provided the daily values of minimum (T_{min}) and maximum temperature (T_{max}) required by the phenological models. Hourly temperature records required for chilling unit accumulation was obtained from the daily maximum and minimum temperatures with the methodology provided by De Wit et al. (1978).

Andalusia region encompasses 145 ENS-Spain02 grid cells (Fig. 3.1). The analyzed periods were 1981-2000 (baseline, B), 2021-2050 (near future, NF) and 2071-2100 (far future, FF). Compared with B period, an increase in mean temperature (T_{mean}) for Andalusia is projected by the ensemble mean of ENS-Spain02 for both future periods (NF and FF), for all seasons (Fig. 3.3). Thus, compared with B period, for autumn T_{mean} increased 1.2 and 3 °C, for winter 1.1 and 2.6 °C, for spring 1 and 3.5 °C, and for summer, 1.5 and 4.3 °C for NF and FF, respectively.

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Figure 3.3. ENS-Spain02 ensemble mean for mean temperature (Tmean) projected for autumn (SON), winter (DJF), spring (MAM) and summer (JJA), for the baseline (1981-2010), near future (2021-2050) and far future (2071-2100) periods.

3.2.4. Approaches for flowering date estimation

Given the diverse approaches proposed for estimating olive flowering dates, in a first step three methods were considered: 1) taking into account the chilling hours accumulation, calculated depending on the hourly temperature, taking into account a lower, optimum and breakpoint temperature above which a penalty is applied, followed by a heating accumulation period until flowering, 2) the chilling hours were accumulated if the hourly temperature is below a threshold, followed by a heating accumulation period until flowering and 3) only considering a heating accumulation period. The parameters provided by De Melo-Abreu et al. (2004) for each method were considered in the study and are identified hereafter with the subscript “org” as the original values. These three methods were evaluated for the cultivars ‘Arbequina’, ‘Hojiblanca’ and

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‘Picual’, as these were the cultivars from our database in common with De Melo-Abreu et al. (2004) study.

Method 1 considers three specie-parameters for the chilling accumulation: optimal temperature (T_o), breakpoint temperature (T_x) above which a dimensionless penalty constant (p) is applied, and the heating accumulation base temperature (T_b), with original fixed values equal to 7.3 °C, 20.7 °C, -0.56 and 9.1 °C, respectively (De Melo-Abreu et al., 2004). Specific cultivar-parameters were the requirement of accumulated chilling hours starting on 1st October (TU) and the thermal time (TT) achieved for the flowering date. This method was evaluated for OU and GH conditions by fixing the TU value provided by De Melo-Abreu et al. (2004) (TU_{org}) and calculating the difference in days between the date when TT_{org} value was achieved and the observed flowering date (obtaining the observed TT value). Method 2 considers two specie-parameters, the limit temperature for chilling accumulation (T_{lim}) and the base temperature (T_b) for the thermal time-based period with values equal to 7°C and 8.8 °C, respectively (De Melo-Abreu et al., 2004). This method was evaluated with the same procedure than in Method 1. Method 3 does not consider chilling requirements but uniquely one specie-parameter (T_b), equal to 8.5 °C, and one cultivar-parameter, TT . This method was evaluated by calculating the difference in days between the date when TT_{org} was reached and the observed flowering date (obtaining the observed TT value), similar to Method 1. For this method the starting date for TT computation was established on the 1st February (De Melo-Abreu et al., 2004; Tanasijevic et al., 2014). A sketch of the procedure for determining the errors from each method is shown in the Fig. 3.4.

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Figure 3.4. Illustrative scheme describing the errors obtained with each method. TU_{org}: chilling units from the original De Melo Abreu et al. (2004) study; TT_{org}: thermal time from the original De Melo Abreu et al. (2004) study; TT: thermal time at the observed flowering date.

In a second step, a new approach was developed for estimating the flowering date based on the experimental data obtained from the ten olive genotypes described in Section 3.2.2. and the performance of the previously described methods. The proposed method, hereafter called Method 4, was divided in two independent processes. The first process is based on the existence of chilling requirements to achieve the olive flowering, previously described by Orlandi et al. (2004), Galán et al. (2005) and Aguilera et al. (2014). Due to the lack of experimental data to determine the specific chilling requirements for the cultivars considered in this study, a range of chilling requirements was considered for all the cultivars, following to De Melo-Abreu et al. (2004). Thus, TU values were set to a maximum, a mean and a minimum value: TU_{max}= 722 U, TU_{mean}= 467 U and TU_{min} =302 U. Then, dates of the end of dormancy (EDO) were estimated when these TU values were reached. This procedure also allowed measuring the EDO uncertainty by calculating the coefficient of variation (CV, %) between dates for a same grid cell. This approach also determines whether chilling requirements are met, indicating flowering failure if the requirements are not fulfilled. The second simulated process in Method 4 was the heat accumulation until the flowering date, as the Method 3. The starting date for heat accumulation and the Tb parameter previously considered in Method 3 were evaluated. Three starting dates (1st January, 1st February and 1st March) and twelve Tb values from 5 to 12.5 °C were tested. The performance of the Method 4 was evaluated by analyzing the simulated flowering date and the GDD reached at flowering under OU and GH conditions.

3.2.5. Evaluation of olive vulnerability to extreme events

Flowering dates for the 145 cells comprising Andalusia region were simulated applying the twelve members (RCM outputs) of the ENS-Spain02 ensemble (see Section 3.2.3.) to the phenological method that provided the best performance (see Section 3.2.4), once this was locally calibrated with the experimental data described in Section 3.2.2. Once the flowering date for each cell, genotype and ensemble member of climate was estimated, the vulnerability caused by the occurrence of extreme Tmax events during flowering was assessed considering the effective pollination period (EPP) in order to obtain the sensitive flowering period. In this study EPP was set to 7 days after flowering for all the genotypes, being in the range of previous studies (Arzani and Javady, 2002; Orlandi et al., 2005b; Cuevas *et al.*, 2009). Once EPP period was estimated for each cell, genotype, year and ensemble member, the vulnerability was assessed by calculating for the baseline and projected climate conditions the number of days during EPP with Tmax above a fixed threshold (hs1d) and the number of events with at least three consecutive days during EPP with Tmax above a fixed threshold (hs3d), following Ruiz-Ramos et al. (2011). Three thresholds were selected (30, 35 and 40 °C) to consider highly, medium and low cultivar sensitivity, respectively. These values were chosen according to previous studies of pollen viability under in vitro conditions and high temperature carried out by Fernández-Escobar et al. (1983) and Koubouris et al. (2009).

Finally, the spatial analysis of chilling requirements (using $TU_{mean} = 467$ U, as the mean chilling requirements determined in De Melo-Abreu et al. (2004) together with the maps of percentage of years with at least one event with Tmax above 35 °C during FF period allowed a general characterization of vulnerable and suitable areas for olive cultivation across Andalusia region in the future.

3.3. RESULTS

3.3.1. Observed phenological behavior for olive crop under baseline and future climate conditions

Observed mean average flowering date for the ten genotypes considered in the study was 8th May (128 DOY) for OU conditions and 29th April (119 DOY) for GH conditions, indicating an advance of around nine days (from 6 to 14 days depending on genotype) between trees located under OU conditions compared to those located in the GH experiment (Table 3.1). The average observed range of flowering dates for the analysed olive genotypes under OU and GH conditions was around 25 days, from 114 to 135 DOY and from 120 to 144 DOY for OU and GH, respectively. ‘Arbequina’ and ‘Koroneiki’ cultivars showed the earliest flowering dates for both conditions (120 and 114 DOY, for OU and GH, respectively) although other genotypes as ‘Chiquitita’, ‘Frantoio’ and ‘Picual’ showed similar flowering dates than ‘Arbequina’ and ‘Koroneiki’ in GH conditions (Table 3.1). In the opposite case the wild olive genotypes ‘GM22’ and ‘GM25’ had the most delayed flowering dates (138 and 130 DOY for OU and GH, respectively, Table 3.1).

Table 3.1. Observed thermal time requirements for flowering (in growing degree days, GDD), and flowering dates (in day of year, DOY) for each genotype using the Method 4 with the optimum parameterisation (starting of heat accumulation on 1st March and Tb=5 °C) and observed climate data, for both outdoors (OU) and greenhouse (GH) conditions.

	DOY (OU)			DOY (GH)	
	GDD	Observed	Simulated	Observed	Simulated
Arbequina	717	120	123	114	111
Arbosana	769	126	126	116	114
Chiquitita	787	128	127	114	115
Frantoio	769	126	126	114	114
FV18	846	128	130	120	118
GM22	1140	144	149	134	131
GM25	1140	142	149	135	131
Hojiblanca	768	124	126	116	114
Koroneiki	717	120	123	114	111
Picual	760	125	125	114	114

3.3.2. Performance of phenological model parameters under baseline and future climate conditions

Considering Method 1 the estimated flowering dates were around 3-6 days earlier than the observed ones under the OU conditions for 'Arbequina', 'Hojiblanca' and 'Picual' and under GH conditions the flowering dates were 19-25 days earlier than observed (Table 3.2). Testing the Method 2, the differences between observed and estimated flowering dates were even larger than with Method 1; the estimated flowering date under OU conditions was 5-9 days earlier than observed, and under GH conditions the differences increased until 28-32 days in advance (Table 3.2). Finally, the differences between observed and estimated flowering dates with Method 3 were smaller, varying between 2-5 days and 13-14 days earlier than observed under OU and GH conditions, respectively (Table 3.2).

For Method 4 the parameterisation that provided the smallest differences between observed and estimated flowering dates under both OU and GH conditions was considering the starting date for heat accumulation on 1st of March and $T_b = 5$ °C. This parameterisation provided an average difference of 2 days between observed and estimated flowering dates, which corresponded to average differences of around 3.9 % of the thermal time reached at the flowering date (GDD), for both OU and GH conditions (Table 3.1). Analyzing the GDD values for each genotype, 'Arbequina' and 'Koroneiki', and 'GM25' showed the lowest and highest GDD values, respectively, and therefore the earliest and latest flowering dates (Table 3.1). The smallest differences between observed and estimated flowering dates were found for 'Picual', for which Model 4 reproduced accurately the observed mean flowering date with differences in GDD between simulated and observed of around 0.4 % for both OU and GH conditions. In the opposite case, the highest differences were found for the wild genotype 'GM25' with differences equal to 5.5 days and 7.9 % of GDD (Table 3.1).

As Method 4 was the approach with the lowest errors in the flowering date assessment, this one was selected for calculating future flowering dates, occurrence of extreme temperature events and vulnerability of current and potential olive cultivation areas.

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Table 3.2 Cultivar parameters (total chilling units (TU_{org}) and thermal time (TT_{org}), both provided by De Melo Abreu et al. (2004), thermal time observed at flowering (TT_{obs}) and differences between simulated and observed flowering dates (F_{obs}-F_{org}) obtained with Method 1, Method 2 and Method 3 for 'Arbequina', 'Hojiblanca' and 'Picual' varieties, under outdoors (OU) and greenhouse (GH) conditions. Negative values mean earlier estimated dates compared with the observed ones.

		Arbequina		Hojiblanca		Picual	
		OU	GH	OU	GH	OU	GH
Method 1	TU _{org}	339		494		469	
	TT _{org}	490		510		495	
	TT _{obs}	529.1	796.9	563	771.3	576.5	758.8
	F _{obs} vs F _{org} (in days)	-3	-25	-4	-19	-6	-19.5
Method 2	TU _{org}	221		177		203	
	TT _{org}	503		559		532	
	TT _{obs}	575.5	856.4	630.2	904.7	646.3	872
	F _{obs} vs F _{org} (in days)	-7	-32	-5	-28	-9	-29
Method 3	TT _{org}	498		536		516	
	TT _{obs}	521.1	701.1	575.8	728.4	589.7	701.1
	F _{obs} vs F _{org} (in days)	-2	-14	-3	-13.5	-5	-13

3.3.3. Projections of future flowering dates

The twelve ensemble members of ENS-Spain02 were applied to the Method 4 detecting a delay in reaching chilling requirements or end of dormancy (EDO) for both NF and FF periods compared with the B period in the whole region (Fig. 3.5, Supplement Table A.3). Thus, considering TU_{min} (302 U), the mean delay in EDO of the ensemble for the 10 previously described genotypes was 9 and 22 days for NF and FF periods regarding B period, respectively. The larger delay was found in the Atlantic Ocean coast area (AOC) with up to 11 and 28 days in Jerez (Fig. 3.5) for the NF and FF periods, respectively. When TU threshold was not reached, flowering failure is generated. This flowering failure across Andalusia region was more frequent in the AOC area, lower section of Guadalquivir Valley (GV) and Southeast coast (SE). For example in Seville (Supplement Table A.3), failure percentage was 0, 0.3 and 10.9 % for B, NF and FF periods, respectively, increasing for Jerez with values equal to 0, 1.7 and 26 %, respectively. The uncertainty of EDO dates projections (calculated as the variability in

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the EDO dates obtained from the different climate models and expressed as the coefficient of variation, CV) was very low (values below ca. 2 % for all periods, Supplement Table A.3b). Considering TU_{min} (302 U), TU_{mean} (467 U) and TU_{max} (722 U) the mean delays in the EDO of the ensemble in the region were very similar between them. Thus, delays in EDO dates compared with B period ranged from 8-11 and 20-25 days for NF and FF periods, respectively, limited affected by the TU considered. However for some areas the occurrence of flowering failure varied significantly with TU. Thus, in AOC area the percentage of years with flowering failure for FF period varied from 26 to 87.1 % depending on the TU value (Jerez location; Supplement Table A.3) However for others areas the impact was very limited, no detecting flowering failure regardless of the considered TU value. Finally, uncertainty in EDO values was low (with the highest values for FF period) and very similar between areas (Supplement Table A.3).

Once the chilling requirements are met, simulated flowering date varied depending on the location, cultivar and period considered (Fig. 3.6, Table 3.3). For the B period, 'Arbequina' cultivar had the lowest GDD requirements (Table 3.1) and then showed the earliest flowering date, varying from 127 DOY in locations nearby AOC (Jerez and Seville) to 148 DOY in locations included in the N-NE (North- Northeast) Mountains area (Baeza). For 'Picual' cultivar, with moderate GDD requirements (Table 3.1), the flowering date ranged from 130 DOY for AOC to 151 DOY in N-NW (North-Northwest) area. Finally, 'GM22' wild genotype had the highest GDD requirements (Table 3.1) and then flowering date varied from 155 DOY in AOC to 175 DOY in N-NE area. As summary, considering the whole Andalusia region a similar advance in flowering date was identified for all the genotypes for future periods compared with B period, being the averaged advances equal to 6 and 17 days for the NF and FF periods, respectively.

The uncertainty in the estimation of flowering date for the analysed area evaluating the ENS-Spain02 ensemble results was very low for all the analysed periods. AOC area showed the lowest values (with values around 1.7 % for the FF period for Jerez location), and the highest for N-NE Mountains area (values equal to 2.5 % for the Baeza location for FF period; Table 3.3).

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Figure 3.5 End of dormancy (EDO) in day of year (DOY) for the baseline (1981–2010), near future (2021–2050) and far future (2071–2100) periods, calculated with minimum (TUmin (a)), mean (TUmean (b)) and maximum (TUmax (c)) total chilling units value.

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Figure 3.6 Simulated flowering date in day of year (DOY) with Method 4 for the baseline (1981–2010), near future (2021–2050) and far future (2071–2100) periods, for the cultivars a) ‘Arbequina’, b) ‘Picual’ and c) the wild genotype ‘GM22’

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Table 3.3. Mean flowering date, for the cultivars ‘Arbequina’ and ‘Picual’ and the wild genotype ‘GM22’ at the selected locations for the baseline (1981–2010), near future (2021–2050) and far future (2071–2100) periods. The values in parenthesis are the coefficient of variation (CV, %) of the flowering dates projected by the 12 climate models considered. DOY: day of year.

Location	Arbequina			Picual			GM22		
	B	NF	FF	B	NF	FF	B	NF	FF
	-----DOY-----								
Jerez	127 (0.3)	123 (1.4)	116 (1.7)	130 (0.3)	126 (1.4)	119 (1.7)	155 (0.4)	150 (1.2)	141 (1.7)
Seville	127 (0.4)	123 (1.4)	116 (1.9)	130 (0.4)	126 (1.4)	118 (1.9)	154 (0.5)	149 (1.2)	139 (1.9)
Osuna	134 (0.4)	129 (1.5)	121 (2.0)	137 (0.4)	132 (1.4)	124 (2)	161 (0.4)	156 (1.2)	145 (1.9)
Antequera	142 (0.6)	137 (1.8)	127 (2.3)	146 (0.6)	140 (1.8)	130 (2.3)	171 (0.5)	165 (1.4)	153 (2.3)
Cordoba	132 (0.5)	128 (1.5)	119 (2.2)	135 (0.5)	131 (1.5)	122 (2.2)	159 (0.5)	153 (1.3)	143 (2.1)
Baena	137 (0.5)	133 (1.4)	124 (2.2)	140 (0.5)	135 (1.4)	127 (2.2)	164 (0.4)	158 (1.2)	147 (2.1)
Martos	140 (0.5)	135 (1.5)	126 (2.3)	143 (0.5)	138 (1.5)	129 (2.3)	166 (0.4)	160 (1.3)	149 (2.3)
Baeza	148 (0.6)	143 (1.7)	131 (2.6)	151 (0.5)	145 (1.7)	134 (2.5)	174 (0.4)	167 (1.3)	155 (2.5)

3.3.4. Extreme temperature events

Once flowering dates were obtained, an analysis of the occurrence of extreme events during this stage was carried out for Arbequina cultivar, the genotype with the lowest GDD requirements for flowering, and GM22, the wild genotype with the highest GDD requirements (Table 3.1).

The results for the whole Andalusia region show an increase in the occurrence of heat extreme events per year for both 1-day and 3-days duration events (see section 3.2.5) (Fig. 3.7 and 3.8). For ‘Arbequina’ the mean occurrence of at least one hs1d-30 event by year increased around 19 and 38 % for NF and FF periods, respectively, compared with B period (Table 3.4), being in North-North East the areas with the highest occurrence of both hs1d-30 and hs3d-30 events. When a higher threshold temperature

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was considered (hs1d-35 and hs3d-35 events) the occurrence was lower (about the half than for events with temperatures higher than 30°C), showing equally the highest frequencies of occurrence in the North-Eastern area. Finally, for hs1d-40 events the highest occurrence was around 10 % for FF period and was also found in the North-Eastern area, while the occurrence of hs3d-40 events was null.

For 'GM22' the occurrence of heat extreme events was higher than for the rest of cultivars and wild olive genotypes (Fig. 3.8, Table 3.4). The mean occurrence of at least one hs1d-30 and hs3d-30 events by year increased around 9 and 22 %, respectively, for the FF period compared with the B period, with maximum occurrences for hs1d-30 events close to the 100 % in North-North East area (e.g. Baeza location) for the three considered periods (Table 3.4).

Regarding the hs1d-35 and hs3d-35 events, the mean number of events and the percentage of years with occurrence was smaller than 30 °C threshold was considered. The occurrence of at least one of these events (hs1d-35 and hs3d-35) increased in FF period compared with B (around 46 and 83%, for hs1d-35 and hs3d-35 respectively) with the maximum occurrences located in North-North East area (Baeza location). Finally, for hs1d-40 and hs3d-40 events the occurrence in FF period varied significantly throughout the region, with the highest occurrences projected for FF at the North-East of the region (e.g. for Baeza location 47.7 and 21.1 % for hs1d-40 and hs3d-40 events, respectively), in the upper section of Guadalquivir River.

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Figure 3.7. Average number of heat extreme events per year during flowering (from the crop point of view) with temperatures above 30 and 35 °C during at least one day (a, hd1d-30 and b, hd1d-35) and during at least three consecutive days (d, hs3d-30 and e, hs3d-35) for Arbequina cultivar (maps for the threshold of 40 °C are not shown due to the lack of events), for the baseline (1981–2010), near future (2021–2050) and far future (2071–2100) periods

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Table 3.4. Percentage of years with at least one event for one (hs1d) and three consecutive (hs3d) days above 30, 35 or 40 degrees during the flowering phase, for the cultivar ‘Arbequina’ and the wild genotype ‘GM22’, for the baseline (B, 1981–2010), near future (NF, 2021–2050) and far future (FF, 2071-2100) periods.

		Arbequina																	
Location	code	hs1d-30 (%)			hs1d-35 (%)			hs1d-40 (%)			hs3d-30 (%)			hs3d-35 (%)			hs3d-40		
		B	NF	FF	B	NF	FF	B	NF	FF	B	NF	FF	B	NF	FF	B	NF	FF
Jerez	A	31.4	41.1	54.1	0.3	1.9	7.4	0.0	0.0	0.0	8.9	13.3	26.5	0.0	0.0	1.4	0.0	0.0	0.0
Seville	B	49.4	58.9	67.4	3.1	8.3	16.5	0.0	0.0	0.6	21.9	30.3	43.2	0.8	0.6	4.5	0.0	0.0	0.3
Osuna	C	41.1	53.9	63.7	2.5	4.4	10.2	0.0	0.3	0.0	11.9	23.9	35.1	0.0	0.0	1.5	0.0	0.0	0.0
Antequera	D	8.6	19.2	37.6	0.0	0.8	1.6	0.0	0.0	0.0	0.0	3.9	9.0	0.0	0.0	0.3	0.0	0.0	0.0
Cordoba	E	61.4	70.3	78.6	8.6	16.9	27.0	0.3	0.3	1.2	28.3	41.4	47.3	0.6	3.1	9.2	0.0	0.0	0.3
Baena	F	61.1	74.4	78.6	11.4	20.3	34.5	0.0	1.4	2.3	30.8	41.1	55.3	1.7	5.6	10.3	0.0	0.6	0.0
Martos	G	70.3	77.8	84.8	16.1	29.2	47.1	0.3	2.2	4.2	35.0	45.6	63.7	3.9	8.3	14.7	0.0	0.8	0.3
Baeza	H	78.9	81.9	90.5	30.6	37.5	55.8	1.9	3.9	10.3	46.4	55.3	67.4	7.5	12.5	20.7	0.0	0.3	0.9
mean		50.3	59.7	69.4	9.1	14.9	25.0	0.3	1.0	2.3	22.9	31.8	43.4	1.8	3.8	7.8	0.0	0.2	0.2

		GM22																	
Location		hs1d-30 (%)			hs1d-35 (%)			hs1d-40 (%)			hs3d-30 (%)			hs3d-35 (%)			hs3d-40		
		B	NF	FF	B	NF	FF	B	NF	FF	B	NF	FF	B	NF	FF	B	NF	FF
Jerez	A	73.6	83.9	92.6	15.6	25.3	42.8	0.0	0.6	3.0	45.0	53.6	70.8	1.7	4.2	15.5	0.0	0.0	0.3
Seville	B	88.9	91.1	98.0	37.2	50.6	66.5	1.4	1.9	14.7	61.1	67.2	84.2	12.5	20.0	36.6	0.0	0.0	2.4
Osuna	C	87.2	89.7	95.3	20.6	30.6	49.6	0.3	1.1	2.7	61.1	66.9	79.7	3.6	8.1	21.4	0.0	0.0	0.3
Antequera	D	70.0	75.0	85.4	5.6	11.7	22.0	0.0	0.0	0.3	31.1	34.7	48.9	0.8	1.1	4.9	0.0	0.0	0.0
Cordoba	E	92.2	95.6	99.4	56.1	61.4	79.6	1.4	7.2	24.9	75.0	81.1	92.6	22.2	31.7	49.8	0.3	1.1	9.3
Baena	F	97.2	96.1	99.0	65.3	66.9	79.9	6.4	13.6	30.4	83.1	83.1	89.4	33.6	37.2	52.6	0.6	4.2	12.0
Martos	G	96.9	97.5	99.2	73.9	71.4	84.5	12.8	18.6	35.2	87.2	85.0	89.1	44.2	47.5	55.0	1.7	5.3	15.4
Baeza	H	98.3	98.6	99.5	78.3	84.2	90.2	18.6	26.9	47.7	89.2	89.2	95.4	46.1	55.8	64.6	4.7	8.6	21.1
mean		88.1	90.9	96.1	44.1	50.2	64.4	5.1	8.7	19.9	66.6	70.1	81.3	20.6	25.7	37.6	0.9	2.4	7.6

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Figure 3.8. Average number of heat extreme events per year during flowering (from the crop point of view) with temperatures above 30, 35 and 40 °C during at least one day (a, hs1d-30, b, hs1d-35 and c, hs1d-40) and during at least three consecutive days (d, hs3d-30, e, hs3d-35 and f, hs3d-40) for ‘GM22’ wild genotype for the baseline (1981–2010), near future (2021–2050) and far future (2071–2100) periods

3.3.5. Vulnerability and alternative suitable areas for olive cultivation at southern Spain

Combining the maps of percentage of years when the mean threshold of chilling requirements were not achieved and the maps of percentage of years with at least one event of one day with T_{max} above 35°C during B and FF period (Supplement, Fig A.3), a spatial analysis evaluating the flowering threats were defined (Fig. 3.9). Overlapping these threat maps with the current cultivated olive areas in Andalusia, the olive areas with the highest vulnerability to climate change as well as new areas suitable for olive cultivation with the analysed genotypes (Fig. 3.9) arose. Thus, considering 'Arbequina' and 'Picual' cultivars for the future period, the areas AOC and SE (Southeast) were those with the highest vulnerability due to the lack of chilling units. Similarly the areas located at NW (Northwest), North (N) and NE (Northeast) were the most vulnerable to high temperature during flowering for the FF period (Fig. 3.9). These areas are larger and with higher percentage of years with at least one event of one day with T_{max} above 35°C than for B period (Supplement A.3). In the opposite case, the areas with the lowest vulnerability to extreme events were N-NW (North-Northwest) and the S (South) for 'Arbequina'. The areas with low vulnerability were reduced for 'Picual', being limited to the Southern area. Finally, the wild genotype 'GM22' was the cultivar most vulnerable to high temperatures during flowering for both B and FF periods. However the percentage of years with at least one event of one day with T_{max} above 35°C was lower in the B than the FF period (Supplement A.3). The suitable areas were smaller to those determined for the rest of genotypes, being limited to the S-SE (South-Southeast) and S areas (Fig. 3.9).

Using similar methodology, new areas suitable for the olive cultivation at the end of the 21st century was identified. Thus, NW and S would be suitable areas for new plantations for 'Arbequina' and 'Picual' cultivars as heat stress during flowering and the possible lack of chilling units in winter were avoided. Equally, for the wild genotype 'GM22' the suitable area will be very limited to the S area of Andalusia (Fig. 3.9), due to the higher incidence of heat stress events on flowering than the others cultivars.

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It should be noted that these areas were obtained evaluating two processes independently, the lack of chilling hour accumulation and the heat stress during flowering.

Figure 3.9. Maps of vulnerable and suitable areas for olive cultivation, for the Arbequina, Picual, and GM22, for the baseline (1981–2010) and far future (2071–2100) periods.

3.4. DISCUSSION

Previous studies have shown the impact of the projected temperatures at the end of the 21st century on the olive phenology considering simulation models calibrated under baseline climate conditions (Osborne et al., 2000; Galán et al., 2005; Avolio et al., 2012). Under these climate conditions, previous models such as the developed by De Melo-Abreu et al. (2004) were validated using data from outdoors experiments (OU) for ‘Arbequina’, ‘Hojiblanca’ and ‘Picual’ cultivars obtaining limited differences between observed and simulated dates (2-5 days with Method 3) and providing similar flowering dates (118 to 120 DOY) than those obtained in previous studies (115-145 DOY by Fornaciari et al., 2000, 120-160 DOY by Osborne et al., 2000, or 122-134 DOY by De Melo-Abreu et al., 2004). In spite of these consistent results under baseline conditions, a huge variability in the calibration parameters was

detected. Thus, Tb values reported by De Melo-Abreu et al. (2004), Galán et al. (2005), Orlandi et al. (2005a, 2010a) or Aguilera et al. (2014), ranged from 5 to 23 °C, and the lower and upper temperature thresholds for chilling accumulation requirements described by De Melo Abreu et al. (2004), Orlandi et al. (2006) or Aguilera et al. (2014) ranged from 5.2 to 7.3 °C and from 12 to 20.7 °C, respectively. This fact indicates the difficulty to develop a general approach for estimating olive flowering date, even under current climate conditions.

The accurate performance of the traditional phenology models when using non-forced climate conditions (De Melo-Abreu et al., 2004) was significantly reduced reproducing experimental data under forced climate, representing future conditions. Thus, the approach that uniquely considered heat accumulation (without chilling requirements) showed the best performance under forced climate conditions but still the large difference between observed and simulated dates (ca. two weeks; Table 3.3) implies that additional studies are required. This result defies our knowledge on the quantity and even on the existence of chilling requirements for olive trees, in agreement with some authors that reported a strong relation between uniquely the flowering date and previous month's temperature (Fornaciari et al., 1998; Galán et al., 2005). Then, to develop alternative approaches for assessing climate change impacts on crop phenology for Mediterranean olive orchards is still required. However the development and local calibration of such models require experimental data under forced climate conditions, which have been almost non-existent up to date.

In order to improve flowering date simulation under baseline and future climate conditions, in this study a new model was developed and tested for ten olive genotypes being locally calibrated using experimental data under baseline (represented by the OU experiment) and forced (represented by the GH experiment) climate conditions. The new approach provided very accurate results for both OU and GH conditions, with differences between observed and simulated flowering date of around 2 days and 3.9% for GDD (Table 3.1), with very low associated uncertainty. The simulated flowering dates with the proposed approach for the B period considering all the cultivars except the three wild genotypes ('FV18', 'GM22' and 'GM25') showed a large spatial variability within Andalusia, ranging from 125 DOY for the Atlantic Ocean

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Coast to 184 DOY for the East Mountains area. These values are within the range of the published data by the Unit of Aerobiology at the University of Granada (RAA, 2015), obtained with pollen databases from 1992 to 2007. According to them, the highest concentrations of olive pollen usually occurs during the second week of May (134 DOY) in Almeria and Jaen provinces (Eastern Andalusia), while in the province of Granada (South-Eastern Andalusia) the highest pollen concentration is delayed to the third or fourth week of May (148 DOY) and even spans July (182 DOY) in the mountainous areas. Analyzing flowering date by genotype, also significant variability was found. Thus, the average flowering date in Cordoba for B period ranged from 132 for 'Arbequina' cultivar to 159 for the wild genotype 'GM22', with similar differences in the rest of the region. When the wild olive genotypes were excluded, the differences persisted but they were smaller, and were in agreement with De Melo-Abreu et al. (2004). The proposed model was calibrated under two contrasting climate conditions that encompassed the current and future climate conditions for the whole region of Andalusia, supporting the application of the locally calibrated model to the rest of Andalusia.

In spite of the impossibility to carry out a complete validation process due to the limited number of climate conditions, the similar parameters determined for OU and GH conditions in the calibration process demonstrated the high quality of the proposed approach (Table 3.1). Equally, the analysis of sensitivity carried out for TU indicated that for obtaining EDO values TU has not a critical importance. However the percentage of years with flowering failure caused by lack of chilling requirements was significantly impacted by the TU value, showing the necessity to promote studies related with the accurate definition of this parameter, and agree with studies carried out by Fornaciari et al. (1998) and Orlandi et al. (2004) that indicated the high uncertainty when olive chilling requirements were estimated.

Advances in the flowering date were foreseen with the proposed approach for the whole Andalusia region under future climate conditions. For FF period and within the current olive cultivated areas in Andalusia, the average advance in flowering date was equal to 17 days compared with the B period. This advance is in agreement to Osborne et al. (2000) and Galán et al. (2005) who indicated advances in flowering date

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for olive of around 15-20 days. These results could be also partially validated taking into account the temperature increase projected for March, April and May at the end of the 21st century (around 2 °C; Fig. 3.3) and the relationship between temperature increase and advance in the flowering date provided by Orlandi et al. (2010c), identifying an advance in flowering date in Cordoba of around 15.2 days.

The use of an ensemble of bias corrected climate projections together with a phenological model calibrated for local varieties has allowed the construction of impact maps to identify vulnerable and potentially suitable areas for olive cultivation in future, as well as to assess the uncertainty of the flowering date estimations. The generation of these maps has been frequent (Ponti et al., 2014; Tanasijevic et al., 2014) although the lack of local calibration, the absence of uncertainty assessment and the reduced number of olive cultivars analysed has limited their applicability.

Thus, this study allowed identifying the most vulnerable and suitable cultivated areas for baseline and future conditions. The spatial analysis of the vulnerable areas by the lack of chilling units (TU) considering high chilling requirements for olive identified the AOC and the SE coast areas as the most susceptible. However, according with the farmers experience and the aggregated reported yields for the AOC area (CAPDR, 2016b), problems associated to the lack of chilling hour requirements have not been found. These results encourage considering low TU values for future impact assessment. In relation with uncertainty, for EDO date projections this was very low (CV values below 3% whenever the period and location), although in this value uniquely uncertainty associated to RCMs under the same emission scenario (SRES-A1B) (Hawkins and Sutton, 2009; Dosio et al., 2012) was considered.

The frequency of occurrence of heat extreme events during olive flowering increased under future climate conditions, identifying the North-Northeast area as the most vulnerable to climate change due to the high temperatures during flowering. Within this area, the percentage of occurrence of at least one event during the sensitive flowering period with temperatures above 35 °C for 'Arbequina' was around 38 and 56 % during NF and FF periods, respectively. This trend is in agreement with previous studies that shows an increase in the number of extreme temperature events for both global (Tebaldi et al., 2006; Teixeira et al., 2013) and Europe level (Beniston et

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al., 2007). Olive cultivars with later flowering (such as 'GM22' genotype) had a higher exposure to extreme events. Thus, for the same area the frequency of occurrence of at least one heat event during the sensitive period of flowering with temperatures above 35 °C for 'GM22' was around 84 and 90 % during NF and FF periods, respectively, and therefore a more severe impact of climate change would be foreseen.

As vulnerability related with heat extreme events varied significantly between cultivars and locations, this should be taken into account for an adequate cultivar selection at a specific location avoiding late cultivars in areas with frequent foreseen heat extreme events. The consideration of the extreme events during the simulated flowering period is a recent and useful methodology (Ruiz-Ramos et al., 2011, Eitzinger et al., 2013, Teixeira et al., 2013; Trnka et al., 2014). However, this methodology is affected by uncertainties such as the accurate estimation of the length of the flowering sensitive period for olive that could be reduced due to the effect of high temperatures (Vuletin Selak et al., 2014), or by the unawareness of the impact of heat extreme events during flowering specifically for olive. Thus, contrary to other crops as sunflower (García-Lopez et al. 2014) or maize (Gabaldón-Leal et al., 2015), the available information about these impacts on olive is very limited. To solve this knowledge gap, extensive experimental studies for understanding and quantifying the impacts of these events on olive are still required.

Adaptation strategies for Mediterranean olive orchards to avoid the lack of chilling units for sensitive areas such as AOC area were very limited, and severely affected by the high uncertainty caused by the lack of knowledge for chilling requirements by genotype. Similarly, adaptation strategies to reduce the impact of the foreseen heat stress events in the near future would be the selection of cultivars with early flowering date, the use of cover crops and soil management practices to modify the albedo to reduce air temperature (Davin et al. 2014), or the consideration of supplementary irrigation to reduce the olive canopy temperature (Doughty et al., 2011; Andrade et al., 2012). Equally, new suitable areas for olive cultivation could be extended in the NW and S areas of Andalusia for 'Arbequina' and 'Picual' cultivars.

Finally, the proposed methodology has been designed for olive orchards under the semi-arid conditions of Southern Spain and has only taken into account changes in

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both mean and maximum temperatures, regardless of changes in rainfall and the soil moisture content. The impact of water stress on olive, promoted by the foreseen climate models of Andalusia region, will have similar relevance on olive yield and studies related with this must be promoted.

Although this study has been focused on olive for Southern Spain conditions, the proposed methodology of using greenhouses to reproduce the projected climate could be applicable for other crops and locations. Thus, the described methodology could be replicated to assess the impact of climate change on others Mediterranean crops such as nut or fruit trees.

3.5. CONCLUSION

This study has evaluated the olive flowering date for ten olive genotypes (seven traditional cultivars in southern Spain and three olive genotypes from Canary Islands) under baseline and future climate conditions. Validation of previous phenological models for flowering date estimation and the development of a new approach adapted to both baseline and projected climate conditions, were carried out considering experimental data. The study was carried out in Andalusia region, located at Southern Spain and considered an ensemble of climate projections from Regional Climate Models (RCMs) with a bias correction in temperature and precipitation. From these simulations, an advance in the flowering date of around 6 and 17 days for 2021-2050 and 2071-2100 periods, respectively, compared with 1981-2010 period was projected. The uncertainty associated to these phenological projections coming from climate projections was very low.

The integration of local experimentation, phenological modelling and climate data from an ensemble of climate throughout Andalusia region allowed developing a spatial analysis of the impacts of climate change on olive flowering and its uncertainty. This analysis was based on the estimation of the flowering date, the chilling hour accumulation and the occurrence of heat extreme events during the flowering stage for ten olive genotypes. We concluded in the identification of those areas more

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vulnerable to climate change (such as the Atlantic Ocean Cost and Northern-East areas of Andalusia) and those potential new areas for olive cultivation (such as the North-West and South area). Late flowering cultivars (such as wild olive genotypes from Canary Islands) were the most vulnerable ones to high temperatures during flowering.

This study highlights the need to promote experimental studies on crop physiology and phenology under future climate conditions to improve the knowledge about the response of Mediterranean olive orchards to climate change. The described methodology is not exclusive for the olive crop and could be replicated to assess the impact of climate change on others crops and locations.

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Appendix. Supplementary data

Supplementary material related to this article can be found in Annex.

GENERAL DISCUSSION

This Thesis has addressed the impacts of climate change on maize and olive crops under semi-arid conditions in Andalusia region. In addition, the incidence of extreme temperature events on flowering, a sensitive phenological period for numerous crops to high temperatures (Koubouris et al., 2009; Gourdji et al., 2013), has been evaluated for both crops. Thus, a model to evaluate the impact of heat stress events during flowering on maize yield has been provided, trying to mitigate the limitations found in current maize grain yield modeling under these conditions (Rezaei et al., 2015). Also for maize, considering modeling tools, possible adaptation strategies were proposed and evaluated in order to minimize the described impacts.

The Thesis is based on the development and use of crop simulation models for the assessment of impacts and adaptation strategies considering the effect of extreme maximum temperatures on the crops. The methodology considers experimental data for local calibration and validation under current and forced climate conditions, being essential this experimentation in order to adjust the model to the future climate regional conditions, with the purpose of generating projections at local and regional scale (Boote et al. 2013). The consideration of experimental data, together with the use of a bias corrected ensemble from regional climate models, has provided future projections with lower uncertainty than previous studies. However further experimental studies are still needed. Thus, in this study uniquely changes in both mean and maximum temperatures has been evaluated, and then changes in rainfall and the soil moisture content have not been considered. The integration of heat and water stress impacts in the crop models will provide a more accurate evaluation of climate change impacts on Mediterranean agriculture.

Future climate projections show an increase in future temperatures, being particularly important for Andalusia region, at southern Spain, with an increase in mean temperature up to 5 °C in the summer months (Van der Linden and Mitchel, 2009). Furthermore an increase in the frequency and magnitude of heat extreme events is projected worldwide with climate change (Tebaldi et al., 2006; Field et al., 2012), again with a higher increase at southern Spain (Sánchez and Miguez-Macho, 2010). This increase would probably lead to a larger incidence of heat stress for crops

compared to current conditions (Schlenker and Roberts, 2009; Lobell et al., 2013; Trnka et al., 2014).

Under future climate conditions, advancement in phenological dates was projected for both maize crop and olive trees, due to the higher temperatures projected at the end of 21st century (IPCC, 2014). These results were obtained using crop models calibrated under local conditions, with errors detected in the calibration of the maize crop model similar than those obtained in previous studies (Meza et al., 2008; Vučetić, 2011; Angulo et al., 2013; Moradi et al., 2013). The impacts of future climate conditions using these models showed a shortening in the maize crop cycle, similar to the results observed by Olesen et al. (2012) and Bassu et al. (2014) in cereals, including maize. These changes lead to projections of maize yield decrease for locations along the Guadalquivir River basin, although smaller than the indicated in previous studies (Guereña et al. 2001; Garrido et al. 2011 and Rey et al. 2011). For some locations as Granada, located in the Southern part of Andalusia and nearby Sierra Nevada mountains, the decrease in yield was more severe due to the reduction in crop cycle was higher than for the other locations. Similarly, the impacts of extreme temperature events on maize during flowering were evaluated following Teixeira et al. (2013) for Andalusia region, showing an increase in the heat stress index, causing a higher production damage index at the end of the 21st century.

Another important impact for maize crop in Andalusia is regarding the irrigation requirements (IRR) and the irrigation water productivity (IWP). The results showed a decrease in the estimated IRR for future periods for all the locations. This decrease could be explained by the reduction of the crop cycle duration and the crop evapotranspiration, caused by warmer temperatures and the reduced stomatal conductance as consequence of future CO₂ concentrations (Cure and Acock 1986; Ainsworth and Long 2005). The increased IWP in the future periods could be related to the described reduction on stomatal conductance (Leahey et al. 2006; Vanuytrecht et al. 2012).

The projection results for maize yield under future climate conditions were evaluated for five locations, four of them along the Guadalquivir river basin, showing similar results and low uncertainty. This low uncertainty exhibited by the projections is partially as consequence of conducting simulations under an optimum irrigation

supply, which excludes the uncertainty linked to precipitation. The precipitation uncertainty is usually higher than for other variables (Christensen and Christensen, 2007) due to the spatially and temporally complex structure and its related physical processes, being especially large in the Iberian Peninsula (Sánchez and Miguez-Macho, 2010). However, Granada area showed higher uncertainty than the Guadalquivir locations expressed as the spread of the ensemble members or differences among RCM outputs. In turn, these differences could be enhanced by the complex orography of Granada area. For instance, while mean altitude for the Guadalquivir Valley locations is 100 m a.s.l, Granada is at 633 m a.s.l. For this particular location, its actual altitude is lower than the mean grid altitude of 1034 m considered by both the observational data set E-OBS and the ensemble of corrected RCM projections ENS-EOBS; this misrepresentation of altitude would introduce an error and contribute to the accumulated uncertainty.

Impacts on olive trees were studied in relation to the flowering date assessment under current and future climate conditions and the occurrence of extreme events during this critical phenological stage. The new approach provided very accurate results for both current (evaluated by experiments under current actual conditions) and forced conditions (considering experiments placed inside a greenhouse reproducing the future climate conditions), with differences between observed and simulated flowering date of around 2 days and with very low associated uncertainty. The simulated flowering dates projected for the baseline period (1981-2010) showed a significant spatial variability within Andalusia (125-184 DOY). These results are in the range of the published data by the Unit of Aerobiology at the University of Granada (RAA, 2015), that found the highest concentrations of olive pollen during the second week of May in the Eastern areas of Andalusia, and up to July in the mountainous areas.

For flowering date estimation in olive, the fulfillment of chilling requirement (or end of endormancy) has a critical importance (Rallo and Martin, 1991). Analyzing this fulfillment for the whole Andalusia region at the end of the 21st century, the most susceptible areas to lack of chilling requirements accumulation were the Atlantic Ocean and South East Coasts. The results related with the lack of chilling units for olive obtained are in agreement with the yield reports provided by farmers and public

institutions for the last years in the Atlantic Ocean Coast area, which did not detect problems of lack of chilling hour requirements (CAPDR, 2016b).

For olive trees the impact of extreme temperature events was evaluated using a similar approach than Ruiz-Ramos et al. (2011), considering number of events during flowering period with temperature above different thresholds. The frequency of occurrence of heat extreme events during olive flowering under projected future climate conditions generally increased with very low uncertainty, with the highest frequency in the North-Northeast area of Andalusia. The increasing trend projected was in agreement with previous studies developed by Tebaldi et al. (2006), Beniston et al. (2007), Ruiz-Ramos et al. (2011) and Teixeira et al. (2013). In the study, differences in vulnerability between cultivars and locations were found and should be taken into account for an adequate cultivar selection at a specific location, avoiding late cultivars (such as the wild genotype GM22) in areas with frequent foreseen heat extreme events (such as North-Northern areas of Andalusia).

The general very low uncertainty associated to the olive crop results was due to the fact that the impacts projections were based only in temperature, variable with lower uncertainty than the precipitation, as mention above. Also, in this study the ensemble of climate models used was ENS-Spain02, especially developed for impact assessment (Ruiz-Ramos et al., 2015). In spite of the low uncertainty detected, this one was slightly higher for future periods compared with the baseline due to inherent uncertainty of the climate models and was in agreement to Ferrise et al. (2011) and Hoffmann and Rath (2013).

It should be noted that the uncertainty evaluated was only that caused by differences in the projections provided by the RCMs under the same emission scenario (SRES-A1B) (Hawkins and Sutton, 2009; Dosio et al., 2012). This is one of the largest uncertainty sources in climate change impact assessment as Iglesias et al. (2010) for olive, Hoffmann and Rath (2013) for apple, Ruiz-Ramos and Mínguez (2010) and Asseng et al. (2013) for wheat and maize described. However there are other relevant uncertainty sources not addressed here, as driving GCM, climate scenarios and others decisions related to climate (Déqué et al, 2007). Equally, uncertainty coming from crop models must be considered and it has arisen as an important uncertainty source (Asseng et al., 2015).

The methodologies used reduce the uncertainty of impact projections improving several uncertainty sources. First, the uncertainty coming from climate model outputs is reduced by the use of regional climate models (RCMs) instead of general climate models (GCMs) providing climate information at the required scale (ca. 5 to 50 km for RCMs vs. 100 to 200 km for GCMs) for local and regional assessments, in areas with complex orography as Andalusia (Guereña et al., 2001). Additional steps for reducing the uncertainty were 1) the use of an ensemble of RCMs instead of a single one projection, to consider the uncertainty from climate model parameterization (Christensen et al., 2007; Semenov and Stratonovitch 2010), and 2) the use of the bias corrected temperature and precipitation ensemble members. Thus, more specifically, two bias corrected climate datasets from the ENSEMBLES European project were used; one of them based on the observational E-OBS dataset, with 2316 stations covering all Europe (50 of them in Spain) (ENS-EOBS) and the second one, using as observational reference a dataset specifically generated for continental Spain and the Balearic Islands based on 2756 quality-controlled weather stations (Spain02, Herrera et al, 2012). For both climate datasets a bias correction in temperature and precipitation following (Dosio and Paruolo, 2011) and delivered by Ruiz-Ramos et al. (2015) (ENS-Spain02) was considered. These improvements resulted in an overall reduction of uncertainty when compared to former studies (Ruiz-Ramos and Mínguez, 2010; Ruiz-Ramos et al., 2015).

The adaptation strategies for maize tested, such earlier sowing dates, or cultivar changes with longer and more effective grain filling period have proven to diminish negative impacts at field, regional, and European levels (Olesen et al. 2011). However, our results emphasize that the adaptations for these events must be local, due to differences in the spatial pattern of extreme events (Teixeira et al. 2013) and local cropping system features.

The adaptations proposed for maize to deal with climate change impacts were an earlier sowing date, in agreement with Moriondo et al. (2011), combined with cultivar changes searching for a longer grain filling period (Tollenaar and Lee 2011; Chen et al. 2013; Ning et al. 2013). The combination of both strategies, sowing dates and improved cultivars yielded the best projection results and are feasible from the breeding and management points of view. With this combined adaptation the

potential yield were recovered in all the locations, and even increased in the Guadalquivir locations.

When impacts and adaptation strategies are evaluated, it is required to consider that actual yield would be lower than the simulated, as the simulations did not include any biotic nor abiotic stresses. Thus, if the effects of extreme maximum temperatures during flowering are considered, in some locations as Granada the yield would still remain around 8 % below current level, even when the adaptation is applied. This aspect stresses the importance of the lack of heat stress consideration by crop models.

When the adaptation strategies were considered irrigation requirements, IRR, were lower for future periods compared with the baseline period. This reduction was due to the earlier maturity dates, avoiding the crop the driest and hottest periods. Equally, with the adaptations implemented, irrigation water productivity also increased because yield increased more than crop transpiration and IRR, which implies that the adaptations are useful not only for increasing or maintaining crop yields, but for saving water and use it efficiently.

Adaptation strategies for Mediterranean olive orchards to reduce the impact of heat stress on olive in the near future are less numerous than for crops as maize, and would be limited to the selection of cultivars with early flowering date (such as Arbequina or Koroneiki), the use of cover crops and soil management practices to modify the albedo to reduce air temperature (Davin et al. 2014), or the consideration of supplementary irrigation to reduce the olive canopy temperature (Doughty et al., 2011; Andrade et al., 2012). An additional adaptation strategy would be the selection of new suitable cultivation areas. Thus, new suitable areas for olive cultivation could be extended in the North-West and South areas of Andalusia region for Arbequina and in the Southern areas for Picual.

After the evaluation of the available crop and phenological models for impact and adaptation strategies assessment, a very significant knowledge gap has been detected for olive crop, contrasting with the available crop models for wheat, maize and other field crops. Thus, key processes such as chilling requirements or heat accumulation must be correctly simulated to make possible a reliable modeling of olive yield formation and therefore, crop yield estimation. Aware of these limitations

previous approaches have been evaluated and a general approach has developed for estimating olive flowering date. The results obtained showed a good fit with the flowering dates for baseline and future conditions, so the new approach was adequate for generating projections of flowering dates under future climate conditions. However, not only olive crop has limitations in the development of approaches for evaluating key components for identifying the effect of climate change on crops. Thus, crop models must be improved to consider the effects of heat stress for both large (Ewert et al., 2015; Rezaei et al., 2015) and local scales. For that reason the simulation of maize grain yield under heat stress conditions has been evaluated.

A heat stress model has been developed and evaluated in order to simulate maize grain yield under heat stress conditions around silking, obtaining satisfactory performance. Thus, a heat stress reduction factor was obtained using experimental data from Argentina and validated with experimental data from Spain, being appropriate for using under climate change conditions. The model performance was improved when canopy temperature was considered as input for the heat stress function instead of air temperature. To use air temperature as input, the critical threshold must be increased from 34 °C, determined by Cicchino et al. (2010), to 39 °C as this critical threshold could be several degrees higher under irrigation conditions due to the irrigation cooling effect (Lobell et al., 2008; Kimball et al., 2015). The improvement in crop modeling for maize and olive crops has accomplished and demonstrated the need to promote experimental studies on crop physiology and phenology under forced conditions to increase the knowledge about the response of different Mediterranean crops to climate change. Furthermore, the importance of access to high quality experimental data, to calibrate and validate crop models under local and forced climate conditions has addressed. The collaboration between modellers and experimentalist has been proved to be useful. In addition, the development of specific experimental designs to feed the crop models to evaluate future climate conditions, as heat events or water deficits under different phenological phases for maize, olive or other crops, is recommended.

Several further maize model improvements could be desirable. Among them, to examine the correlation between hourly heat stress and radiation use efficiency under high temperatures. Furthermore the evaluation of the canopy temperature model

under rainfed conditions could be useful, as uniquely under irrigated conditions has been analyzed. This evaluation under different conditions could improve the model applicability across different climate regions and management options. Regarding the olive model, a complete phenological characterization under different climate conditions, as warmer winters, could be useful to parametrize the chilling requirements and phenological stages. Furthermore an evaluation of the temperature profile along the olive tree could be useful to evaluate the impact of high temperatures during flowering under irrigation or rainfed conditions, as well as evaluating the flowering quality after high temperature exposure during flowering. Finally, the accurate assessment of the impact of water stress during critical phenological stages as flowering could provide a complete approach for determining the impact of climate change on olive crop.

The study is in line with the Climate-smart agriculture (CSA) approach proposed by FAO, as it is focused on the evaluation of the adaptations strategies to cope with the impacts of climate change. In addition, the improvement of crop models for the simulation of crop phenology and yield under heat stress conditions may contribute to further research in the world regions with the largest food security challenges.

GENERAL CONCLUSIONS

The present Thesis has confirmed that:

- A reduction of uncertainty of impact and adaptation projections can be achieved by combining 1) bias corrected, reduced uncertainty climate projections, and 2) site-specific calibrated and validated crop models.
- Considering the impacts of extreme events in reducing the crop yield is crucial when assessing adaptations strategies. Crop models needs to be improved to capture these effects.

The present Thesis has concluded that:

- An irrigated maize yield reduction (6-20 %) is projected at the end of the 21st century due to the shorter crop cycle that will cause crop evapotranspiration reduction and an increase in heat stress events frequency.
- Adaptation strategies such as earlier sowing dates and cultivar changes, when they are locally addressed, have the potential to compensate and even increase maize yields in Andalusia.
- The irrigation requirements of maize at the end of the 21st century were reduced around 25 % compared with the baseline period without adaptation strategies due to the reduction in crop evapotranspiration and higher water use efficiency. With the selected adaptation the decrease in the irrigation requirements showed a limited decrease or it was slightly higher in Granada compared to those without adaptation. This was due to the earlier maturity dates, which allowed the crop to avoid the driest and hottest period for the maize crop; however the irrigation requirements were still lower than those of the baseline period.
- Extreme temperature events during flowering may limit the effect of the adaptation measures for maize in some areas of Andalusia (as Granada) due to the later flowering date compared with the others locations studied.

- SIMPLACE <Lintul5,HS,Tc> model performed correctly in simulating grain yield maize reductions based on the accumulated stress thermal time above a critical threshold temperature during the critical period of flowering.
- The SIMPLACE <Lintul5,HS,Tc> model performed better when canopy temperature was used as input in the heat stress function.
- When air temperature was considered for the critical threshold for heat stress in SIMPLACE <Lintul5,HS,Tc> model, this threshold has to be increased from 34 °C (which is a physiologically meaningful threshold) to 39 °C (as the maize was considerably cooler than the air due to ambient cooling caused by irrigation).
- Increasing the critical temperature is an alternative option when air temperature is considered in the heat stress reduction function under irrigated conditions, but is not expected to be a suitable approach under rainfed conditions due to the lack of irrigation cooling effect.
- For olive flowering date estimation under climate change conditions a new approach adapted to future climate conditions was proposed and evaluated.
- For the entire Andalusia area, compared with 1981-2010 period, an advance in the flowering date of around 6 and 17 days for 2021-2050 and 2071-2100 periods, respectively, was estimated.
- These estimations for olive crop are robust due to the low associated uncertainty.
- The integration of local experimental data, phenological modelling and climate data from an ensemble of climate models throughout Andalusia allowed developing a spatial analysis of the impacts of climate change on olive flowering.
- Based on the estimation of the flowering date, chilling requirements and the occurrence of extreme events during the flowering stage, identification of vulnerable and potential new areas for olive cultivation was defined. Thus, Atlantic Ocean area and South-East coast were found to be vulnerable due to lack of chilling units in winter and the Northern-East region due to the high

temperatures during flowering. Olive crop could be potentially extended to new areas as the southern area in the future.

- The described methodology is not exclusive for the olive crop and could be replicated to assess the impact of climate change on others Mediterranean crops such as nuts or fruit trees, requiring previous local calibration based on field experiments.

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ANNEX

Appendix. Supplementary material related to the Chapter 3 “Impact of changes in temperature and extreme events caused by climate change on olive flowering at southern Spain”

Figure A.1. Topographic map of Andalusia region

Figure A.2. a) Daily maximum (Tmax) and b) daily minimum (Tmin) temperatures inside greenhouse (GH; in continuous line) and outdoors (OU; in dotted line)

Figure A.3. Maps of threat for olive flowering overlapping the lack of chilling and the occurrence of extreme events during flowering period for Arbequina, Picual, and GM22, considering $TU=467$ U and at least one event of 1-day with T_{max} above 35 °C, for the baseline (1981–2010) and far future (2071–2100) periods. Colors represent the percentage of years with at least one event of T_{max} , (dark color--lower number, light color--higher number), lines represent the percentage of years that the chilling requirements were not achieved (no lines—lower number, dense lines—higher number).

Table A.1. Comparison of advance in flowering days estimated with the Method 4 using the climate data from the outdoors (OU) and greenhouse (GH) conditions and for the baseline (1981–2010), near future (2021–2050) and far future (2071–2100) periods of ENS-Spain02 ensemble of climate. DOY: day of year.

	Flowering dates (DOY)				Days in advance	
	With OU data	With B data from ENS-Spain02	Observed (GH)	ENS-Spain02 (FF)	Difference (GH-OU)	Difference (FF-B) from ENS-Spain02
Arbequina	123	132	111	119	12	13
Arbosana	126	136	114	122	12	14
Chiquitita	127	137	115	124	12	13
Frantoio	126	136	114	122	12	14
FV18	130	141	118	127	12	14
GM22	149	159	131	143	18	16
GM25	149	159	131	143	18	16
Hojiblanca	126	136	114	122	12	14
Koroneiki	123	132	111	119	12	13
Picual	125	135	114	122	11	13

Table A.2 a) Percentage of years where the chilling requirements (TU) were not reached, and b) the coefficient of variation (CV (%)) of the end of endormancy (EDO) dates projected with the ENS-Spain02 ensemble and Method 4 for the minimum (TU_{min} (302 U)), mean (TU_{mean} (467 U)) and maximum (TU_{max} (722 U)) chilling requirements, for the baseline (B, 1981–2010), near future (NF, 2021–2050) and far future (FF, 2071–2100) periods at eight selected locations

a)		%Years TU not reached/period								
		TUmin			TUmean			TUmax		
Location		B	NF	FF	B	NF	FF	B	NF	FF
Jerez		0	1.7	26	0	10.6	56.5	7.5	42.2	87.1
Seville		0	0.3	10.9	0	1.9	32.9	1.1	18.3	75.1
Osuna		0	0	1.2	0	0.3	4.9	0	0.8	33
Antequera		0	0	0	0	0	0.9	0	0	6.1
Cordoba		0	0	0.3	0	0	2.2	0	0.3	22.5
Baena		0	0	0	0	0	0	0	0	1.5
Martos		0	0	0	0	0	0	0	0	0.3
Baeza		0	0	0	0	0	0	0	0	0

b)		CV_{EDO} (%)								
		TUmin			TUmean			TUmax		
Location		B	NF	FF	B	NF	FF	B	NF	FF
Jerez		0.6	1.5	1.8	0.7	1.6	2.1	0.9	1.9	3.1
Seville		0.4	1.4	1.8	0.5	1.4	1.9	0.5	1.7	1.9
Osuna		0.3	1	1.6	0.4	1.1	1.9	0.4	1.3	2.1
Antequera		0.2	0.9	1.3	0.3	0.9	1.5	0.3	1.1	2.1
Cordoba		0.3	0.9	1.6	0.3	1	1.6	0.4	1.2	1.7
Baena		0.3	0.7	1.1	0.3	0.8	1.2	0.4	0.8	1.5
Martos		0.3	0.8	1.1	0.3	0.8	1.2	0.4	0.8	1.5
Baeza		0.3	0.9	1.2	0.3	0.9	1.3	0.4	0.9	1.7