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Prospective regional analysis of olive and olive fly in Andalusia under climate change using physiologically based demographic modeling powered by cloud computing

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ABSTRACT

The Spanish region of Andalusia is the world-leading olive oil producer. Its olive-dominated landscapes are among the most biodiverse drylands of the globe and prospectively among the areas most affected by climate change. This analysis used physiologically based demographic modeling (PBDM) to assess the impact of climate change on the olive/olive fly system of Andalusia. The analysis was implemented on cloud computing, allowing PBDM models to be run from any computer connected to the internet, to interface with state-of-the-art climatic drivers, and to scale efficiently with increasing computational loads and user requests. Findings include that chilling required for olive blooming will decrease in large areas of the Andalusian provinces of Jaen, Cordoba, and Sevilla, with some areas not meeting the minimum chilling threshold and some accumulating no chilling by the end of the century under the high greenhouse gas (GHG) emission scenario. Olive blooming will occur up to five weeks earlier in the Jaen, Cordoba, Sevilla, and Granada provinces, but olive yield is expected to increase or remain stable. Olive fly infestation will decrease with climate change, with infestations below the reference economic threshold of 4 % towards the end of the century in some areas under high GHG emission scenario. Measures to adapt Andalusian olive systems to climate change include: selecting olive cultivars with lower chilling requirements; implementing cover crops to enhance water use efficiency under increased CO_2 concentration and uncertain precipitation projections; and targeting the spring generation of the fly and diversifying the olive landscape to reduce infestation levels.

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Practical implications

Enhancing the use of climate services for all stakeholders in the agri-food value chain requires that scientists have the capacity to assess the effects of biotic (e.g., crop, pests, and natural enemies) and abiotic (e.g., climate) components of the agroecosystem on sustainable yields (Beveridge et al., 2018; Challinor et al., 2017; Cuddington et al., 2013; Gutierrez et al., 2010). This is prerequisite for dealing with the increasing complexity of agricultural systems under global change including technological changes, invasive species, and climate change (e.g., Ponti et al., 2015). Mechanistic weather-driven physiologically based demographic models (PBDMs) provide a powerful methodology for assessing the bioeconomic biology of species and their interaction including human economics (Fig. 1). In practice, PBDMs have been used to map the regional bioeconomic consequences of crop-pest-natural enemy interactions in several crop systems globally (e.g., cassava, coffee, cotton, grape, olive, rice, and other systems) (see Gutierrez and Ponti, 2022). PBDM agrosystem models for the olive and coffee systems were implemented under the MED-GOLD project ("Turning climate-related information into added value for traditional MEDiterranean Grape, OLive and Durum wheat food systems", see 10.3030/776467) on a scalable computing ICT platform (the MED-GOLD ICT platform; see MED-GOLD consortium, 2023).

Andalusia, Spain is the world-leading olive growing region (FAO, 2019; International Olive Council, https://www.internationaloliveoil.org/), and in this paper, a collaborative CASAS-PBDM system model (see http://www.casasglobal.org/, hereafter PBDM) for olive (*Olea europaea* L.) and olive fly [*Bactrocera oleae* (Rossi)] was used to assess the effects of climate change on the Andalusian olive system. The analysis was run on a web-based application programming interface (Web API, part of the MED-GOLD ICT platform) and the results were mapped using a custom GRASS-based GIS script (Supplementary Information, Appendix A). The Web API allows PBDM models to be run from any computer connected to the internet (Appendix A) using the MED-GOLD ICT platform. A quick overview of the PBDM approach is provided by a short video available at the following link https://youtu.be/dl69l9l8FAM. Further information is available in the MED-GOLD infographics (10.5281/zenodo.7928703) and the manual for stakeholders and practitioners (Appendix A).

PBDMs provide the capacity to assess crop systems at local and regional level on how best to allocate limited resources for agroecosystem management (Gutierrez, 1996), providing information that is extremely difficult, time-consuming, and costly to obtain experimentally (see Toko et al., 2019). The MED-GOLD project sought to make the PBDM models easy to access and interface with climatic drivers such as state-of-the-art climate data available from the Copernicus Climate Change Service through the Climate Data Store (https://cds.climate.copernicus.eu/) (Buontempo et al., 2022, 2020).

For the Mediterranean region, climate warming projections from multiple models are consistent throughout the 21st century across all seasons and under low, intermediate, and high GHG emission scenarios, with projected summer warming being higher than the rest of the globe, and highest in the Iberian Peninsula (Cos et al., 2022). However, in contrast to projected temperature changes, changes in precipitation over the Mediterranean Basin are uncertain and spatially heterogeneous with projected amounts remaining close to the historical baseline, except for the summer period where rainfall on average will decrease up to 33 %, with 50 to 60 % decreases in the Iberian Peninsula (Cos et al., 2022). Such shortfalls are comparable to the current historically dry summer in Andalusia (Sumner et al., 2001). We note that olive yield is greatly affected by rainfall in the previous fall and winter (see Gratsea et al., 2022; Rapoport et al., 2012; Rodrigo-Comino et al., 2021). Changes in projected precipitation during winter have a larger uncertainty in the range of −31 to +4 % for the long-term period 2081–2100 in Andalusia (Cos et al., 2022). These fall and winter decreases in precipitation are expected to have limited impact on olive growing in Andalusia (Fraga et al., 2021; Ponti et al., 2014), with the impact on olive yield buffered by increasing tree density and the increased CO_2 concentration (due to GHG emissions) that enhances photosynthesis and water use efficiency (Mairech et al., 2021).

The main results of the PBDM analyses across Andalusia are:

(1) **Chilling hour degrees required for olive blooming** (hour degrees below 7.3 °C, i.e., HD < 7.3°C) are projected to decrease under climate change during the rest of the 21st

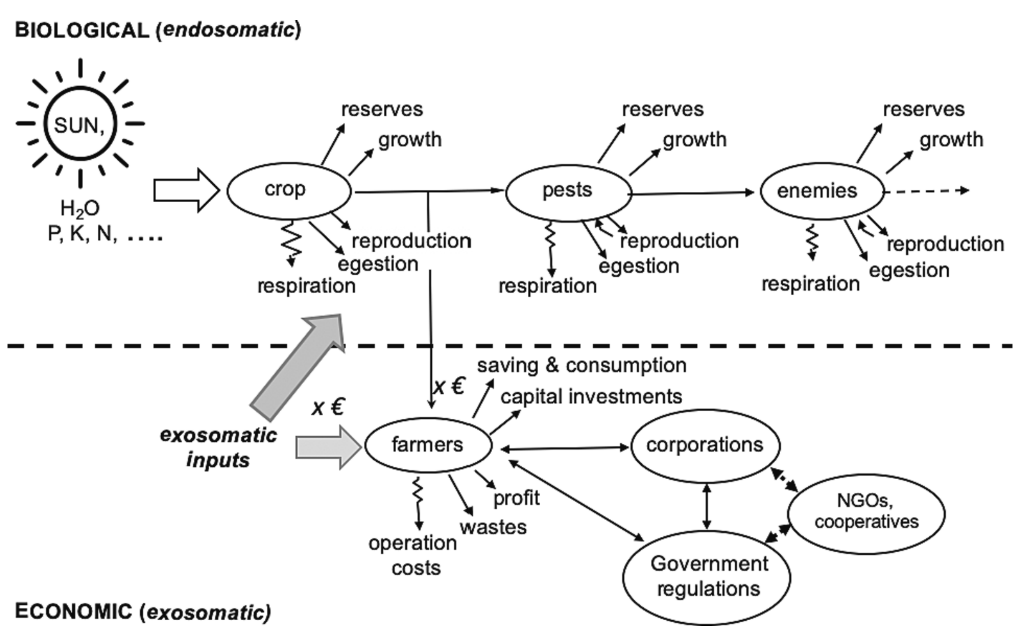

Fig. 1. Conceptual linkages of the bioeconomics of resource acquisition and allocation across trophic levels in a crop system including human harvesting of renewable resources (c.f. Gutierrez, 1992; Regev et al., 1998; Gutierrez and Regev, 2005) with endosomatic (natural) and exosomatic (artificial) inputs to the system (cf. Georgescu-Roegen, 1976).

century, with large areas in the top olive-producing provinces of Jaen, Cordoba, and Sevilla failing to meet the reference minimum threshold for olive blooming of 450 HD < 7.3°C under the high GHG emission scenario towards the end of the century, with some areas accumulating no chilling.

(2) **Olive blooming** is projected to occur earlier under climate change, with bloom dates being four to five weeks earlier in large areas of the provinces of Jaen, Cordoba, Sevilla, and Granada and more than six weeks earlier in Malaga under the high GHG emission scenario towards the end of the century.

(3) Without considering the effect of uncertain rain projections in our study, **olive fruit yields** are projected to increase or remain stable under climate change across GHG emission scenarios and future time periods, with highest increases expected in the southeastern provinces of Malaga, Almeria, and Granada towards the end of the century.

(4) **Olive fly infestation** will decrease due to the adverse effects of increased temperatures on fly vital rates, particularly in the provinces of Jaen, Cordoba, and Sevilla under the high GHG emission scenario towards the end of the century. Infestations are projected to remain below the reference economic threshold of 4 % in some areas of the three provinces.

In practice, adapting the predominantly rainfed Andalusian olive systems to climate change implies:

a) Olive phenological diversity could be screened to select cultivars with lower chilling requirements (Belaj et al., 2020), as chilling accumulation for release of flower bud dormancy will decrease sharply under climate change.
b) Measures such as cover crops should be used to help maximize soil water storage and conservation (Fraga et al., 2021) to protect potentially stable or increasing yields in the face of uncertain projections of future precipitation (Cos et al., 2022).
c) The spring generation of the fly should be targeted (Caselli and Petacchi, 2021) and olive landscape further diversified (Rescia and Ortega, 2018) to reduce season-long infestation levels, as reliable projected climate warming is expected to lower olive fly risk.

Data availability

Data shared via Zenodo.

1. Introduction

Olive (*Olea europaea* L.) is an ancient, drought-tolerant, and ubiquitous crop in the Mediterranean Basin with considerable ecological, socio-economic, and cultural importance. Most of the world's olive is grown in the Mediterranean Basin, with the region of Andalusia in Southern Spain being the world leader (Galán et al., 2008; FAO, 2019; see International Olive Council, https://www.internationaloliveoil.org/). Olive is perceived as the "life and identity" of the Mediterranean Basin (Loumou and Giourga, 2003), and can well be considered a world heritage biocultural system (Ponti et al., 2016). Olive is a long-lived species tolerant to drought, with a geographic distribution limited northward mostly by frost and southward by high temperature and to a lesser extent by soil water in arid regions (Bongi, 2002; Fiorino, 2003; Vitagliano and Sebastiani, 2002). Olive is an ecological (Almeida, 2016), economic (Ramos-Román et al., 2019), and cultural keystone species in the Mediterranean (Ferrara and Ingemark, 2023). Further, it is an important agroforestry tree (Burgess and Rosati, 2018) and is a key species in the Mediterranean drylands of southern Spain which are among the most biodiverse drylands in the world (Maestre et al., 2021). Biological diversity in these drylands is comparable to that found in tropical biodiversity hotspots such as Peninsular Malaysia (Grobler and Cowling, 2022). Additionally, the over 2,000 cultivated olive varieties plus wild olive are foundational as a genetic source for developing climate-adapted cultivars for the Mediterranean olive agroecosystems (Aurelle et al., 2022) and the olive agroforestry systems (Mantovani et al., 2016; Paolotti et al., 2016).

The Mediterranean has long been recognized as a hotspot region where climate change will be amplified compared to the global average (Giorgi, 2006), and yet expected changes in precipitation are less predictable and more spatially variable than warming (Cos et al., 2022). Recent climate projections confirm the Mediterranean is a climate change hotspot with highest temperature increases projected to occur in the Iberian Peninsula and the Balkans (Cos et al., 2022). These changes will impact olive growing in the Mediterranean Basin (Fraga et al., 2021; Ponti et al., 2014), with reduced climate suitability posited for Andalusia most likely linked to reduced precipitation (Arenas-Castro et al., 2020; Fraga et al., 2020). However, projected future changes in precipitation have greater associated uncertainty and spatial heterogeneity than temperature changes over the Mediterranean region (Cos et al., 2022), and this may reduce the reliability of precipitation-based assessments of climate change impacts on olive. Weather affects olive yield directly through its physiology and indirectly by affecting pest organisms such as the obligate olive fruit fly, *Bactrocera oleae* (Rossi) (Caselli and Petacchi, 2021). Olive fly is endemic in the Mediterranean Basin (Katsoyannos, 1992), and is the major pest in most commercial olive-growing regions of the world (Daane and Johnson, 2010; Nardi et al., 2005).

Climate-informed decision-making and policy-making are key to increasing regional resilience (Grafton et al., 2019; Hewitt et al., 2020). The growing awareness of risks arising from climate change increased interest in climate services, defined as: *the provision of data, knowledge information, and assessments that help society manage potential climate risks and impacts resulting in increased resilience to climate change* (Hewitt et al., 2020). In 2015, the European Commission (2015) launched a research and innovation roadmap that recognized climate services have the potential to become the basis for the transition to a climate-resilient low-carbon society. An important component of climate services is the Copernicus Climate Change Service (C3S, 2020, https://climate.copernicus.eu/), one of the six thematic services provided by the European Union's Earth observation program (i.e., the Copernicus program https://www.copernicus.eu/). To this end, the MED-GOLD project was funded by the EU to turn climate-related information into added value (i.e., climate services) for decision and policy-making in traditional Mediterranean grape, olive, and durum wheat food systems (see 10.3030/776467). This paper reports as a MED-GOLD case study a mechanistic assessment of climate change effects on the olive/olive fly system (Gutierrez et al., 2009; Ponti et al., 2009a) in Andalusia.

Problem overview - The perception that nature is too complex to be modeled explicitly as driven by weather, has led to the widespread use of bioclimatic indices as proxies for assessing climate change on natural and agricultural ecosystems. Ecosystems are perceived as being frustratingly complex, temporally variable, and full of direct and indirect interactions among species, preventing holistic assessments of coupled economic-social-ecological systems (see Palladino, 1991). Further, they are viewed as too complex for sufficient realism to be included mechanistically in climate impact assessments (Born et al., 2021; Ceglar et al., 2020; Dormann et al., 2017; Findlater et al., 2021; Loboguerrero et al., 2018; Rangwala et al., 2021). This perception has been a major hindrance to the development of holistic analyses and in developing viable policy and management decisions under projected climate change. The IPCC 6th Assessment Report (IPCC, 2022) stated: "*A challenge for future projections that continues from previous IPCC reports is accurately characterizing and quantifying the interactions of climate change […] that cause ecological change, [and that] can be particularly complex for invasive species, pests, pathogens and human infectious diseases. Modelling of risks at the species level requires […] a mechanistic understanding of functional traits relevant to ecosystem integrity, functioning and resilience to climate change.*" This capacity is prerequisite for analyzing the complexity of agricultural systems under global change, including technological change, invasive species, and climate change (Ponti et al., 2015).

An efficient methodology for decomposing and assessing the complexity of natural and agricultural systems under climate change are weather-driven physiologically based demographic models (CASAS-PBDMs, hereafter PBDMs) that explicitly capture the mechanistic bioeconomics of all species including human economic endeavor, making the predictions independent of time or place (Fig. 1; Gutierrez, 1996). The MED-GOLD project sought to tackle the complexity of assessing climate change effects on agricultural ecosystems wherein each species has different climatic and other requirements for growth, survival, and reproduction that result in myriad possible weather-driven dynamics (e.g., Deutsch et al., 2018; Gutierrez, 1996; Hamann et al., 2021; Lehmann et al., 2020; Renner and Zohner, 2018; Ziska et al., 2018). The PBDM approach used here for modeling tri-trophic agroecosystems (i.e., crop/pest/natural enemy systems) is based on early insights by R.D. Hughes (CSIRO, Australia), N.E. Gilbert (University of British Columbia, Canada), A.P. Gutierrez (University of California at Berkeley, USA), and J.U. Baumgärtner (ETH, Zurich, Switzerland) (Hughes and Gilbert, 1968; Gilbert and Gutierrez, 1973; Gutierrez and Baumgärtner, 1984; Gutierrez, 1996; Baumgärtner, 2017). Continued development and implementation of the PBDM approach have been fostered by the Center for the Analysis of Sustainable Agricultural Systems (CASAS, http://www.casasglobal.org/) with international MED-GOLD project collaborators (10.3030/776467). The theoretical, biological, and economic bases of PBDMs are found in Gutierrez (1992), Gutierrez et al. (1994), Gutierrez and Regev (2005) and Regev et al. (1998). PBDMs have been used to map the regional bioeconomic consequences of crop-pest-natural enemy interactions in several crop systems globally (e.g., cassava, coffee, cotton, grape, and olive; see https://www.casasglobal.org/). Good examples of such analyses are the bio-economic analyses of Indian hybrid Bt cotton and farmer suicides (Gutierrez et al., 2020), and the holistic local analysis of the coffee system (Cure et al., 2020). A quick insight into the PBDM approach is summarized in the short video https://youtu.be/dl69l9l8FAM, with the application in a geographic information system (GIS) context shown herein and illustrated in the manual for stakeholders and practitioners (Supplementary Material, Appendix A).

PBDMs are one of the major technological components and bases of the MED-GOLD project (see 10.3030/776467). The capacity for modeling tri-trophic agroecosystems (i.e., crop/pest/natural enemy systems; Gutierrez, 1996) using PBDM agro-ecosystem models of the olive system was implemented in MED-GOLD on a scalable modern computing platform (ICT platform). Specifically, the PBDM olive/olive fly system (Gutierrez et al., 2009; Ponti et al., 2009a) was implemented using a dedicated Python-based application programming interface (API) accessible via the Web (MED-GOLD consortium, 2023) (i.e., a Web API). An illustration of how the PBDM Web API fits into the MED-GOLD ICT platform is available as infographics (10.5281/zenodo.7928703), together with the instruction manual for stakeholders and practitioners (Supplementary Material, Appendix A). As used here, the MED-GOLD ICT platform supports implementation of legacy PBDM software developed in other computer languages (e.g., Fortran, Borland Pascal, C++) by running and connecting the executables and weather data used to run them (e.g., the Copernicus Climate Data Store, https://cds.climate.copernicus.eu/) (Buontempo et al., 2022; 2020). PBDM functionality in the Web API is independent of the operating systems of client computers. An added advantage is that the PBDM Web API was designed to efficiently scale with increasing computational loads and user requests. The PBDM Web API enables more users and regions to benefit from the PBDM approach. The computer code implementing the PBDM Web API was developed under the auspices of MED-GOLD funding and is open source.

The added value of PBDM analyses accrues in terms of improved agricultural management strategy that provides insights on how best to allocate limited resources for agroecosystem management under ongoing climate change. PBDMs introduce realistic, process-based, and multitrophic biological information layers that may complement the more widely used index-based proxy approach to climate services (Buontempo et al., 2020; Mihailescu and Bruno Soares, 2020; Gratsea et al., 2022; Dell'Aquila et al., 2023) and agroecosystem assessments (Gutierrez et al., 2010).

This study reports a prospective MED-GOLD regional PBDM analysis of the olive/olive fly system in Andalusia under future climate change in a GIS context. The goals of the study were to benchmark the use of PBDMs as part of the MED-GOLD ICT platform as a holistic analysis of the olive/olive fly system under climate change and to enhance delivery of climate services for olive in Andalusia. The following sections outline the methodology used and the application to the olive system in Andalusia.

2. Materials and methods

2.1. Pbdms for olive and olive fly in a climate service context

The underpinning assumption of PBDMs is that analogous demographic and physiological processes occur across trophic levels (Fig. 2) and can be modeled by similar bio-demographic functions (Gutierrez, 1996; 1992; Gutierrez and Baumgärtner, 1984; Gutierrez and Ponti, 2013). The olive/olive fly PBDM explicitly captures the weather-driven biology of the interaction between the olive tree and the olive fruit fly, and predicts prospectively the geographical distribution and relative abundance of the two species across time and space, independent of observed species distribution data, using extant and climate change weather scenarios as drivers of the system (Gutierrez et al., 2009; Ponti et al., 2009a). The mathematical formulation of the models is outlined in the appendix of Gutierrez et al. (2009) and is reviewed here. The weather-driven PBDM was used to simulate the phenology, age-structured growth, and population dynamics of olive and olive fly at different geographic locations and scales (Gutierrez et al., 2009; Ponti et al., 2014, 2009b; 2009a), and is used here to analyze the olive system in Andalusia, Spain.

2.2. Modeling the dynamics of olive and olive fly

Briefly, the per capita age–mass structured population dynamics model of olive and age-structured dynamics of olive fly predict their growth, development, reproduction, and behavior and their interactions (Gutierrez et al., 2009). All biological processes are driven by weather, making the model independent of time and place (see de Wit and Goudriaan, 1978) and are cast in a demographic form (Gutierrez and Baumgärtner, 1984; Gutierrez, 1996). In PBDMs, common processes across trophic levels allow the same population dynamics, functional response, and other vital rate biodemographic models to be used for modeling the number and mass dynamics and interactions of olive and olive fly (Gutierrez et al., 2009). The PBDM for olive consists of the age–mass structured population dynamics of five functional populations ($n = 1 \ldots 5$): the dynamics of olive leaf mass {models $n = 1$}, stem plus shoots {$n = 2$}, root {3} and fruit mass and number {4, 5}. The PBDM for immature olive fly in fruit {6}, and for reproductive and dormant adult olive fly {7, 8} have similar structure. The biology of resource acquisition and allocation (Fig. 3) (Gutierrez and Baumgärtner, 1984; Gutierrez, 1996) is embedded in a distributed maturation time demographic model that simulates the dynamics of age–mass structured populations, where time (t) and age (a) in physiological time units differ for each species (see Fig. 1a in Gutierrez et al., 2009 and see Appendix 2 in Gutierrez et al., 2009 for model values).

The following is the general model for the i-th age class of a population (e.g., plant subunits {1–5} and adult fly {7–8} populations), while a two-dimensional distributed maturation time model is used for olive fly larvae {6} because the eggs are deposited in different age fruit that continue to develop on the plant time scale in response to temperature T, while the egg–larval stages continue to develop on the fly's time scale that changes with T and the age-related quality of fruit (see Gutierrez

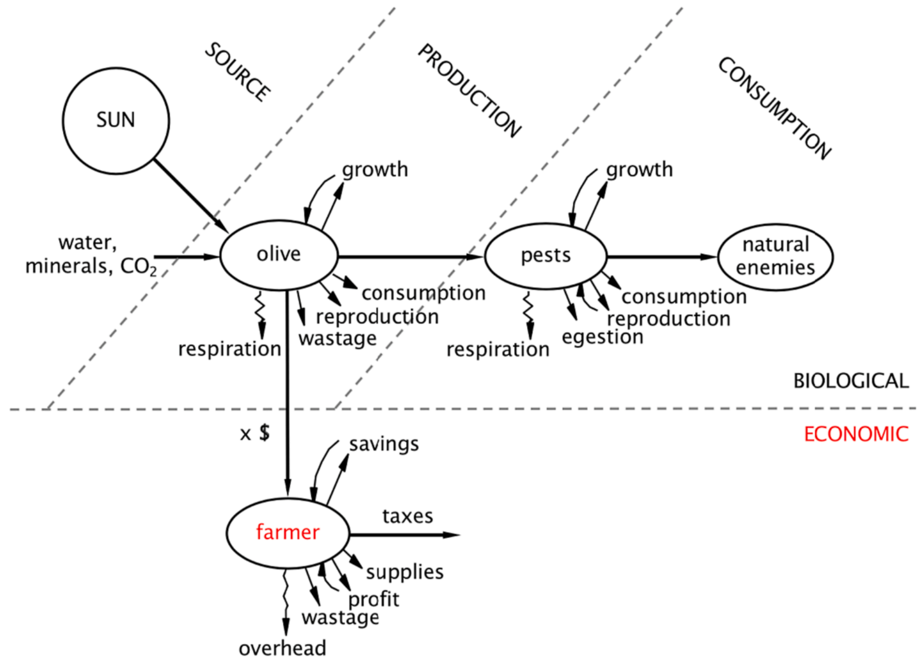

Fig. 2. Conceptual linkages of per capita resource acquisition and allocation across trophic levels including economics of human firm harvesting renewable resources (Gutierrez, 1996).

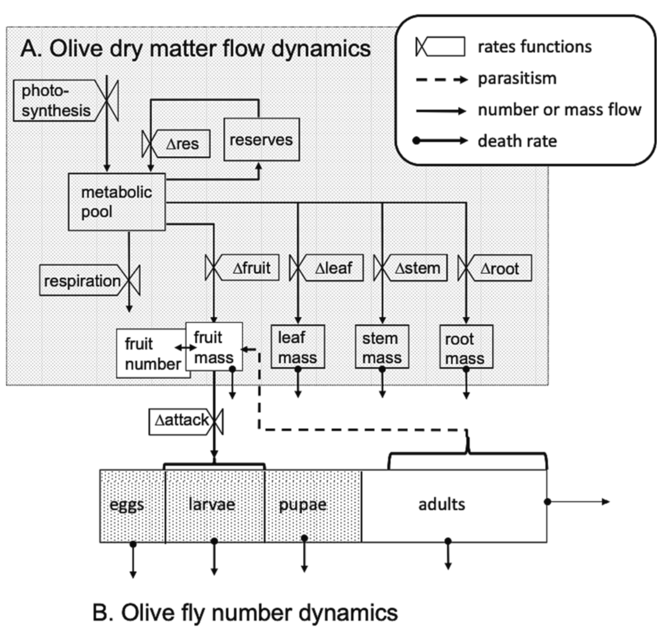

Fig. 3. Multitrophic biology of the olive/olive fly system. (a) Dry matter flow in olive and to olive fly, and (b) dynamics of olive fly number (Ponti et al., 2014). Note that the diapause stage of olive fly is not indicated.

et al., 2009). The dynamics model for any age class *i* within a stage (Manetsch, 1976; Vansickle, 1977) is as follows:

$$\frac{dN_i}{dt} = \frac{k\Delta a(T)}{del}[N_{i-1}(t) - N_i(t)] - \mu_i(t)N_i(t)$$

N_i is the density of the *i*-th cohort of consumer, the Erlang parameter $k = del^2/var$ is the number of different age cohorts, *del* is the expected mean developmental time of a plant subunit or of olive fly with respective variance *var*, Δa is an increment in physiological age at time *t* and temperature *T*, and $-\infty < \mu_i(t) < \infty$ is the proportional net loss rate that includes all age-species specific growth, birth, death and net immigration (see Fig. 1b, c in Gutierrez et al., 2009). The flow (aging) occurs between age classes, and individuals in a cohort emerge at final age with an Erlang distribution with mean and variance of developmental times.

2.3. Climate datasets

Daily weather data (maximum and minimum temperature, precipitation, solar radiation, relative humidity, and wind) to run the linked PBDMs for olive and olive fly were derived from the following sources:

- AgMERRA (Ruane et al., 2015) and AgERA5 (Boogaard et al., 2020) climate forcing datasets for agricultural modeling based on climate reanalysis of observed weather.
- Weather station data provided by the Andalusia government, Junta de Andalusia (IFAPA, 2022).
- EURO-CORDEX (Jacob et al., 2014) climate change projections from regional climate models (RCMs).

A brief description of the climate data used and how they were accessed is as follows. Both AgMERRA and AgERA5 were specifically developed for use in an agroecological modeling context. AgMERRA (144 grid locations for Andalusia, with spatial resolution ~25 km) was created as an element of the Agricultural Model Intercomparison and Improvement Project (AgMIP, https://agmip.org/) to provide consistent, daily time series over the period 1980–2010 (Ruane et al., 2015), and was accessed through the web portal of the Goddard Institute for Space Studies (GISS) of the National Aeronautics and Space Administration (NASA, https://data.giss.nasa.gov/impacts/agmipcf/). The similar but more recent AgERA5 dataset (888 grid locations for Andalusia, with spatial resolution ~10 km) was developed by the C3S (Boogaard et al., 2020), spans a longer period (1979–2018) with a higher spatial resolution, and was accessed through the C3S Climate Data Store (https://cds.climate.copernicus.eu/).

Daily weather station data for the period 2002–2017 were provided by Junta de Andalucía through the Andalusian Institute of Agricultural and Fisheries Research and Training (Instituto Andaluz de Investigación y Formación Agraria, Pesquera, Alimentaria y de la Producción

Ecológica, IFAPA, 2022) web portal (https://www.juntadeandalucia.es/agriculturaypesca/ifapa/riaweb/web/). Data from this source were extracted for the following locations: Jaen, Cordoba, Iznalloz (Granada), Rinconada (Sevilla), Malaga, Gibraleon (Huelva), Basurta-Jerez de la Frontera (Cadiz), and Almeria, corresponding to the eight provinces of Andalusia.

For the climate change PBDM analyses, data were taken from the high-resolution ensemble of regional climate change projections established for Europe in the framework of the Climate Research Program Coordinated Regional Downscaling Experiment (EURO-CORDEX, http://www.euro-cordex.net/) initiative (Jacob et al., 2014), and were recast by the MED-GOLD project specifically to run PBDMs (see Sanderson et al., 2019).

The ensemble of regional climate projections used in the MED-GOLD project (Table 1) was selected based on the following criteria (Bartók et al., 2019):

(1) Model performance criterion, where the selected RCMs should realistically represent the main climate features for both the variables examined and the regional area of interest.
(2) Climate sensitivity criterion, where the sub-ensemble (i.e., the RCMs used, see Table 1) should be selected to represent the climate sensitivity range of the full ensemble of climate models (i.e., how much climate change is predicted by the different models in response to increased GHG concentrations in the atmosphere) so that uncertainties in global climate projections can be accounted for.
(3) The structural diversity (i.e., different model formulation) of global climate models (GCMs) used as boundary conditions for running the selected RCMs is also an important criterion because it avoids undue weight of some model behaviors (Masson and Knutti, 2011).

However, an additional data processing step was implemented in MED-GOLD for PBDMs, using the three out of five RCMs listed in Table 1 that provided the required input variables (daily maximum and minimum temperature, precipitation, solar radiation, relative humidity, and wind) for running PBDM simulations, particularly solar radiation required for running the olive plant model. Hence, PBDM simulations were run using climate change projections from the following three RCMs: CNRM-CM5 RCA4 (537 grid locations, with spatial resolution ~ 12 km), HadGEM2 ES RCA4 (591 grid locations, with spatial resolution ~ 12 km), and ICHEC EC-EARTH RACMO22 (552 grid locations, with spatial resolution ~ 12 km), forced with intermediate (RCP 4.5) and high (RCP 8.5) greenhouse gas (GHG) emission scenarios for the near future (years 2031–2060) and distant future (years 2071–2100), in addition to baseline climate projections under observed GHG concentration for years 1971–2000 (see Table 1; Bartók et al., 2019). The climate change projections data for temperature and precipitation were bias corrected by implementing the empirical quantile mapping (*eqm*) function (Bedia et al., 2020) from the downscaleR software package (Iturbide et al., 2019; Varotsos et al., 2021) using daily gridded observed weather data for Europe from the E-OBS dataset version 19 (Cornes et al., 2018; C3S, 2020). Bias correction is the process of adjusting climate model outputs to account for their systematic errors relative to observations (see e.g., Thrasher et al., 2013).

The first criterion (i.e., model performance criterion) was evaluated under the MED-GOLD project by comparing the output of the selected regional climate models with the E-OBS observed weather data version 17 (Haylock et al., 2008) for temperature and precipitation during years 1971–2000 in Andalusia, showing that the selected regional climate projections capture well the spatial and temporal variability of the observed climate (Sanderson et al., 2019). The second (climate sensitivity criterion) and the third criteria (diversity of GCMs) were used by Bartók et al. (2019) for the European domain to select the five RCMs listed in Table 1.

Table 1
List of Regional Climate models used in the MED-GOLD project (see Bartók et al., 2019).

Institutional acronym	Regional climate model	Driving global climate model
SMHI	RCA4	HadGEM2-ES
SMHI	RCA4	CNRM-CERFACS-CNRM-CM5
IPSL-INERIS	WRF331F	IPSL-IPSL-CM5A-MR
KNMI	RACMO22E	ICHEC-EC-EARTH
MPI-CSC	REMO2009	MPI-M−MPI−ESM−LR

Definition of institutional acronyms: SMHI, Swedish Meteorological and Hydrological Institute; IPSL, Institut Pierre-Simon Laplace, France; INERIS, French National Institute for Industrial Environment and Risks; KNMI, Royal Netherlands Meteorological Institute; MPI, Max Planck Institute for Meteorology, Germany; CSC, Climate Service Center, Helmholtz-Zentrum Geesthacht, Germany). Additional information on regional and global climate models listed can be found in (Bartók et al., 2019) and publications cited therein.

2.4. Simulation design and analyses

Many aspects of the daily age-mass structured dynamics of olive and olive fly are computed by the model but only the following are reported here: (i) chilling accumulation for release of flower bud dormancy (hour degrees below 7.3 °C, HD < 7.3 °C), (ii) Julian bloom dates (days after 1st January), (iii) season yield (relative olive fruit weight in grams of dry matter per tree), and (iv) fruit infestation levels by olive fly (percent fruit attacked) in the absence of control. A larger subset of variables is available and listed in Supplementary Figures and Tables (Supplementary Material, Appendix B) including: (v) annual precipitation (mm per year), (vi) freezing degree days below −8.3 °C, (vii) season length for olive (degree days above the olive thermal threshold of 9.1 °C), and (viii) olive fly pupae per season (cumulative pupae per season per tree). Appendix B (Supplementary Material) reports area statistics for all the eight variables listed above for each of the eight provinces of Andalusia, computed using the *r.report* GRASS module (GRASS Development Team, 2022). Soil moisture was assumed non-limiting in our study given the ability of the crop to resist prolonged drought (Fernandez and Moreno, 1999; Connor and Fereres, 2005; Sofo et al., 2008). The effect of soil moisture could be implemented in the future as needed given appropriate soil data (see Ponti et al., 2013). Further justification is that olive yield is affected most by rainfall in the previous fall and winter (Gratsea et al., 2022; Rapoport et al., 2012; Rodrigo-Comino et al., 2021), but projected precipitation changes during winter have high uncertainty across climate models, scenarios, and time periods in Andalusia (Cos et al., 2022). Hence, excluding the effect of soil water on olive gives an assessment of climate warming projected to be higher in the Mediterranean Basin than in the rest of the globe, and be highest during summer in Andalusia (Cos et al., 2022).

Using daily weather data as input, model runs were carried out via batch processing across years and locations, and the geo-referenced summary output data were written to an output text file by year for GIS processing and mapping. The same initial conditions for olive and olive fly were used at all locations, and the model was run continuously with a daily time step across the simulation periods from 1 January of the first year to 31 December of the last year of each period: 1980 to 2010 for AgMERRA; 1979 to 2018 for AgERA5; 2002 to 2017 for weather stations; and for 1971 to 2000, 2031 to 2060, and 2071 to 2100 for each of the three EURO-CORDEX regional climate models. The first year of simulation allowed the model dynamics to equilibrate to local weather, and hence these data were not used to compute means and coefficients of variation of the output variables.

2.5. GIS analysis

All GIS layer datasets used in the analysis are available online as open access (Ponti et al., 2023), and most of them were sourced from the public domain repository *Natural Earth* (https://www.naturalearthdata.com/). The open source GIS software GRASS (GRASS Development Team, 2022; Neteler et al., 2012) (see http://grass.osgeo.org/) was used to map PBDM output data. Inverse distance weighting or bicubic spline interpolation was used to map model output as a continuous raster surface, and hence the spatial patterns reflect not only the site-specific effects of weather on the biology of the species but also the resolution and coordinate reference system of the weather grids. The digital elevation model used has a 1-km resolution (GeoTIFF file elevation_1KMmd_GMTEDmd; Amatulli et al., 2018).

The GRASS-based GIS mapping and analysis of PBDM model output is custom software (*map.pbdm.andalusia*) written in the Bash shell scripting language that uses a wide variety of GRASS modules to map output and to generate an HTML summary of maps, plots, and statistics. The script includes a graphical user interface (GUI) for easier user interaction (see Supplementary Material, Appendix A).

The output of the olive/olive fly PBDM system model is mapped for Andalusia as clipped for the SIGPAC olive growing area (Sistema de Información Geográfica de Parcelas Agrícolas, Geographic Information System for Agricultural Plots, https://www.mapa.gob.es/es/agricultura/temas/sistema-de-informacion-geografica-de-parcelas-agricolas-sigpac-/). SIGPAC olive growing areas of Andalusia were generated from the Spanish SIGPAC 2018 cadastral vector dataset filtered through an SQL query selecting plots that include olive trees (see http://www.juntadeandalucia.es/agriculturaypesca/sigpac/). Visualization of PBDM output mapped for SIGPAC olive growing areas was enhanced using a 3-km buffer that makes the fine spatial detail of the SIGPAC areas easier to grasp visually on maps included in figures (see Results), but still retain a similar shape. The raster statistics reported in the tables (see Supplementary Material, Appendix B, Supplementary Figures and Tables) were computed based on the original SIGPAC olive growing area. Raster layers generated from PBDM model output variables are mapped using the Turbo color map (Mikhailov, 2020) to maximize the capacity to discriminate between different values (i.e., graphical inference; see Reda and Szafir, 2021). Raster layers representing change in PBDM model output variables under climate change are mapped using ColorBrewer schemes (Brewer, 2022).

Maps for present climate results are based on AgERA5 climate data, a downscaled and bias-corrected version of the global reanalysis ERA5 (Hersbach et al., 2020) tailored to the needs of most agricultural and agro-ecological models. Similar but coarser resolution results obtained using AgMERRA climate data can be found in Figs. B1-B8, Tables B1-B8 in Appendix B. AgERA5 is a more recent climate dataset having a higher spatial resolution similar to that of the climate change data.

All data generated from PBDM simulations and GIS analysis for the present study, as well as the base geographic layers used to make maps, are available online as open access data at 10.5281/zenodo.4721903 (Ponti et al., 2023).

2.6. Integrating PBDMs into the MED-GOLD ICT platform

Over the last four decades, valuable heritage software has been developed in Fortran, Borland Pascal, C++, and other languages and computer-specific systems (Windows, Linux, DOS, etc.). The MED-GOLD ICT platform was designed to support the integration of executables of this heritage PBDM software by connecting them to AgMERRA, AgERA5, and EURO-CORDEX weather data. This capacity enables PBDM functionality as a Web API that works independent of client computer operating systems. An added advantage that is critical in the provision of climate services is that the cloud-based MED-GOLD ICT computing infrastructure can scale efficiently with increasing computational loads and user requests. The integration of PBDMs in a cloud computing platform was developed by cloud engineer Federica Stocchino under the auspices of project partner Lutech.

Integration of the Pascal-based PBDM for olive and olive fly into the ICT platform required development of several interface components. First, an adapter was required that reads and converts climate data files from their native NetCDF or GRIB binary format to the CSV text format used as input by the PBDMs that in some cases involves conversion of units (e.g., Fahrenheit to Celsius degrees) and computation of daily values for climate variables that are provided on a different time step in the binary source file. Second, to run simulations, a Windows environment is provided by the ICT platform as a virtual machine to run Windows executable PBDMs. Third, access to all this functionality is made available using a Web API. In our analysis, PBDM simulations were run using the PBDM Web API (MED-GOLD consortium, 2023; see details in Supplementary Material, Appendix A, manual for stakeholders and practitioners). A shortcoming of the system is that additional financial resources will be needed to extend operation of the PBDM Web API on cloud computing beyond the MED-GOLD project.

3. Results

As a preamble, we must keep in mind the following caveats:

1. PBDMs are designed for strategic analysis rather than tactical forecasting or precise predictions of olive yield and infestation level.
2. The limiting effect of rain on olive yield and of relative humidity (or vapor pressure deficit) on fly vital rates were not included. Consequently, despite the high degree of drought tolerance in olive (Fernandez and Moreno, 1999; Connor and Fereres, 2005; Sofo et al., 2008), yield effects may not be captured in years with extremely low winter rainfall < 300 mm (see Ponti et al., 2021).
3. PBDM simulations of yields and fly infestation levels are compared to subjective assessments by MED-GOLD industrial partner DCOOP (https://www.dcoop.es/) of good and bad years for olive oil production across the major olive growing areas of Andalusia (see description of criteria for good vs. bad years in Ponti et al., 2021).
4. The plots and maps and the Supplementary Figures and Tables (Appendix B) refer to 144 (AgMERRA), 888 (AgERA5), or 537 to 591 weather grid locations (regional climate models), and eight locations, one in each of the eight Andalusian provinces (line plots) representing a range of regional climatic conditions.

With the above caveats, PBDM predictions provide metrics of relative abundance and geographic distribution of olive stages and yield, and of olive fly infestation levels under observed and projected future climate scenarios. Reference maps for rainfed and irrigated olive production in Andalusia (Fig. 4) are useful for interpreting PBDM/GIS maps in the following sections.

3.1. Olive phenology and yield

Using downscaled and bias-corrected weather data from the ensemble of three EURO-CORDEX regional climate models (see Methods) to run the PBDM, four maps accrue for combinations of intermediate (RCP 4.5) and high (RCP 8.5) GHG emission scenarios (map rows) and for the near (2031–2060) and distant (2071–2100) future time periods (map columns). Hence, each map shows average values of PBDM simulations run using output from the three regional climate models. Further, a simulation run under observed GHG concentration for years 1971–2000 for each EURO-CORDEX regional climate model is used as a baseline to compute changes between future and baseline PBDM simulations. The projected changes in PBDM output variables under climate change ($Change_{PBDM} = Future_{PBDM} - Baseline_{PBDM}$) are shown either directly in maps of projected changes (positive or negative) or added to PDBM variables simulated based on AgERA5 climate data for years 1980–2018 used to develop maps of projected future values for the different PBDM variables. Finally, to ease comparison between the four maps of the two time periods x two GHG scenarios showing the effect of climate change on the different PBDM variables (presented as either projected changes or projected future values), the same color legend is

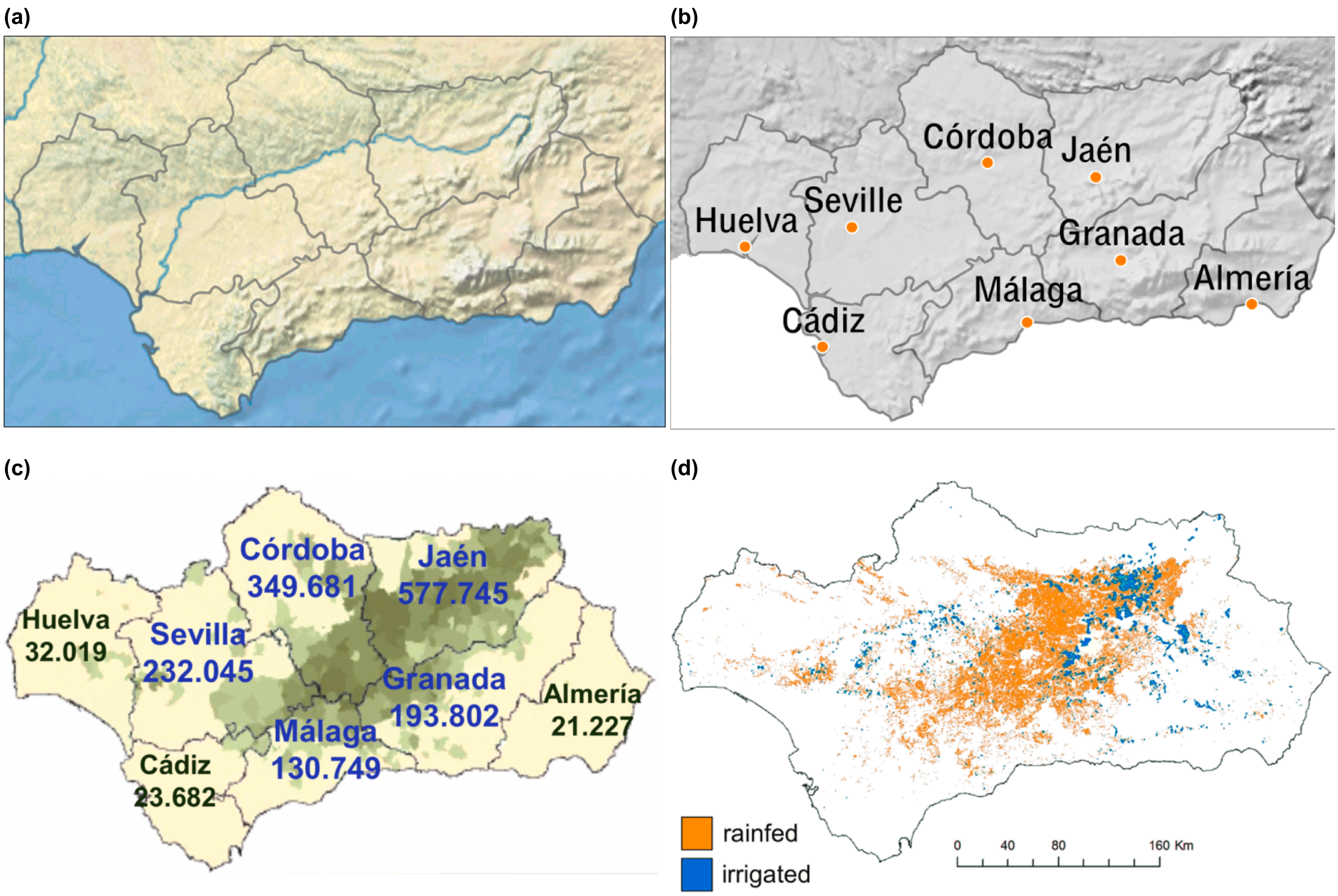

Fig. 4. Reference maps for Andalusia, Spain: (a) shaded relief and land cover coloring based on satellite observations; (b) provinces of Andalusia; (c) olive growing area (hectares) in each province (total olive growing area 2017–2018 is 1,561,950 ha of which 77.22 % is rainfed; Yearbook of Agricultural and Fisheries Statistics and Agricultural Census, Junta de Andalucía, https://www.juntadeandalucia.es); (d) rainfed (orange) and irrigated (blue) olive growing area (modified from Carpio et al., 2016). (a) and (b) were developed from data available at http://www.naturalearthdata.com/.

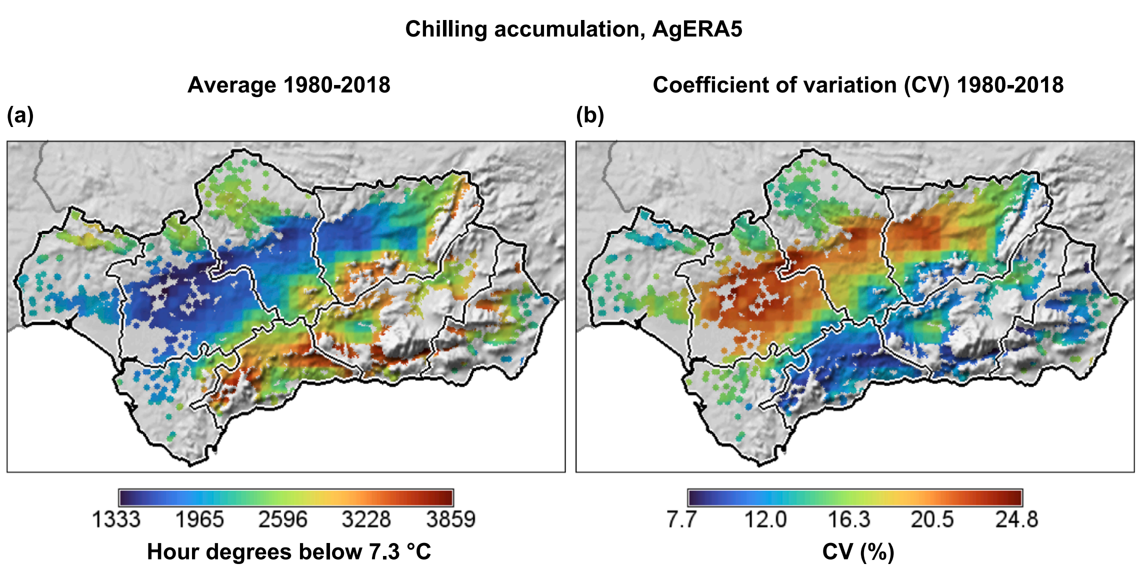

Fig. 5. Chilling (hour degrees below 7.3 °C) accumulation for release of flower bud dormancy in Andalusia, Spain, mapped as averages (a) and coefficient of variation (b) as projected by the PBDM using downscaled bias-corrected AgERA5 observed reanalysis weather for the period 1980–2018. About 450 h < 7.3 °C are required to stimulate spring fruit bud initiation leading to flowering in olive (De Melo-Abreu et al., 2004; see Gutierrez et al., 2009).

used that extends from the minimum value to the maximum value across the four maps. For delta change maps, the zero-change value is always located at the separation line between the blue (negative) and the orange (positive) section of the color legend.

Chilling requirements for blooming – A reference minimum chilling accumulation threshold of 450 HD < 7.3 °C (hour degrees below 7.3 °C) is posited required for successful olive blooming (De Melo-Abreu et al., 2004). Under present climate (1980–2018), average HD < 7.3 °C is lowest with highest variability (Fig. 5a and 5b, respectively) in the Guadalquivir River Valley (blue line in Fig. 4a that crosses the Jaen, Cordoba, and Seville provinces), while higher chilling accumulation with lower variability occurs at higher altitudes. However, with climate change, HD < 7.3 °C is projected to decrease, with large areas in the top olive-producing provinces of Jaen, Cordoba, and Sevilla not meeting the threshold value.

Under climate change, chilling required for olive blooming is projected to decrease progressively from period 1971–2000 baseline values, with the smallest decreases predicted by the intermediate GHG emission scenario for 2031–2060, and the highest changes in the high GHG emission scenario towards the end of the century (2071–2100) (Fig. 6).

Annual accumulated HD < 7.3° C decrease along the four combinations of GHG emission scenarios and time periods (Fig. 7). Chilling requirements are met in all areas based on the intermediate GHG emission scenario during the 2031–2060 period (Fig. 7a), but areas of the Sevilla and Cordoba provinces fail to meet requirements during 2071–2100 (Fig. 7b). Using the high GHG emission scenario, small areas in the province of Sevilla will fail to meet the chilling threshold for blooming during the 2031–2060 period (Fig. 7c), but during 2071–2100 large areas Jaen, Cordoba, and Sevilla provinces are predicted to fail to meet the reference minimum chilling threshold (Fig. 7d). Supplementary Figs. B4, B12, B32-B35 and Tables B4, B12 in Appendix B provide further detail and area statistics.

Bloom dates – Under present climate (1980–2018), olive blooming occurs earlier with higher variability in the Guadalquivir River valley, while later blooming with lower variability occurs at higher altitudes (Fig. 8).

Under climate change, olive is projected to bloom earlier than under present climate across Andalusia (Fig. 9), with bloom dates getting earlier along the four combinations of GHG emission x time period scenarios, with earliest bloom occurring under the high GHG emission scenario towards the end of the century (Fig. 9d, See Supplementary Figs. B5, B13, B36-B39 and Tables B5, B13 in Appendix B for further detail and area statistics.

Changes in bloom date with climate change were estimated by subtracting the baseline climate estimates (years 1971–2000) from future climate estimates for years 2031–2060 or distant future years 2071–2100; see Fig. 10). The changes in olive bloom dates across Andalusia for the four combinations of GHG emission x time period scenarios are illustrated in Fig. 10. The smallest changes are predicted for the near term under the intermediate GHG emission scenario (Fig. 10a), with the highest changes predicted under end of century with high GHG emissions when predicted blooming occurs four to five weeks earlier in large areas of Jaen, Cordoba, Sevilla, and Granada provinces and five to seven weeks earlier in parts of Malaga (Fig. 10d).

Olive yields – Under present climate, relatively high olive yields with low variability are predicted in much of Andalusia (Fig. 11a and

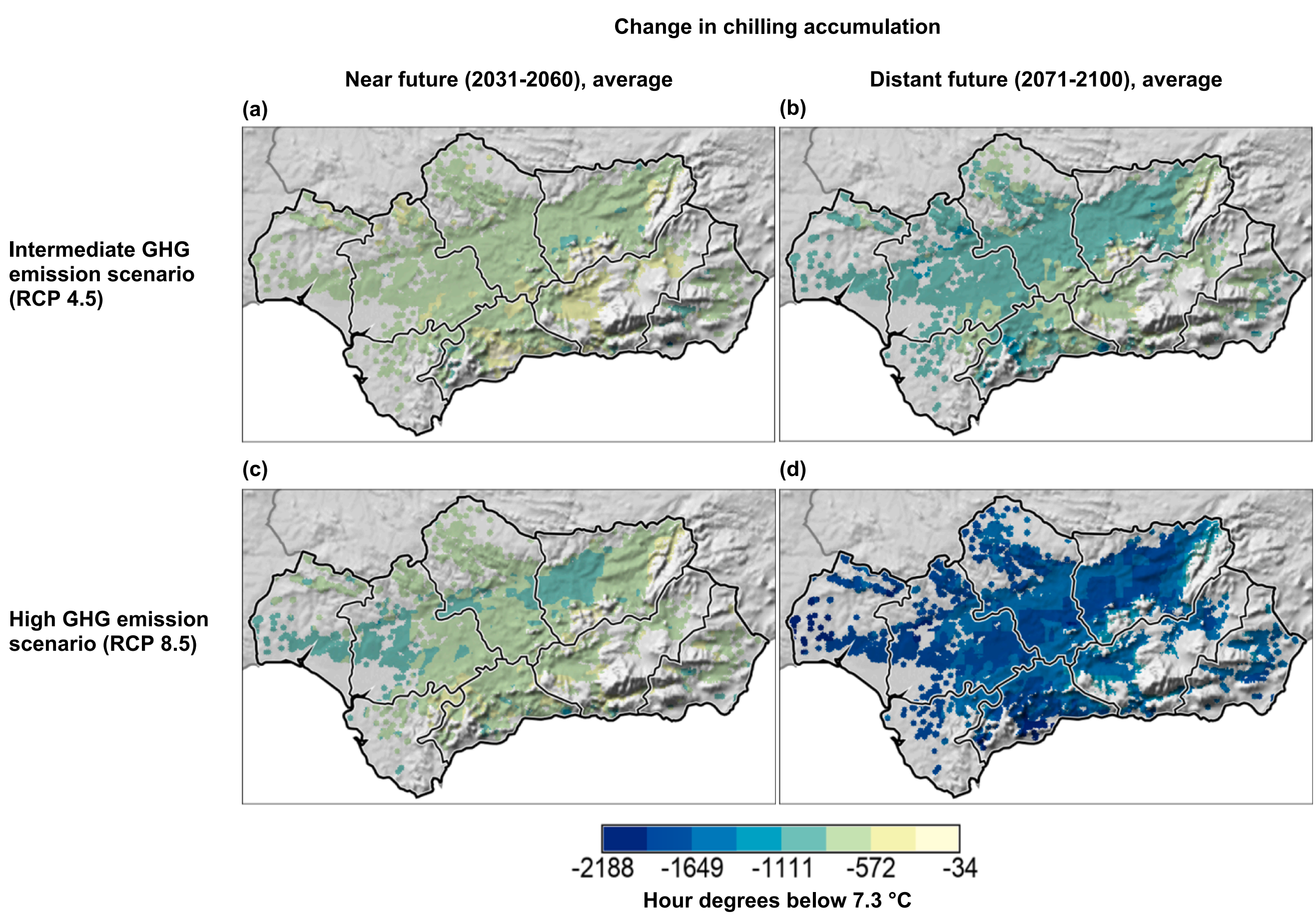

Fig. 6. Average projected decreases in chilling accumulation (hour degrees below 7.3 °C) for release of flower bud dormancy under climate change in Andalusia, Spain from the baseline period 1971–2000. Mean ± SD: (a) −654.8 ± 108.6; (b) −880.6 ± 127.0; (c) −751.2 ± 123.6; (d) −1623.01 ± 158.3. About 450 h < 7.3 °C are required to stimulate spring fruit bud initiation leading to flowering in olive (see De Melo-Abreu et al., 2004; see Gutierrez et al., 2009).

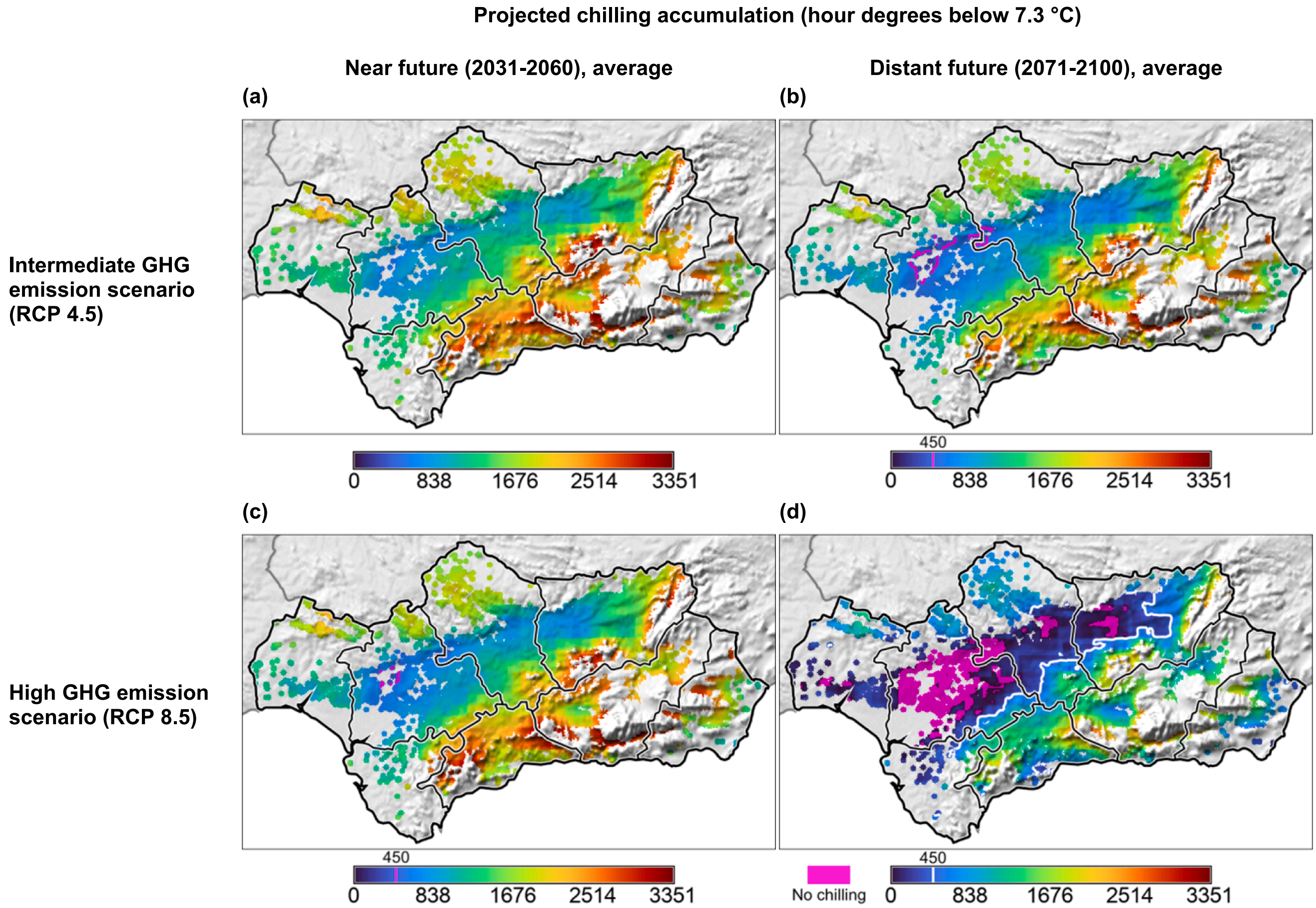

Fig. 7. Average projected chilling accumulation (hour degrees below 7.3 °C) for release of flower bud dormancy (see Gutierrez et al., 2009) under climate change in Andalusia, Spain. About 450 h < 7.3 °C are required to stimulate spring fruit bud initiation leading to flowering in olive (see Gutierrez et al., 2009). Maps show projected changes from baseline period 1971–2000 (Fig. 6), added to PBDM simulation output based on AgERA5 observed reanalysis weather for the period 1980–2018 (Fig. 5). The isolines in (b), (c), and (d) indicate chilling accumulation of 450 h < 7.3 °C. Areas colored in magenta in (d) indicate that no chilling accumulation below 7.3 °C is projected.

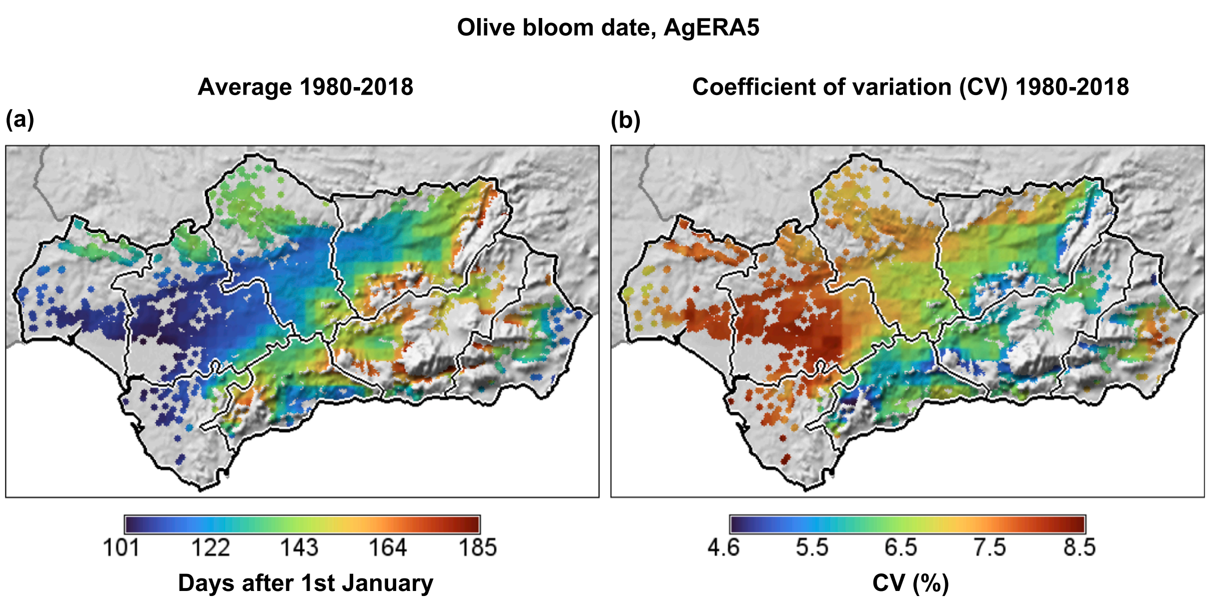

Fig. 8. Olive bloom date (days after 1st January) (see Gutierrez et al., 2009) in Andalusia, Spain: average (a) and coefficient of variation (b) as projected by the PBDM using downscaled bias-corrected AgERA5 observed reanalysis weather for the period 1980–2018.

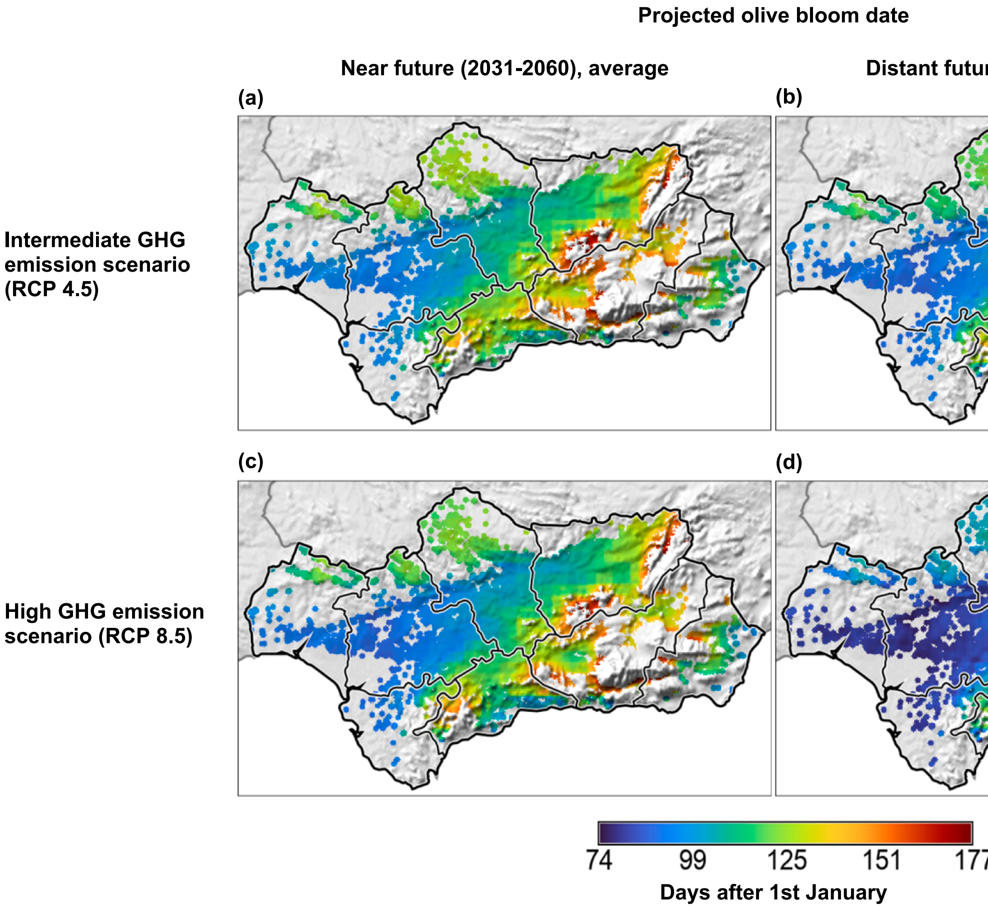

Fig. 9. Average projected olive bloom date (days after 1st January) (see Gutierrez et al., 2009) under climate change in Andalusia, Spain. Maps show projected changes from baseline period 1971–2000 (Fig. 10), added to PBDM simulation output based on AgERA5 observed reanalysis weather for the period 1980–2018 (Fig. 8).

Fig. 11b, respectively) (see histograms in Supplementary Fig. B14, Appendix B).

Under climate change, yields in the top olive-producing provinces of Jaen and Cordoba will move toward the midrange, while yields in Sevilla, Huelva, and Cadiz will remain in the upper range (Fig. 12 vs. Fig. 11).

Olive fruit yields depend on factors such as tree size, age, and weather, and hence projected yields are relative metrics (see Ponti et al., 2014). In Andalusia, relative yields are projected to increase or remain stable under climate change across the GHG emission x time horizon scenarios (Fig. 13), with highest increases expected in the southeastern provinces of Malaga, Almeria, and Granada in the distant future x high GHG emissions scenario (Fig. 13d). See also Supplementary Figs. B6, B14, B40-B43 and Tables B6, B14 in Appendix B for further detail and area statistics. A detailed discussion of how PBDM predictions of olive yield should be interpreted can be found in the Supplementary Information appendix of Ponti et al. (2014).

3.2. *Olive fly infestation*

Under present climate, predicted olive fly infestation (% olive fruit attacked) without control in the Guadalquivir River valley is lower (i.e., in the midrange) with higher variability compared to higher infestations levels in other areas of Andalusia (Fig. 14a, b) (cf. histograms in Supplementary Fig. B16, Appendix B). Projected high temperatures in the Guadalquivir River valley adversely affect fly vital rates (Gutierrez et al., 2009) resulting in lower fly densities and infestation rates.

Under climate change, increased temperatures will decrease olive fly infestations generally (Fig. 15), with the most notable decreases occurring in the top-producing Andalusian provinces of Jaen, Cordoba, and Sevilla under the high GHG emission x end of the century scenario (Fig. 15d). However, under the other three scenarios, olive fly infestations are predicted to increase in the southeastern provinces of Almeria, Granada, and Malaga where temperatures remain more favorable, especially under the near future scenarios (Fig. 15a and 15c), but less so under the distant future scenario with intermediate GHG emissions (Fig. 15b).

High increased risk of olive fly infestation is predicted in the southeastern provinces of Almeria, Granada, and Malaga for both the near-future scenarios (Fig. 16a and c) and distant future scenario of intermediate GHG emissions (Fig. 16b). In contrast, the top-producing provinces of Jaen, Cordoba, and Sevilla gradually move toward a lower risk level when compared to present climate. In the distant future scenario of high GHG emissions, infestations decrease in the provinces of Jaen, Cordoba, and Sevilla to the lower quarter of the infestation range, with some areas falling below a reference economic threshold of 4 % (magenta isolines; Viggiani, 1989; see Kapatos and Fletcher, 1983) (Fig. 16d). In this extreme scenario, olive fly infestation risk also decreases in the southeastern provinces (see Fig. 15d) as temperatures approach the upper thermal limit of the fly (see Gutierrez et al., 2009). See also Supplementary Figs. B7, B8 B15, B16, B44-B41 and Tables B7, B8 B15, B16 in Appendix B for further detail and area statistics.

3.3. *Good and bad years for olive production*

Simulated patterns of olive yield and olive fly infestation in the “good

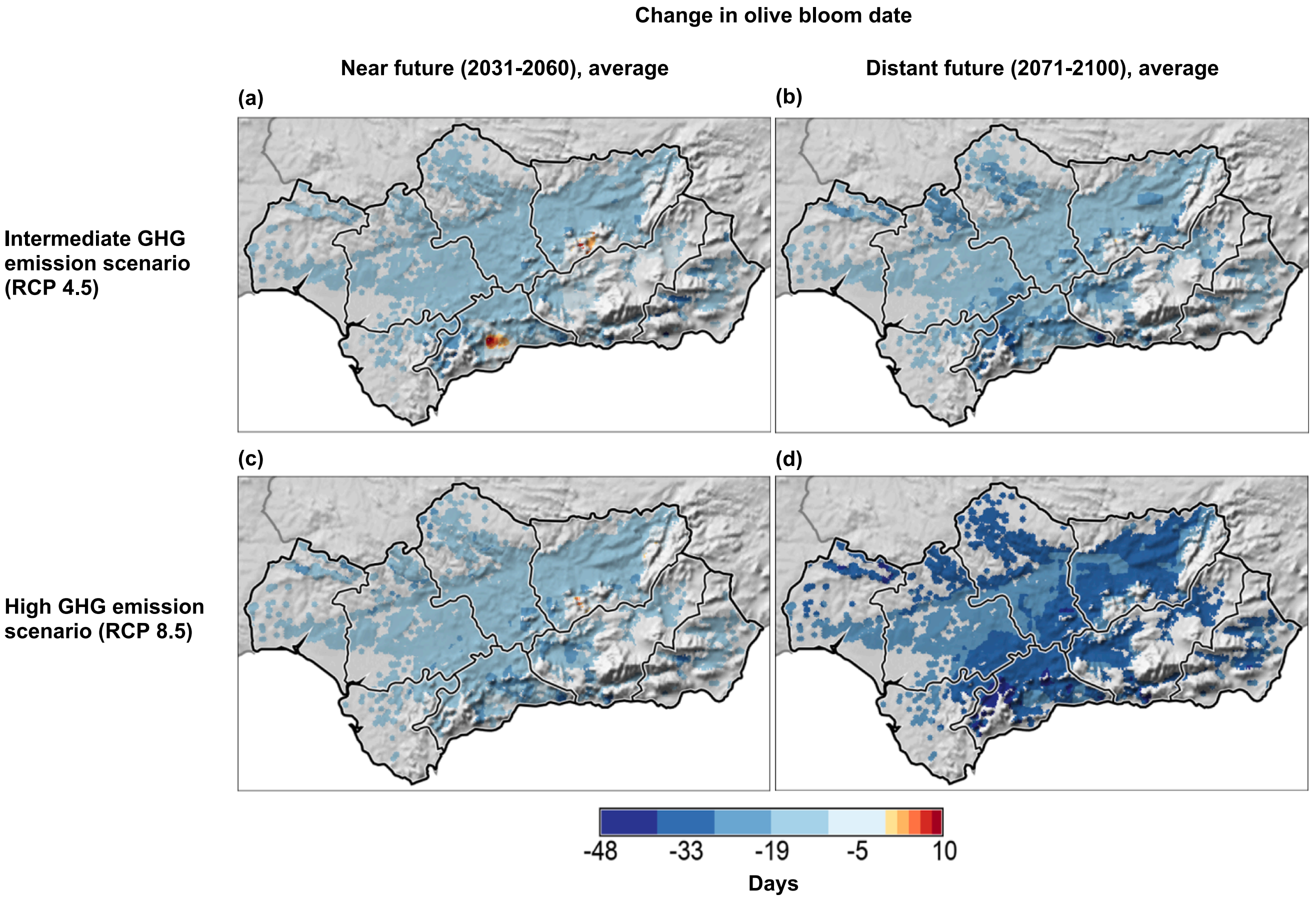

Fig. 10. Average projected changes in olive bloom date (days after 1st January) (see Gutierrez et al., 2009) under climate change in Andalusia, Spain from the baseline period 1971–2000. Mean ± SD: (a) −12.4 ± 3.9; (b) −17.5 ± 3.5; (c) −15.8 ± 2.9; (d) −30.5 ± 4.2.

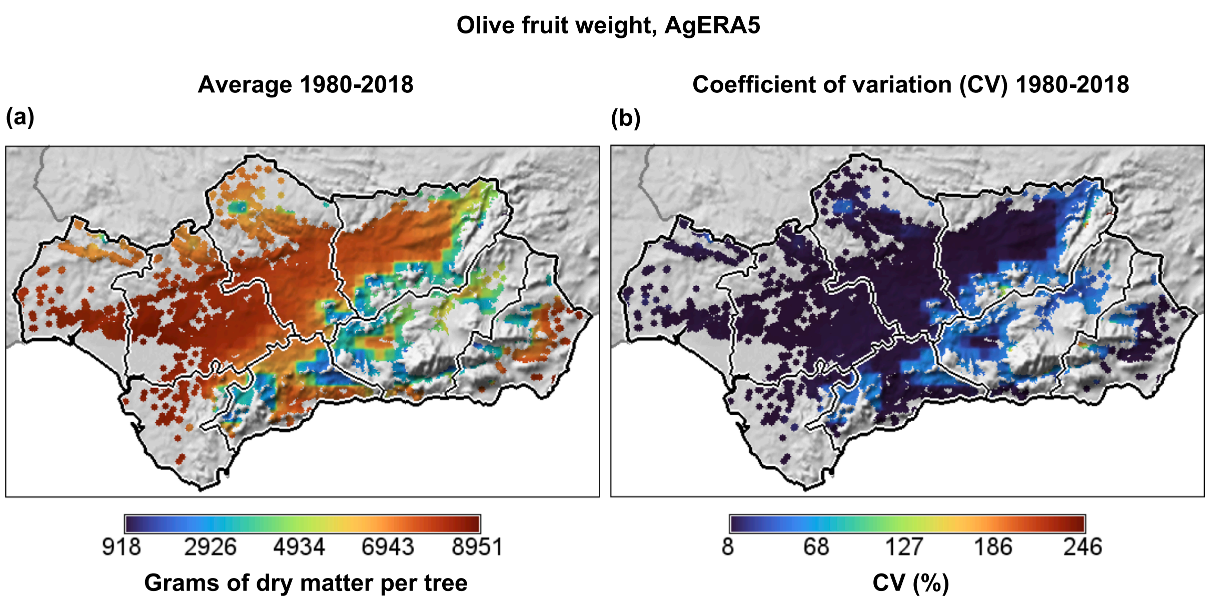

Fig. 11. Relative olive fruit weight (grams of dry matter per tree) in Andalusia, Spain (see Gutierrez et al., 2009), mapped as average (a) and coefficient of variation (b) as projected by the PBDM using downscaled bias-corrected AgERA5 observed reanalysis weather for the period 1980–2018. Values in the top half of the color legend in (b) are located in small areas at high elevations in the provinces of Jaen, Granada, and Almeria.

and bad years" identified by DCOOP collaborators (Ponti et al., 2021) are reasonably well captured by the PBDM as low yield and high infestation years using weather station data. PBDM simulations for Jaen in Jaen Province are shown as an example (Fig. 17), while plots using weather stations data for locations in Cordoba (Cordoba Province), Iznalloz (Granada), Rinconada (Sevilla), Malaga (Malaga), Gibraleon

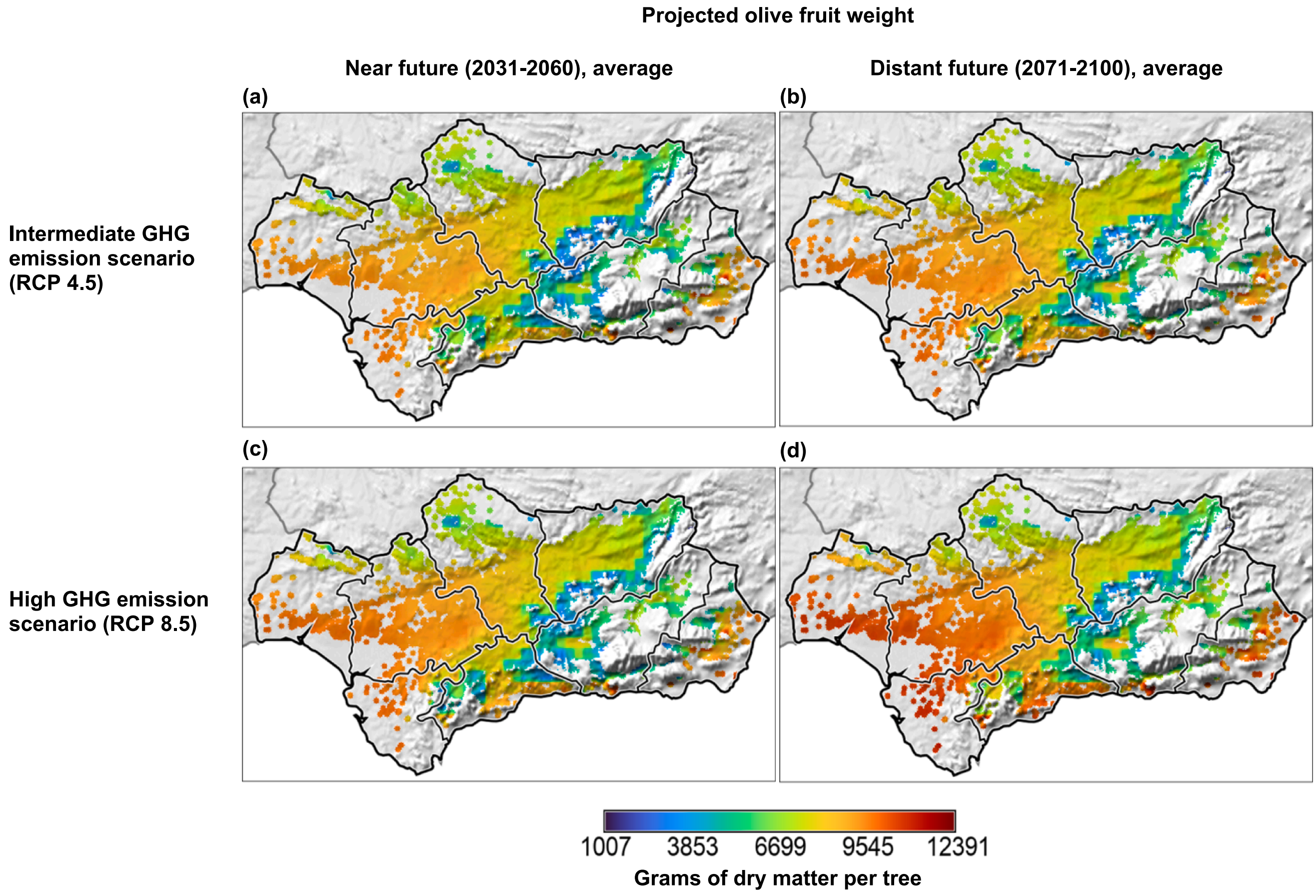

Fig. 12. Average projected relative olive fruit weight (grams of dry matter per tree) (see Gutierrez et al., 2009) under climate change in Andalusia, Spain. Maps show projected changes from baseline period 1971–2000 (Fig. 13), added to PBDM simulation output based on AgERA5 observed reanalysis weather for the period 1980–2018 (Fig. 11).

(Huelva), Basurta-Jerez de la Frontera (Cadiz), and Almeria (Almeria) are summarized in Supplementary Fig. B19 (Appendix B). Yearly maps using AgERA5 data for the entire region of Andalusia are summarized in Supplementary Figs. B17 and B18 (Appendix B).

Except for 2015, the simulation captures the observed pattern of good and bad years for olive production for Jaen in Jaen Province (Fig. 17). The year 2005 had poor olive production, while 2013 was a good year. The 2004–2005 olive season was recorded as having particularly low yields for the Jaen Province when compared to yield estimates provided by the Andalusian government in December 2004 and February 2005, for errors of 192.8 % and 104.2 %, respectively (Galán et al., 2008). The differences are likely the result of severe frost in January 2005 (see temperature plot in Fig. 17) that was reported to kill entire olive trees in Spain (Hammond, 2005; Schwager, 2010). The same results are observed in the simulation plots based on weather station data from each of the locations in each of the eight Andalusian Provinces (Supplementary Fig. B19) and clearly in the yearly simulation maps for Andalusia (Supplementary Fig. B17). In the absence of pest control, high olive fly infestation years were 2008, 2014, and to some extent 2011. This result is also seen in the predicted yearly maps for Andalusia (Supplementary Fig. B18).

4. Discussion

Globally, an important step in enhancing the use of climate services for stakeholders in the agri-food value-chain is the development of methods that enhance the capacity of scientists to mechanistically assess the complex effects on yield and sustainability of biotic (e.g., crop, pests, and natural enemies) and abiotic (e.g., climate) components of the agroecosystem (Beveridge et al., 2018; Challinor et al., 2017; Cuddington et al., 2013; European Commission, 2015; Gutierrez et al., 2010; IPCC, 2022). This is a prerequisite for managing the complexity of agricultural systems, the complexity of which will likely increase under future global change (e.g., see Ponti et al., 2015). A methodology for assessing this complexity are weather-driven physiologically based demographic models (PBDMs) that model mechanistically the bio-economic biology of all species including human economic endeavor in the system (Gutierrez, 1992; Regev et al., 1998). PBDMs have been used to map the regional bioeconomic consequences of weather-driven crop-pest-natural enemy interactions in several crop systems globally (e.g., cassava, coffee, cotton, grape, and olive) with excellent recent examples provided by Cure et al. (2020) and Gutierrez et al. (2020).

The linked PBDM models for olive and olive fly as driven by weather (Gutierrez et al., 2009) were tested against field data for the island of Sardinia where it reliably predicted olive bloom dates (Ponti et al., 2009a). The effects of climate change on relative olive yield were simulated based on eco-physiological data in the literature (Gutierrez et al., 2009). The olive fly component of the PBDM (Gutierrez et al., 2009) was implemented by Blum et al. (2015) in Israel to successfully simulate seasonal population dynamics of olive fly, using release-recapture field data to assess population density (Rempoulakis and Nestel, 2012). However, our PBDM/GIS based analysis of the olive/olive fly system should be considered a heuristic tool rather than a tool for predicting yield locally or regionally in Andalusia (and elsewhere) under climate change.

The PBDM models are driven by observed (including reanalysis of observed weather) and climate model data. In the Mediterranean region, climate warming as projected by climate models is (i) statistically

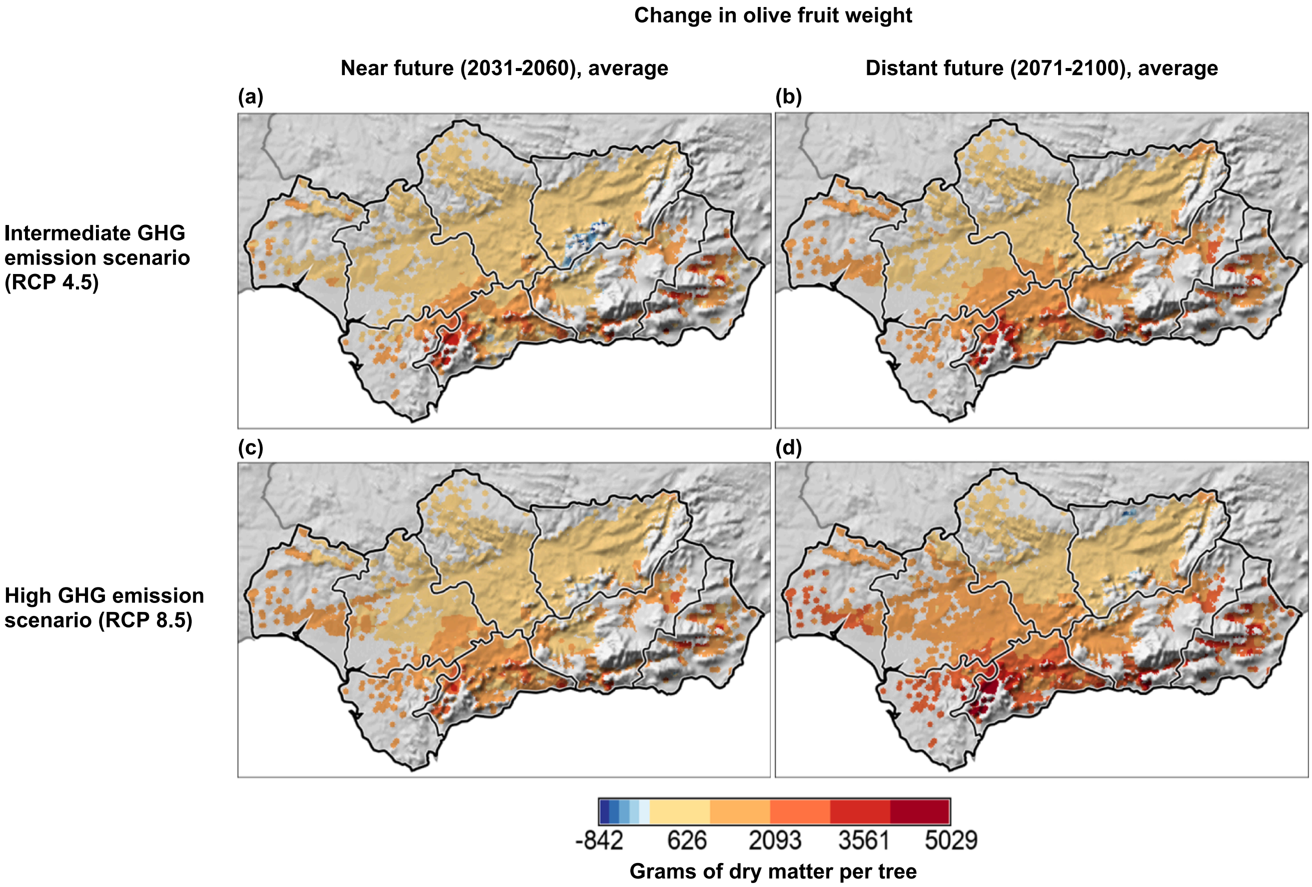

Fig. 13. Average projected change in relative olive fruit weight (grams of dry matter per tree) (see Gutierrez et al., 2009) under climate change in Andalusia, Spain from the baseline period 1971–2000. Mean ± SD (% change with respect to Fig. 11a): (a) 774.3 ± 610.2 (+11.9); (b) 1034.0 ± 631.8 (+15.9); (c) 938.0 ± 517.4 (+14.4); (d) 1394.2 ± 857.7 (+21.5 %).

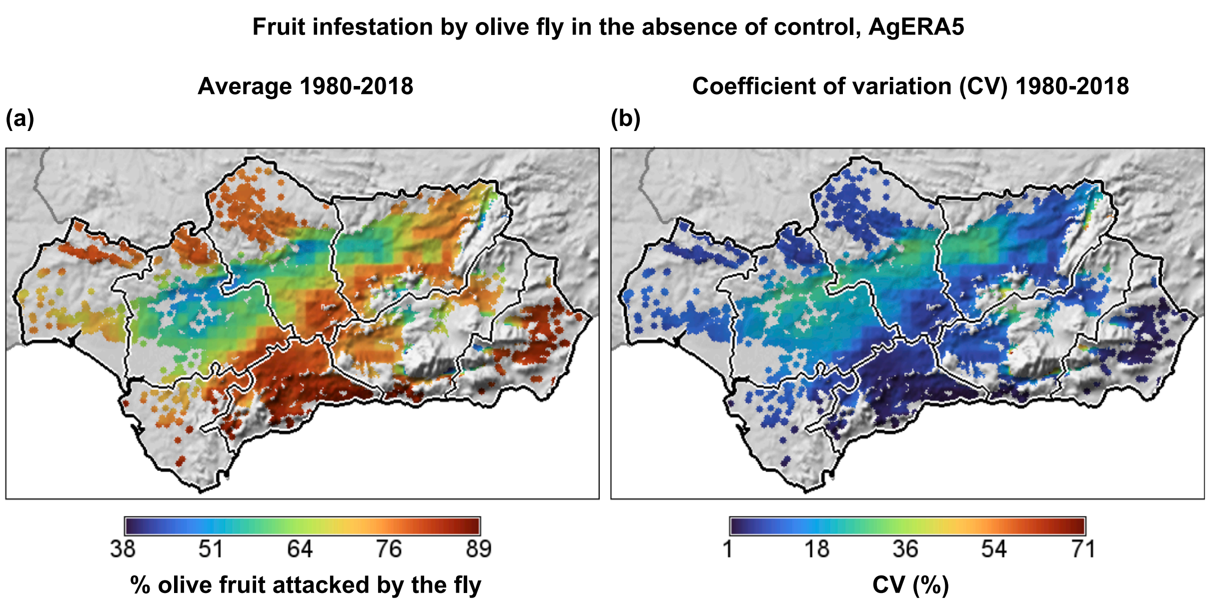

Fig. 14. Fruit infestation by olive fly in the absence of control (% olive fruit attacked by the fly) in Andalusia, Spain (see Gutierrez et al., 2009), mapped as average (a) and coefficient of variation (b) as projected by the PBDM using downscaled bias-corrected AgERA5 observed reanalysis weather for the period 1980–2018.

robust, with at least 80 % of climate models agreeing that temperature will warm in the future, (ii) will be statistically significant, with 95 % confidence level, and (iii) be higher than the global mean (Cos et al., 2022). Specifically, Andalusia is one of the areas in the Mediterranean Basin where highest warming is expected, particularly during summer (Cos et al., 2022). In contrast, changes in projected precipitation remain uncertain for Andalusia during winter (Cos et al., 2022) when rain is crucial for yield formation in olive (Gratsea et al., 2022; Rapoport et al.,

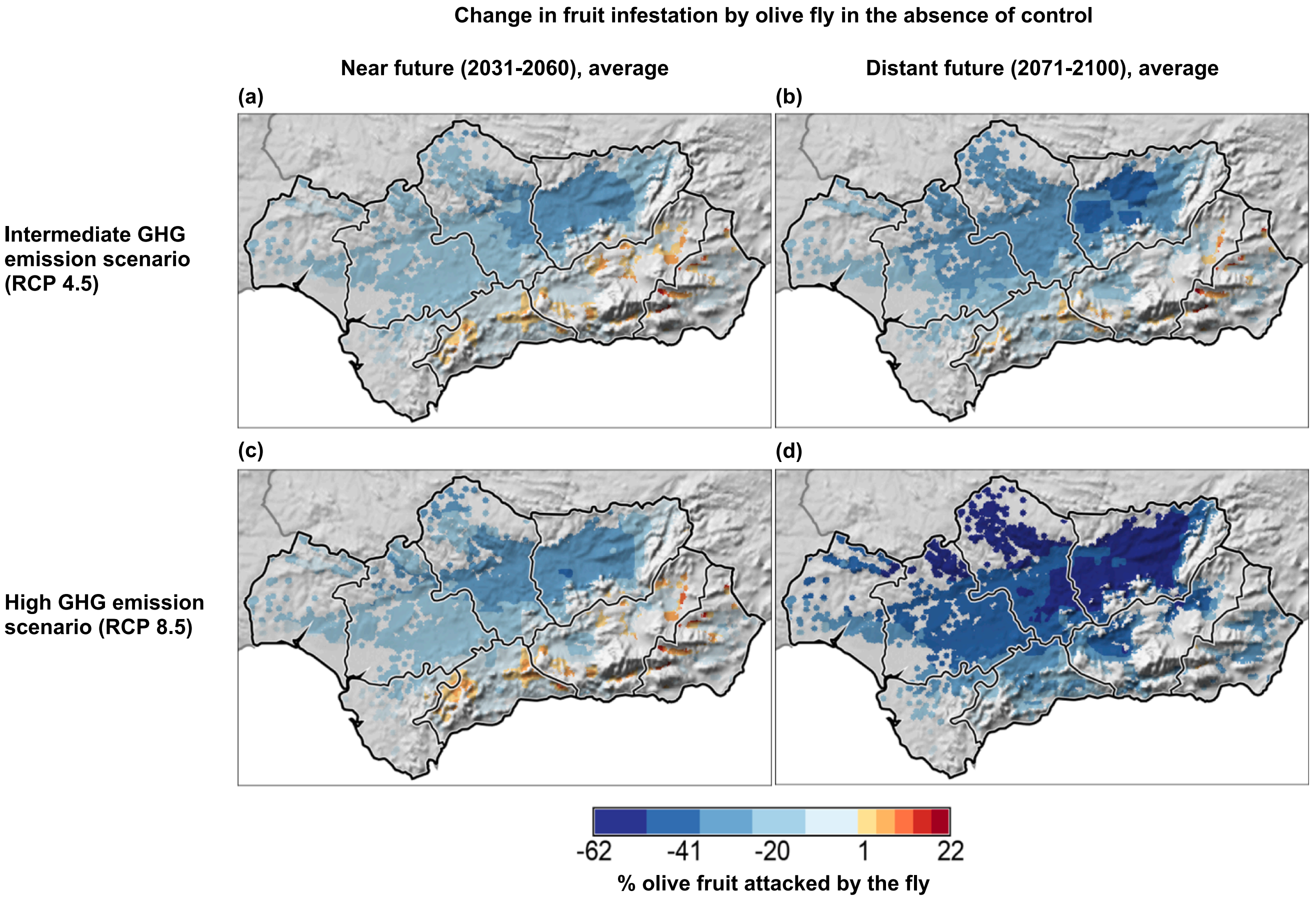

Fig. 15. Average projected change in fruit infestation by olive fly in the absence of control (% olive fruit attacked by the fly) (see Gutierrez et al., 2009) under climate change in Andalusia, Spain from the baseline period 1971–2000. Mean ± SD: (a) −15.0 ± 9.9; (b) −21.4 ± 11.4; (c) −16.9 ± 11.1; (d) mean: −40.9 ± 12.5.

2012; Rodrigo-Comino et al., 2021). Specifically, greater uncertainty and spatial heterogeneity (i.e., disagreement between climate models) was found for winter rainfall compared to temperature changes. Precipitation decline is projected statistically robust and significant in Andalusia only during summer at the end of the century (2081–2100) for the high GHG emission scenario (−33 % on average for both CMIP5 and CMIP6). Only about 5 % of yearly rainfall accrued during the very dry summer seasons of 1964–1993 in Andalusia (Sumner et al., 2001). Uncertainty in precipitation is important as Cos et al. (2022) cautions that conclusions must be drawn carefully from ensembles of multiple climate models, especially when substantial disagreement exists between models as is the case for projected precipitation change during winter in Andalusia. Our analysis did not include the effect of soil water on olive, and while this is a shortcoming, it also comes with the advantage of avoiding strategic recommendations based on ensembles of climate models that substantially disagree on projected winter precipitation changes in Andalusia. Our results also remain valid for about 23 % of the olive growing area in Andalusia where irrigation is available (Fig. 4d).

The main findings of our analysis for Andalusia concerning climate change effects on olive blooming, yield, and olive fly infestation, are discussed below.

Olive blooming is projected to occur earlier under climate change, with bloom dates being four to five weeks earlier in large areas of the major olive-producing provinces of Jaen, Cordoba, Sevilla, and Granada (with peaks of more than six weeks in Malaga) under the high GHG emission scenario towards the end of the current century (i.e., years 2071–2100). Chilling is required for olive blooming with a value of 450 HD < 7.3 °C (i.e., hour degrees below 7.3 °C) required before blooming occurred, representing early (e.g., Arbequina) to late blooming cultivars (e.g., Hojiblanca) reported by De Melo-Abreu et al. (2004). All of the studies reviewed here used the De Melo-Abreu et al. (2004) chilling accumulation model, with differences between the studies appearing to be due to differences in the underlying climate datasets, possibly reference olive cultivars used, and the methods used to compute HD. Failure to meet chilling requirements under climate change has occurred in Andalusia (Gabaldón-Leal et al., 2017; Fraga et al., 2019; Cabezas et al., 2020), and insufficient chilling has been shown to lead to failed or poor flowering (Hartmann and Porlingis, 1957) and increased length of bloom period causing erratic floral bud-break with negative impacts on yield and quality (Medina-Alonso et al., 2020). Failure to meet chilling threshold has also been reported in other areas of southern Europe (Grillakis et al., 2022).

Our model predicts that under the distant future 2071–2100 scenario with high GHG emissions, large areas in the provinces of Jaen, Cordoba, and Sevilla will fail to meet the reference minimum 450 HD < 7.3 °C threshold required for olive blooming, with some areas accumulating no chilling (Fig. 7). Cabezas et al. (2020) used a model with low input requirements (AdaptaOlive) to develop impact response surfaces based on observed weather data from the Spanish State Meteorological Agency and five global climate models, and found no crop damage linked to flowering failure due to lack of chilling in Jaen or Granada, while 74 % of the years in Sevilla had severe damage. AdaptaOlive is intermediate in complexity between simple approaches based on FAO crop coefficients (Allen et al., 1998) and more complex mechanistic crop models such as OliveCan (López-Bernal et al., 2018). Mairech et al. (2021) using OliveCan found that in European areas of the Mediterranean Basin, including Andalusia, prospective decreases in winter chilling are not expected to be enough to produce significant flowering anomalies or failures. Mairech et al. (2021) used the same RCP4.5 and RCP8.5 GHG

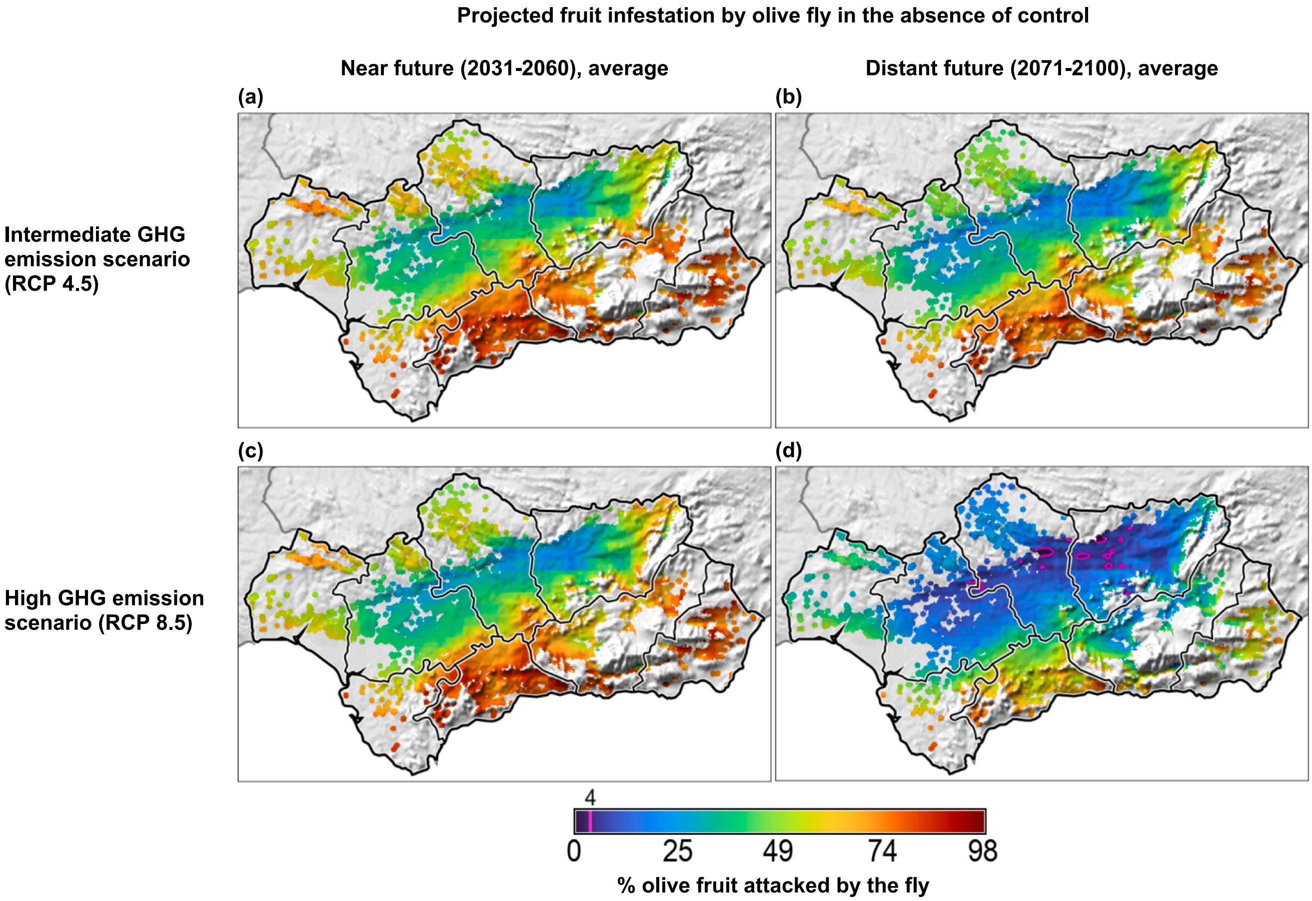

Fig. 16. Average projected % fruit infestation by olive fly in the absence of control (see Gutierrez et al., 2009) under climate change in Andalusia, Spain. Maps show projected changes from baseline period 1971–2000 (Fig. 15), added to PBDM simulation output based on AgERA5 observed reanalysis weather for the period 1980–2018 (Fig. 14). The magenta isolines in (d) indicate an economic threshold for fruit infestation by olive fly of 4 % (Viggiani, 1989; see Ponti et al., 2014).

emission scenarios and similar future time periods as in our study, but based their chilling accumulation predictions on climate projections from a single regional climate model (GUF-CCLM4) that has a lower spatial resolution (~48 vs. ~12 km) than the regional state-of-the-art EURO-CORDEX models used here. We also used the reference threshold of 450 HD < 7.3 °C to represent the range of early (Arbequina) to late blooming cultivars (Hojiblanca) used by De Melo-Abreu et al. (2004). Cabezas et al. (2020) used 469 HD chilling units for the intermediate cultivar Picual, and Mairech et al. (2021) used a set of five cultivars with chilling requirements ranging from 339 for Arbequina to 722 for Moraiolo. This difference, if real, suggests that olive phenological diversity could be screened to select cultivars with lower chilling requirements (Belaj et al., 2020).

Earlier olive blooming will extend the growing season, but also increase exposure to an increased frequency of extreme weather events during olive flowering period (Gabaldón-Leal et al., 2017), including spring frosts (see Orlandi et al., 2010; Ponti et al., 2009a), and to extreme high temperatures (see Gabaldón-Leal et al., 2017). Both factors can damage flowers and impair fruit set (Rapoport, 2014) when outside the optimal fluctuating temperatures range of 2 to 19 °C (Connor and Fereres, 2005), with damage to floral buds occurring below 0 °C (Denney et al., 1985), and inhibition of floral initiation and bud break above 30 °C (Rapoport, 2014).

Changes in olive bloom dates predicted here are similar to those reported by Gabaldón-Leal et al. (2017) for the same region despite the following differences in scenarios (herein vs. Gabaldón-Leal): (1) RCP 4.5 and RCP 8.5 vs. SRES A1B emission scenarios, (2) year time periods (baseline 1971–2000 vs. 1981–2000; near future 2031–2060 vs. 2021–2050; the same distant future 2071–2100 for both), (3) climate model downscaling experiments (EURO-CORDEX vs. ENSEMBLES), and (4) climate models spatial resolution (25 vs. 50 km). Gabaldón-Leal et al. (2017) projected that olive will bloom 6 and 17 days earlier in near future 2021–2050 and far future 2071–2100, respectively, while we projected earlier blooming of 12.4 and 17.5 days in near future 2031–2060 and distant future 2071–2100, respectively, for the intermediate GHG emission scenario (RCP 4.5), and 15.8 and 30.5 days in near and far future, respectively for the high GHG emission scenario (RCP 8.5). Our predicted changes in olive bloom dates are similar to those reported by Mairech et al. (2021) for the main olive-farming regions in southern Europe, using the same RCP 4.5 and RCP 8.5 scenarios, similar time periods (baseline 1971–2000 vs. 1980–2010; near future: 2031–2060 vs. 2041–2070; distant future: 2071–2100 for both). Mairech et al. (2021) used a single regional climate model (GUF-CCLM4) with lower spatial resolution (~48 km), the output of which was downscaled to 10 km resolution using observed weather data. Specifically, Mairech et al. (2021) projected that in 2071–2100, olive will bloom < 15 days earlier under the RCP 4.5 and 12 to 30 days earlier under the RCP 8.5 scenario, compared to our average values for Andalusia of 17.5 and 30.5 days, respectively. Differences in computing HD could also influence the results.

Our model predicts relative **olive fruit yields** will increase or remain stable under climate change across GHG x time horizon scenarios, ranging from +11.9 % under intermediate GHG emissions in 2031–2060 to +21.5 % under high GHG emissions in 2071–2100, with highest increases expected in the southeastern provinces of Malaga, Almeria, and Granada towards the end of the century under high GHG emissions (Fig. 13).

Previous research assessing climate change effects on olive yield in Andalusia used a range of approaches, including correlative species

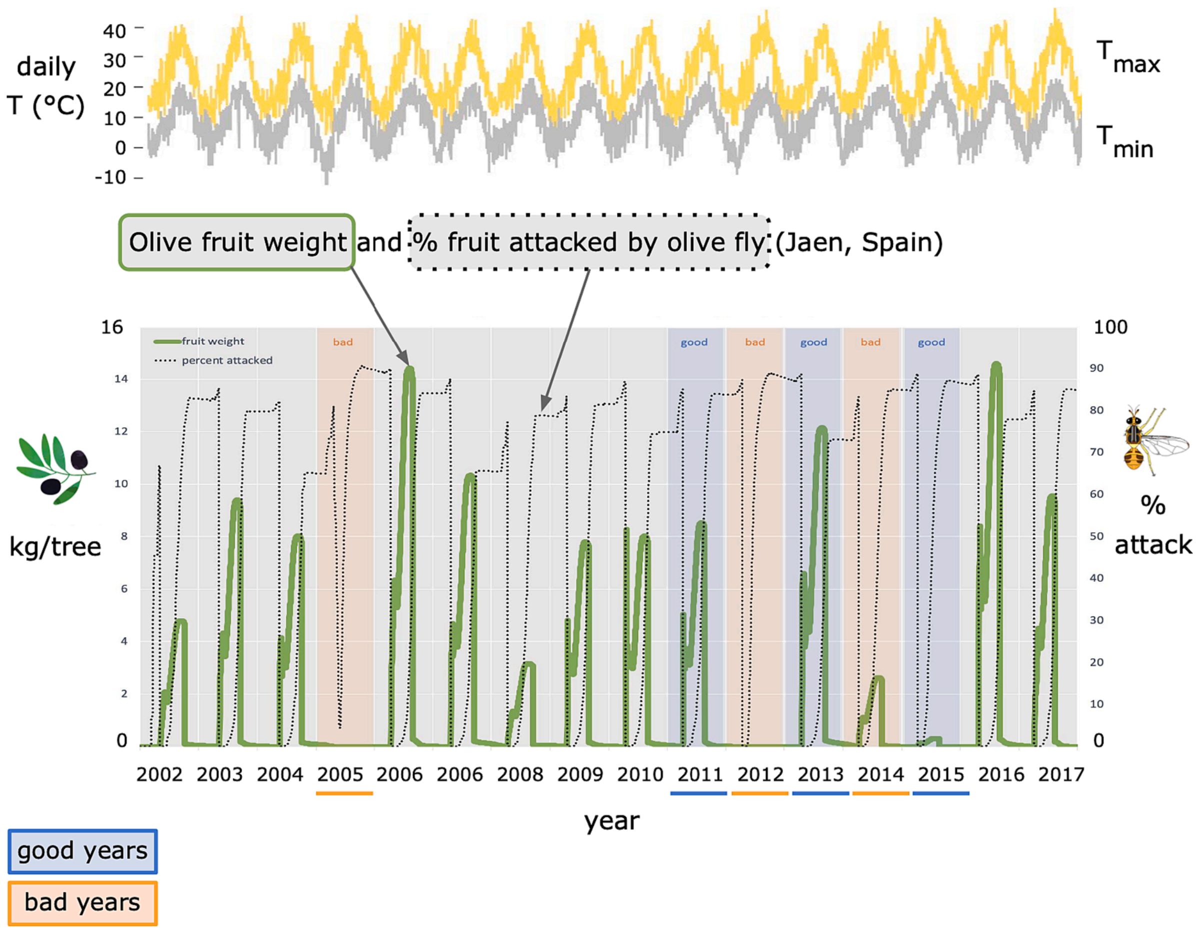

Fig. 17. Simulated olive fruit weight (kg dry matter per tree) and % fruit attacked by olive fly for Jaen, Jaen Province during the period 2002–2017 using weather data from the Andalusian Institute of Agricultural and Fisheries Research and Training – Instituto de Investigación y Formación Agraria y Pesquera (IFAPA, 2022). Classifications of "good" and "bad" years for olive oil production were identified by DCOOP collaborators. (Note that the winter temperatures in bad years were low.).

distribution models (SDMs), hydrological approaches, and simulation of more nuanced olive biology. Arenas-Castro et al. (2020) assessed climate change effects on olive yield in Andalusia based on soil properties, geomorphology, evapotranspiration, and bioclimatic indices as correlates of olive presence data (seven olive varieties and wild olive) to fit an ensemble of species distribution models (SDMs) ('biomod2′ R package, see Thuiller, 2014). Bioclimatic indices were computed at monthly time step with unknown spatial resolution from a single global climate model simulation (CNCM3) under the A1B scenario for a baseline period (1961–2000) and three future periods (2011–2040, 2041–2070, and 2071–2100) (Arenas-Castro et al., 2020). Under climate change, Arenas-Castro et al. (2020) predicted decreased olive production for most Andalusian provinces due decreased autumn precipitation, except for Granada and Almeria where increased yield was as high as predicted by our study. For the major olive-producing provinces of Jaen, Cordoba, and Sevilla, the highest decreases in olive production projected by Arenas-Castro et al. (2020) were 0.2 % in year 2011–2040, −9.1 % in 2071–2100, and −29.4 % in 2071–2100, with average decreases across the eight Andalusian provinces of −6.9 % for years 2011–2040, −5.8 % for 2041–2070, and −8.4 % for 2071–2100. Climate change projections used by Arenas-Castro et al. (2020) predicted a substantially drier and warmer climate across Andalusia, with precipitation levels slightly higher during summer (4.78 % on average across time periods) and substantially lower during autumn (−64 %, −76 % and −48 % in future periods 2011–2040, 2041–2070 and 2071–2100, respectively); values that contrast sharply with state-of-the-art analysis of ensemble climate projections for the Mediterranean area (Cos et al., 2022). The SDMs used by Arenas-Castro et al. (2020) to predict olive suitability and yield are correlative, explicitly lacking biology, hampering transferability to future climate conditions (e.g., Werkowska et al., 2017; Charney et al., 2021).

Fraga et al. (2020) modeled olive yield explicitly as a function of soil moisture dynamics using the ecohydrological approach developed by Viola et al. (2012). Fraga et al. (2020) used a mechanistic water balance model to constrain yield potential that predicted the highest reductions in olive yield for Andalusia under climate change among the studies reviewed here. Fraga et al. (2020) used daily weather data from an ensemble of four EURO-CORDEX regional climate models (Jacob et al., 2014) for the baseline period 1989–2005 and for future period 2041–2070 under RCPs 4.5 and 8.5 GHG emission scenarios, providing no detail on how the four regional climate models were selected, with climate variables bias-corrected using EURO-CORDEX evaluation runs as a reference. The Fraga et al. model is the most heavily biased by uncertainty in projected precipitation under climate change because olive yield, including the effects of [CO_2] but excluding flowering, is linked explicitly to soil moisture availability as the main yield constraint. According to Fraga et al. (2020), olive yields will decrease in Andalusia under climate change forced by both GHG emission scenarios, with extreme values reaching −45 % and average declines of −17 % and −21 % under RCP 4.5 and 8.5, respectively. This is a direct result of projected increases in water deficit (Fraga et al., 2020), the projections of which remain a major source of uncertainty in Andalusia (Cos et al., 2022).

Using the more nuanced olive biology included in the OliveCan model (e.g., flowering, dry matter partitioning to plant organs, and three-dimensional shape of the canopy), Mairech et al. (2021) predicted that rainfed low-density olive orchards will be the most vulnerable to climate change, with decreases in yield of −18 % under RCP 4.5 and −20 % under RCP 8.5 for years 2071–2100 relative to 1980–2010 across the Iberian Peninsula. Mairech et al., (2021) found the detrimental impacts of climate change on olive yield can be buffered by increasing plantation density with irrigation at 30 % of maximum requirements, suggesting increased yields in super-high-density Andalusian olive orchards in 2071–2100 under both GHG emission scenarios. Further, increased CO_2 concentration resulted in enhanced water use efficiency that, together with irrigation, partly offset the negative effects of increased drought under climate change (Mairech et al., 2021). Hence, enhanced water management in olive is requirement in Andalusia in the face of highly uncertain precipitation projections (Cos et al., 2022) and increased water use efficiency under increasing [CO_2] (Mairech et al., 2021).

Given precipitation projections remain uncertain under climate change for Andalusia during the winter period (Cos et al., 2022) when rain is crucial to yield formation in olive (Gratsea et al., 2022; Rapoport et al., 2012; Rodrigo-Comino et al., 2021), it may strategically be sound to maximize soil water by implementing multi-purpose adaptation measures such as cover crops that increase soil organic matter and soil water holding capacity, reduce soil water evaporation, increase infiltration, and prevent soil erosion (Fraga et al., 2021) under intensified heavy rainfall events (Noto et al., 2022), and would enhance soil fertility (Novara et al., 2021).

Our model predicts that **Olive fly infestation** will decrease with climate change, particularly in the top-producing provinces of Jaen, Cordoba, and Sevilla, with infestations remaining below a reference economic threshold of 4 % in some areas of the three provinces under the high GHG emission scenario towards the end of the century. Olive fly numbers will decrease with climate change that pushes summer temperatures beyond the fly's upper thermal limits, particularly in the top-producing Andalusian provinces of Jaen, Cordoba, and Sevilla. This may be complemented by the capacity of diversified olive landscapes to limit fly infestation levels and variability when compared to olive monocultures (Paredes et al., 2022; Rescia and Ortega, 2018), facilitating implementation of ecologically-based preventive management strategies targeting the spring generation of the fly to reduce season long infestation levels (Marchini et al., 2017; Caselli and Petacchi, 2021). Hence, with adequate support from local government, research institutions, and organization of producers (Sánchez-Martínez et al., 2020), improved opportunities for integrated (Hinojosa-Rodríguez et al., 2014) and organic (Pleguezuelo et al., 2018) olive production may arise in Andalusia under climate change (Rocamora-Montiel et al., 2014).

Further, some areas with low predicted olive fly infestations under climate change overlap with areas with olive landscape diversity (Rescia and Ortega, 2018) and protected designation of origin for virgin olive oil in Andalusia (Aparicio-Ruiz et al., 2019). This convergence would provide a unique opportunity to increase market value and competitiveness by combining the environmental protection and highest food quality attributes associated with Andalusian extra virgin olive oil.

5. Concluding remarks

The year 2023 was the warmest on record globally and followed a series of warmest years since 2015 (see Dawson, 2023). This underscores the ongoing reality of climate change, which negatively affects olive production in Andalusia (Resco, 2022). As olive farms confront a multifaceted climate crisis across the Mediterranean Basin (We Are Water Foundation, 2023), the Andalusian government is proactively developing a strategy to bolster the resilience of the olive sector (DeAndreis, 2023).

Most of the unexplored potential for increasing the resilience of social-ecological agricultural systems to climate change is found at the strategic rather than tactical level. For example, if climate information is used only at the tactical level to improve water or pest management, the adaptation potential (and hence resilience) is constrained by the extant strategic approach. However, if the strategy itself is redesigned based on climate change projections, resilience is deliberately increased by design. Strategic recommendations that emerge for olive/olive fly in Andalusia include maximizing soil water use efficiency under uncertain rain projections (Cos et al., 2022) and taking advantage of reduced pest pressure by olive fly under ongoing climate change to implement preventive pest management strategy that targets the spring generation of the fly to keep developing population levels low (Marchini et al., 2017; Caselli and Petacchi, 2021). Previous studies focused on climatic stress on olive and did not consider biotic factors such as pests. In contrast, our physiologically based demographic model (PBDM) explicitly predicted the geographic distribution, relative abundance, and daily population dynamics of both the olive crop and its major pest, the olive fly, and their interaction. The major deficiency of our work is that water balance was not included in the analysis, but this aspect has considerable future uncertainty. However, a qualitative validation of the model for the area of interest has been presented after systematic consultation with local experts on the outcome of recent harvests.

Furthermore, PBDMs can be quickly updated with added information, and physiological refinements can be added (e.g., water balance), and can be the bases for holistic analyses to deconstruct agroecosystem complexity by separating the ecological core from the economic and climate drivers. PBDMs view climate change as simply a novel weather pattern that drives the biology of the system. PBDMs provide realistic biological information layers that complement the more widely used index-based proxy approach to climate services (Buontempo et al., 2020; Dell'Aquila et al., 2023; Gratsea et al., 2022; see Gutierrez et al., 2010). The models can be updated with new data and increased physiological and other biological components as they become available. PBDM can be used to deconstruct complex agroecosystems, with recent illustrative examples being the bio-economic analysis of Indian hybrid Bt cotton and farmer suicides (Gutierrez et al., 2020), and the holistic local analysis in Colombia and Brazil of the control of coffee berry borer (*Hypothenemus hampei*, the major pest of coffee worldwide) (Cure et al., 2020).

The PBDM approach to modelling the olive agroecosystem was implemented in the MED-GOLD ICT platform in a flexible and scalable way that allows wide scale access to its functionality. The MED-GOLD ICT platform implemented the PBDM approach in a climate service context as a first step towards developing a modeling platform with a high level of generalization and abstraction useful for implementing PBDMs for other crop systems. A general modeling platform would make the PBDM/GIS methods widely accessible with minimal expertise and infrastructure requirements, and would have immense long-lasting potential for helping solve critical environmental, agricultural, and health problems globally (e.g., Gutierrez et al., 2019), and would provide a sound mechanistic basis for developing climate services in natural resource management. Such capacity is currently unavailable.

CRediT authorship contribution statement

Luigi Ponti: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Andrew Paul Gutierrez:** Conceptualization, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Writing – original draft, Writing – review & editing. **Christos Giannakopoulos:** Data curation, Funding acquisition, Methodology, Writing – review & editing. **Konstantinos V. Varotsos:** Data curation, Funding acquisition, Methodology, Writing – review & editing. **Javier López Nevado:** Data curation, Funding acquisition, Validation, Writing – review & editing. **Silvia López Feria:** Data curation, Funding acquisition, Validation, Writing – review & editing. **Freddy Wilmer Rivas González:** . **Federico Caboni:** Data curation, Methodology, Software, Writing – review & editing, Funding acquisition. **Federica Stocchino:** Data curation, Methodology, Software, Writing – review & editing, Funding acquisition. **Adolfo Rosati:** Funding acquisition, Methodology, Validation, Writing – review & editing. **Damiano Marchionni:** Funding acquisition, Methodology, Validation, Writing – review & editing. **José Ricardo Cure:** Funding acquisition, Validation, Writing – review & editing. **Daniel Rodríguez:** Funding acquisition, Methodology, Software, Writing – review & editing. **Marta Terrado:** Funding acquisition, Methodology, Visualization, Writing – review & editing. **Matteo De Felice:** Funding acquisition, Project administration, Validation, Writing – review & editing. **Alessandro Dell'Aquila:** Funding acquisition, Project administration, Validation, Writing – review & editing. **Sandro Calmanti:** Funding acquisition, Project administration, Validation, Writing – review & editing. **Ricardo Arjona:** Funding acquisition, Validation, Writing – review & editing. **Michael Sanderson:** Data curation, Funding acquisition, Validation, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data shared via Zenodo.

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Author contributions

L.P. and A.P.G. conceived and designed the work and wrote the initial draft of the manuscript. L.P. performed the PBDM/GIS analysis and with F.S. developed the weather data to run the PBDMs. F.S. was the main developer of the PBDM Web API as a component of the MED-GOLD ICT platform. All authors contributed to the interpretation of data, substantively revised the manuscript, and have approved the submitted version.

Appendices A and B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cliser.2024.100455.

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