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## Adaptability of Mediterranean Agricultural Systems to Climate Change. The Example of the Sierra Mágina Olive-Growing Region (Andalusia, Spain). Part I: Past and Present

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### ABSTRACT

This research focuses on the adaptability of olive-growing systems to climate change in the Sierra Mágina region of Andalusia. The authors combined a retrospective and prospective analysis, an interdisciplinary approach, collaboration among climatologists, geographers, and sociologists, and the participation of local farmers and stakeholders, all contributing their own knowledge.

This paper assesses the adaptability of olive-growing systems to climate irregularities over the past 50 yr. First, a climatic study shows that rainfall decreased by 18% during the period 1955–2009. Water resource availability has declined 2 or 3 times more than rainfall, in part because of the expansion of irrigation, which ameliorated the effects of droughts and increased profitability. Second, relationships between rainfall and both irrigated and rainfed olive yields are assessed. These show that the cumulative rainfall of the 2 yr preceding the crop explains 41% of the variability of irrigated olive tree yields and 46% of rainfed yields; this result was unexpected for irrigated yields. Third, this study examines the perceptions of climate variability of 15 farmers, the views of 16 local stakeholders [developers, olive oil professionals, local authorities, a conservationist, and a representative of a local nongovernmental organization (NGO)]. The perceptions of the farmers are interpreted with respect to their socioeconomic status. All farmer and stakeholder interviewees know to a certain extent the climatic influence on olive yields, and most of them acknowledge the recent climatic changes. These findings will be valuable for future assessments of the adaptability of the agricultural and social systems to climate change.

### 1. Introduction

#### *a. A retrospective–prospective analysis of the adaptability of Mediterranean agriculture to climate change*

In Mediterranean regions, the most common climate change scenarios foresee an increase in temperatures and a decrease in rainfall (Christensen et al. 2007; Stocker et al. 2014; Giorgi and Lionello 2008; Magnan et al. 2009; Gualdi et al. 2013), and an increase in extreme episodes (Hertig et al. 2013), with potential consequences for

agricultural yields (FAO 2008) and natural resources. In this context, we must look beyond the question of sustainable development and risk and incorporate the concepts of vulnerability, adaptation, and the resilience of socioeconomic systems facing environmental change. Generally, climate scientists use the concept of *adaptation* (Christensen et al. 2007; Stocker et al. 2014; Simonet 2009). We decided to employ the concept of *adaptability* (Walker et al. 2004), since it takes into account the flexibility and heterogeneity of societies' responses to environmental changes. Indeed, interactions between society and nature depend on natural resources, such as groundwater, that are to a certain extent integrated into the economy and are sensitive to environmental changes, particularly to climate change (Latiri et al. 2009).

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Vulnerable drought-prone agricultural systems are relevant examples to examine adaptability to climate change, since these systems are local models of global ecological issues. Adaptability to climate change depends on local societies' choices, agricultural models promoted by public policies, international markets (CCAFS 2009; O'Brien et al. 2011; World Bank 2010), and community-level organization (Heltberg et al. 2009). Drought experience may also "solidify people's perception about certainty of [future climatic] change" [Diggs 1991, p. 129; this result is also found by Australian Bureau of Statistics (2009) and Seres (2010)].

Because of the long life duration of the olive trees, olive growing provides a useful example to investigate the adaptability to climate change. While Sofo et al. (2008) consider the olive tree as a paradigm for drought tolerance in Mediterranean climate, Moriana et al. (2003) show a negative relation between olive yield and evapotranspiration, suggesting that olive yields are sensitive to rainfall irregularity and that irrigation should improve it. According to Galán et al. (2008), spring (flowering season) and summer (fruiting season) rainfall and both maximum and minimum temperatures in summer and autumn (harvest) are the major weather-related parameters affecting fruit production. García-Mozo et al. (2010), Avolio et al. (2012), and Orlandi et al. (2012) show how temperature influences the phenological phases of the olive tree. Besides, the yield of the olive tree is alternatively high and low (*vecería*; biennial bearing). The vegetative growth produces nodes every 2 yr that will bear potential floral buds the following year (Lavee 1996; Angles 1997). Other features should influence olive yields, including the interspecific competition from weeds and the intraspecific competition due to olive tree planting density.

Moreover, olive growing is an increasingly interesting alternative for the local development of Mediterranean sloping lands [higher profits than cereal or cattle breeding, increased demand (Moriana et al. 2003), increased yield due to irrigation]. This trend is acute in countries such as Spain that have benefited from guaranteed prices and subsidies after joining the European Union (EU) in 1986 (Milli and Gatti 2005; Araque Jimenez 2008), although, it is noteworthy that these benefits have been decreasing since the 2000s. Simultaneously, rainfall as well as water resources have decreased in southern Spain during the twentieth century (Duran et al. 2006; Lorenzo-Lacruz et al. 2012). The water resource decline has been exacerbated by inefficient water management (Liggins 2008; Gómez-Limón et al. 2012).

Despite the importance of this issue, the adaptability of olive-growing regions to climate change has not been taken into account in previous studies (Stroosnijder

et al. 2008). Within the scope of the French Scientific Interest Group (GIS) Climate, Environment, and Society Program, we have attempted to link three aspects of the adaptability to climate change: the climate variability, the agriculture adaptability, and the perception and strategies of stakeholders and farmers in a highly specialized and market-dependent olive-growing region, Sierra Mágina (Andalucía, Spain). To achieve this objective, we have combined climatological and geographical quantitative analyses and a sociological qualitative study. We linked retrospective and prospective analyses to assess how the society–nature systems have developed adaptability to past and present climate irregularities (Beck et al. 2006; Enfors and Gordon 2007; Mengistu 2011) and how useful the stakeholders' experiences and perceptions are for the future. Our method attempts to contribute to the improvement of adaptability assessment of rural areas to climate change (Lynch et al. 2008) and to be responsive to stakeholders' concerns. Nevertheless, our study is not thoroughly conclusive due to the small size of our sociological sample and due to the complex interactions that might impact future trends.

Our study is published in two companion papers (Parts I and II, retrospective and prospective analyses, respectively). Part I is dedicated to the past and present. In section 2, we present our method, and in section 3, we present our results; in section 3a, we analyze the evolution of climate and water resources since 1955. In section 3b, we carry out a study on the relationships between climate and olive yield. In section 3c, we combine these results with the farming and climate variability knowledge of farmers and stakeholders. Finally, we draw conclusions in section 4.

In a companion paper, about the future, we carry out research on the future local climate change, its consequences on olive yield and water resources, and on farmers and stakeholders' points of view on these issues (Ronchail et al. 2014).

#### *b. Presentation of the case study*

The rural region of Sierra Mágina (776 km<sup>2</sup>; 56 675 inhabitants; INE 2010) is located in Andalusia, Jaén Province, in the upper reaches of the Guadalquivir basin, on the Mediterranean-facing range of the Betic Mountains (Fig. 1). It has a typical Mediterranean climate, modulated by altitude as Sierra Mágina peaks at 2167 m (section 3a). Agrarian surface covers 48.5% of the total surface (Fig. 2; MAGRAMA 2006). Olive growing has become a monoculture, particularly after Spain joined the EU in 1986 (section 1a). In Sierra Mágina, olive groves represented 66% of cultivated land—55 000 ha—in 1986 and 85% in 2006—66 000 ha (Sanchez-Martinez and Gallego-Simon 2009; Sanchez-Martinez et al. 2011). In Jaén Province, the area extent of olive groves

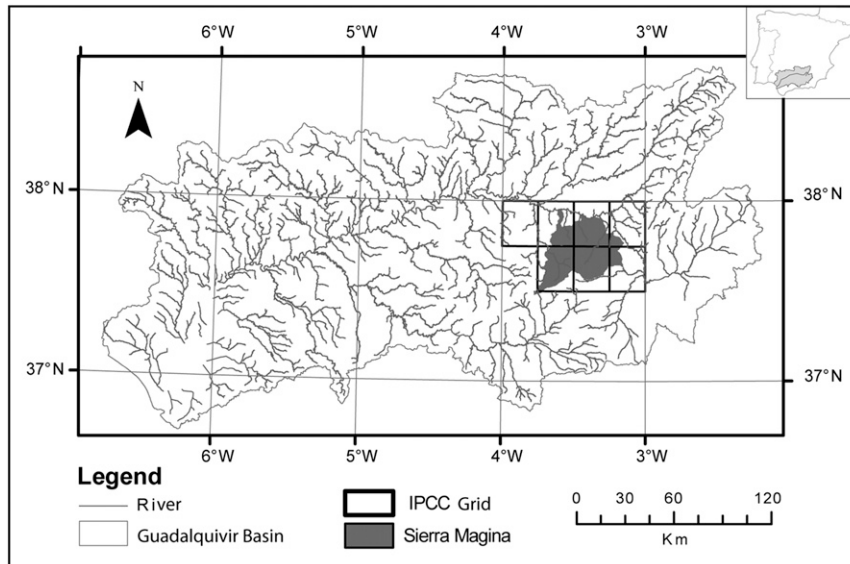


FIG. 1. Location map of the Guadalquivir basin drainage, of the Sierra Mágina region, and of the grid points of the climatic simulations within the Ensemble-Based Predictions of Climate Changes and their Impacts (ENSEMBLES) project (<http://ensemblesrt3.dmi.dk>).

increased from 330 000 ha in 1945 to 455 000 ha in 1986 and to 570 000 ha (approximately) since 2002 [Ministerio de Agricultura, Alimentación y Medio Ambiente (MAGRAMA)]. Sierra Mágina is a good example of the intensification of agriculture and water resources extraction and of their negative environmental consequences in the Jaén Province (Araque Jimenez 2008; Ballais et al.

2013). In Sierra Mágina, the proportion of irrigated olive groves increased significantly from 27% in 1986 (15 000 ha) to 51% in 2006 (34 000 ha) (Sanchez-Martinez and Gallego-Simon 2009). In Jaén Province, this proportion remained less than 10% during the period 1945–79, grew slowly until the drought of the mid-1990s (1995, 14%), and grew dramatically afterward, varying

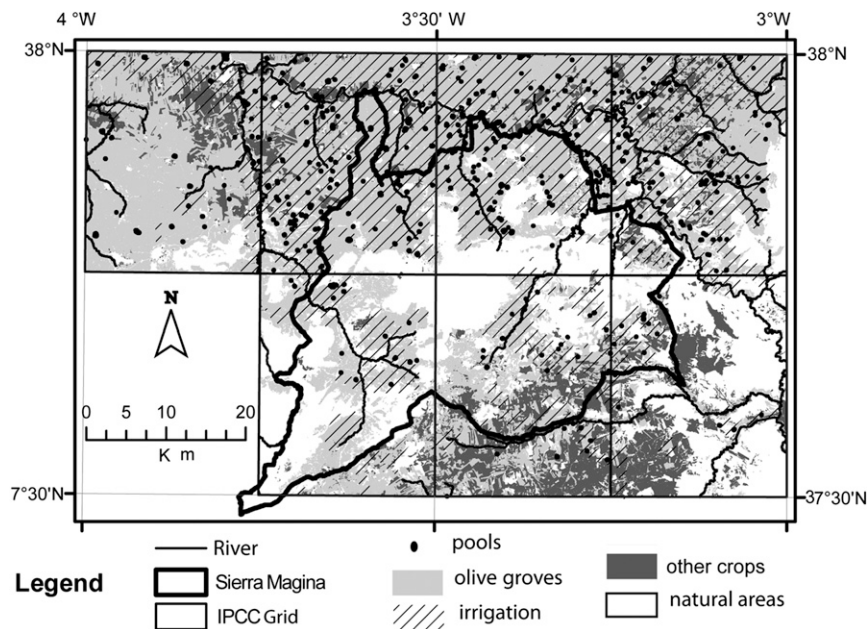


FIG. 2. Land use in the study area. [Sources are MAGRAMA (2006), CHG (2010), the ENSEMBLES project, and [www.juntadeandalucia.es](http://www.juntadeandalucia.es)].

between 30% and 33% since 2004 (MAGRAMA). Numerous reservoirs have been built by the irrigation communities to store water for periods of low flow (Fig. 2), and today water resources are largely devoted to irrigation and are overexploited in some areas (section 3a). Moreover, the weed control, especially below the trees (*ruedo*), restrains the interspecific competition; it is operated by tilling, or by the use of chemical means that are encouraged by the Common Agricultural Policy since the 2000s, in order to restrain erosion (Ballais et al. 2013).

Jointly with economic factors (section 1a) and other technical improvement in groves management (e.g., harvesting techniques), these changes allowed a dramatic increase in olive yields (section 3b) and generated prosperity in the olive sector during the period 1986–2005 with a positive societal outcome, stopping the exodus of the rural population observed from 1950 to 1990 (INE 2010; IEA 2010).

As in other sloping lands in Mediterranean Europe (Stroosnijder et al. 2008), various types of olive-growing systems are observed in the Sierra Mágina region, varying according to the use of irrigation and mechanization, the density of olive trees, and the use of chemical herbicides. Mechanization and irrigation are the main factors of the farms' viability (Sanchez-Martinez et al. 2011). The increase of planting density is recommended since the 2000s to improve the viability (Porras Piedra et al. 1997). High-density olive groves ( $>200$  trees  $\text{ha}^{-1}$ ) reached 18% in Andalucía in 2012 (MAGRAMA-SGT 2013). The implementation of high-density groves is more difficult in Jaén Province, due to the lower capacity of small farm owners to invest, with 70% of the holdings covering less than 5 ha (INE 2010; Sanchez-Martinez et al. 2011). During the same period, the decrease of olive oil price (since 2005; [www.internationaloliveoil.org/](http://www.internationaloliveoil.org/)) and of government subsidy (since 1999) are making the local economy vulnerable. Because of these characteristics, Sierra Mágina is a representative example of olive-growing diversity, constraints, and potentials in Mediterranean Europe.

## 2. Data and methods

### a. Sharing knowledge between disciplines and with local stakeholders

A Sierra Mágina local action group (Asociación para el Desarrollo Rural) requested that our team investigate the future of olive growing in Sierra Mágina in the context of climate change. Our collaboration with stakeholders and farmers developed to the extent that we incorporated their “lay science” with our scientific and modeling process (Corburn 2007). This process, called “post-normal science” by other scientists, is suitable for research incorporating complex issues and

significant level of uncertainty, which is the case for olive-growing adaptability to climate change (Saloranta 2001; Lynch et al. 2008).

This process followed several steps: First, we analyzed projections of climate in Sierra Mágina, focusing on the parameters that stakeholders considered as limiting olive growth, in order to benefit from their knowledge and promote their buy in of our projections. Second, we observed during the interviews that farmers expressed doubt about climate change since they are used to dealing with interannual climate variability. Consequently, we verified and mapped which parameters of climate and water resources had changed over the last decades and to what extent. Third, when we presented the results of the climatic study to local stakeholders, they responded that the uncertainties in our scenarios were making their decision making difficult. They asked us to determine the impacts of climate change specifically on olive production. Fourth, while modeling the relations between climate and olive yield, we used the local knowledge and additional agronomical information to better understand the discrepancies between observed and simulated yield values.

Moreover, the members of each discipline sought to communicate their results in simple terms in order to disseminate their findings. The results of the interviews, presented in a table, played the role of a common pool of knowledge; each discipline used it to assess its hypotheses, improve its methods, and finally to compare its results with the local knowledge.

In this bottom-up research, the process of exchanging knowledge between disciplines and with stakeholders and farmers led to the innovation and improvement of our scientific approach and of its results. This process required open-mindedness on the part of each researcher.

### b. Data

#### 1) CLIMATIC DATA

The analyses of the local climate<sup>1</sup> and its evolution are based on local daily rainfall and temperatures from the Spanish Meteorological State Agency database [Agencia Estatal de Meteorología (AEMET)] (Fig. 3; see the appendix; Table A1). The description of the current climate is based on 29 rainfall gauges and 12 temperature stations (Fig. 3), with datasets that cover a rather short time period (1988–2008; H. Garcin 2010,

<sup>1</sup> In what follows we refer to both climate change on time scales of decades and climate indices or variables such as precipitation and temperature averaged over months or years. We use the word climate alone to refer to either one of these when the context is clear.

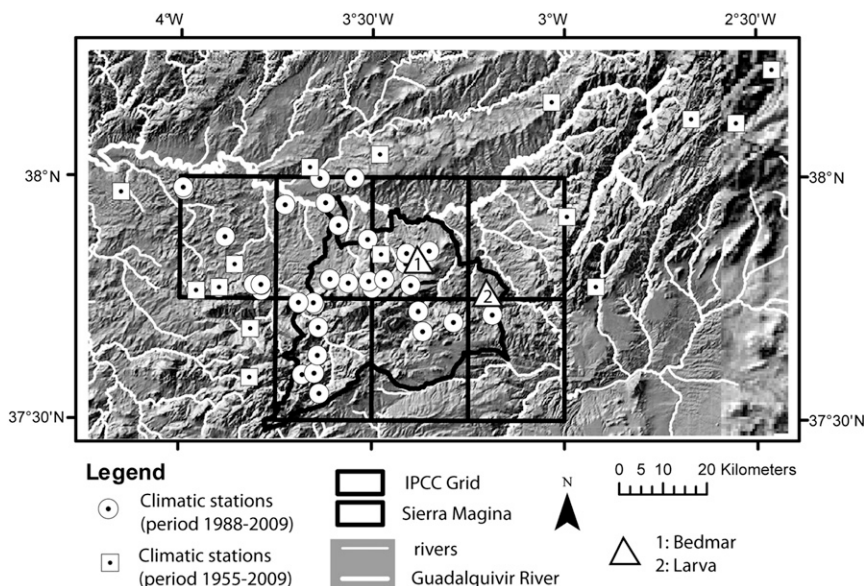


FIG. 3. AEMET stations and study villages. [Sources are [www.juntadeandalucia.es](http://www.juntadeandalucia.es), the ENSEMBLES project, AEMET, and [CHG \(2010\)](http://www.chg.org)].

unpublished manuscript). The analysis of climate variability has been carried out using a smaller number of stations (Fig. 3 and Fig. 4), but with longer time series (from 1955 to 2009 for 15 rainfall gauge stations and from 1974 to 2009 for 7 and 8 stations measuring maximum and minimum temperature, respectively). All the stations are geolocated and integrated in a GIS system, using Arcgis 10.0 software (Table 1).

## 2) YIELD, WATER RESOURCES, AND LAND USE DATA

From 1999 to 2009, areal extent, olive production, and yield data of rainfed and irrigated olive groves are available for the province of Jaén, at the annual time scale, on the Agriculture, Food, and Environment Department website (MAGRAMA; <http://www.magrama.gob.es>). We copied older data (period 1955–99) from MAGRAMA's provincial registers in Jaén. Olive harvesting runs from November (year  $Y - 1$ ) to January–February (year  $Y$ ), and the MAGRAMA database attributes the corresponding yield to year  $Y$ .

The MAGRAMA data Sistema de Información Geográfica de Parcelas Agrícolas (SIGPAC) (common agricultural policy GIS; [MAGRAMA 2006](http://www.magrama.gob.es)) provide information about land use, and the Guadalquivir Basin Authority data ([CHG 2010](http://www.chg.org)) provide information about irrigation. An aerial photography of the region is available online ([www.juntadeandalucia.es/medioambiente/site/rediam](http://www.juntadeandalucia.es/medioambiente/site/rediam)) for 2004. Water resources data are available on the Confederación Hidrográfica del Guadalquivir (CHG) website (and at

[www.conocetusfuentes.com](http://www.conocetusfuentes.com)). We integrated these data in a GIS (Table 1; Fig. 5). The Centro de Estudios y Experimentación de Obras Públicas (Center for Studies and Experimentation of Civil Works; CEDEX) website (<http://hercules.cedex.es/anuarioaforos/default.asp>) provides data on river discharge in several stations (Fig. 5b; Table 2).

## 3) FARMERS AND STAKEHOLDERS

We conducted semistructured interviews of 31 people—stakeholders and farmers—in November 2009, March 2010, and May 2012. We selected the 16 stakeholders in order to collect a diversity of opinions on climate change: 4 developers, 7 olive oil professionals, 3 local authorities, 1 conservationist, and 1 representative

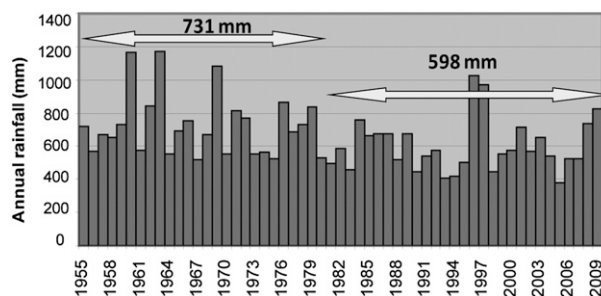


FIG. 4. Annual Rainfall Regional Index for 15 stations during the period 1955–2009. The 1979 break is indicated as well as changes in mean rainfall during the periods 1955–1979 and 1980–2009 respectively (mean rainfall during the period 1955–2009: 615mm). Source: AEMET

TABLE 1. Multisource data integrated in the GIS database Sierra Mágina.

Themes	Shapefile	Spatial unit	Source	Information selected
Climate	Designed by authors from georeferenced data	Climatic station (point)	AEMET	Temperature and rainfall
Topography	Designed by authors Junta de Andalusia	IPCC grid Pixel	ENSEMBLES Junta de Andalusia website ( <a href="http://www.juntadeandalucia.es">www.juntadeandalucia.es</a> )	Half-degree grid Digital terrain model (DTM)
Land division	SIGPAC	Local authority shape	MAGRAMA (2006)	Shape of Sierra Mágina district
Land use	Aerial photography	Plot of land (polygons)	Junta de Andalusia website ( <a href="http://www.juntadeandalucia.es">www.juntadeandalucia.es</a> )	Land use high-density groves
Irrigation	Designed by authors from CHG (2010)	Area of irrigated land (polygons)	CHG (2010)	Origin of water resource used for irrigation, regulation
Pools	Junta de Andalusia	Pools (polygons)	Junta de Andalusia website ( <a href="http://www.juntadeandalucia.es">www.juntadeandalucia.es</a> )	Pools used to store water for irrigation
Rivers	CHG website	Segments of rivers (lines)	CHG (2010) Berbel (2008)	Name of rivers, presence of dams
Groundwater	Designed by authors from CEDEX map	Discharge stations (points)	CEDEX website	Situation of rivers in 2015
	CHG website	Aquifers (polygons)	CHG (2010) IGME (1997) and González-Hernando and González-Ramón (2002)	Evolution of discharge since 1955
Springs	Designed from georeferenced data by J. Salamé (2010, unpublished manuscript)	Springs (points)	Conoce Tu Fuentes Initiative Website ( <a href="http://www.conocetusfuentes.com">www.conocetusfuentes.com</a> )	Name, use (irrigation), minimal and maximal stream in $\text{m}^3 \text{s}^{-1}$

from a local nongovernmental organization (NGO). For the same reason, we selected 15 farmers according to the size of their property (6 small-scale farmers and 9 medium- and large-scale farmers). The size of holding is not usually a sampling criterion of olive system studies (Stroosnijder et al. 2008) or of climate change studies (Seres 2010; Merot et al. 2012). Its influence on the perception of climate change has not been thoroughly established (Diggs 1991; Australian Bureau of Statistics 2009). Nevertheless, we assume in our case study that the farm size, which determines the importance of agriculture in household income, may influence farmers' concerns about climate change.

We chose to investigate farmers' perceptions of climate change in two villages of Sierra Mágina, with different farming and climatic systems, in order to test the influence of these variables (Diggs 1991; Australian Bureau of Statistics 2009; Seres 2010; Merot et al. 2012). The first one, Bedmar, is a medium-size village (3127 inhabitants; IEA 2010) located in the northeastern part of the region (Fig. 3). It receives from 469 to 568 mm of  $\text{rain yr}^{-1}$  according to the different Bedmar stations (AEMET). The olive grove system is traditional ( $<200$  trees  $\text{ha}^{-1}$ ; MAGRAMA-SGT 2013), and the groves are largely drip irrigated (83.6%; INE 2010). The second, Larva, is the smallest village of the region with 478 inhabitants (IEA 2010). It receives 402 mm of  $\text{rain yr}^{-1}$

(in Cabra del Santo Cristo; see the appendix; Table A1). Over the last decade, after a decrease in rainfall, farmers have replaced the rainfed cereal crops with drip-irrigated olive groves thanks to the diversion of the Guadiana Menor River (not mapped in Fig. 2). Some of these new groves are intensive ( $>200$  trees  $\text{ha}^{-1}$ ). Larva's farmers have thereby showed their adaptability to recent climate changes within a market-dependent context. The 15 farmers were selected among the members of the cooperative of Bedmar "S. C. A. Bedmareense" and the irrigation community "Llanos de Larva."

### c. Methods

We use statistical and cartographic methods—for climate, water resource, and yield data—and qualitative methods—for sociological data—and we combine and compare their respective results.

#### 1) STATISTICAL AND CARTOGRAPHIC METHODS

Principal component analysis (PCA) was performed on annual climate series in order to summarize the variability of climate in the Sierra Mágina region and to assess whether the sets of rainfall and temperatures stations exhibit uniform time-space variations or not.

We computed the Bravais-Pearson coefficient of correlation ( $r$ ) between time and climate indices in order to detect trends in the series, as well as between climate

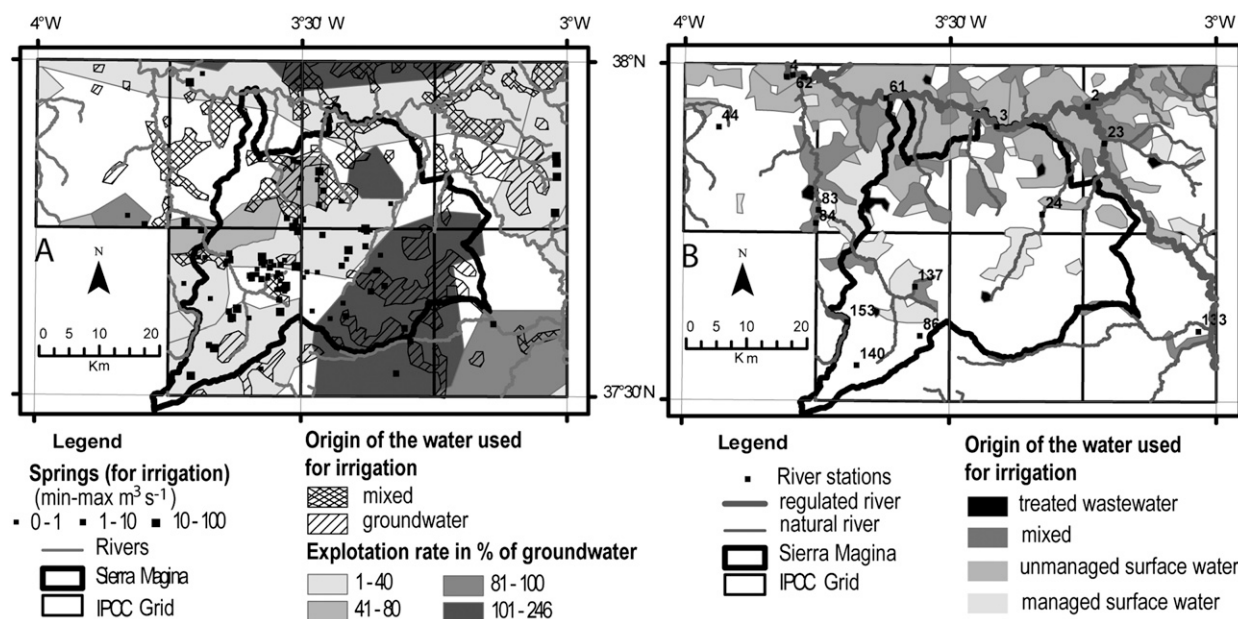


FIG. 5. Origin of the water used for irrigation. (a) Groundwater and (b) surface water. [Sources are CHG (2010), <http://hercules.cedex.es>, ENSEMBLES project, [www.juntadeandalucia.es](http://www.juntadeandalucia.es), and [www.conocetusfuentes.com](http://www.conocetusfuentes.com).]

indices and yield data to measure their relationship. Generally,  $r$  is considered significant when the  $p$  value is lower than 0.05.

Linear regression is used to relate yields to time. Detrended yields values (independent from the trend) are obtained by subtracting the regression estimates from the observed values. Moreover, wavelet analysis allows removing the variability due to the biennial bearing (section 1a) from detrended yields series. The multiresolution analysis is used to provide an orthogonal dyadic decomposition of the signal (Labat et al. 2000). Then, it is possible to isolate a given frequency or period and to filter it from the signal by simply removing it from

the multiresolution analysis and then to sum up again all the other components. This method proves its efficiency compared to Fourier filtering when the signal is not stationary. The resulting yield values, detrended and without the biennial bearing, are called residual yields.

Linear regression is also used for modeling the relationships between climatic indices and detrended yields (Figs. 6, 7, 8). The statistical significance of these models is assessed using F tests to confirm the goodness of fit of the model and by  $t$  tests of individual parameters to verify the significance of the estimated parameters (see the appendix; Table A2). Finally, we use break tests

TABLE 2. Discharge of the main rivers during the periods 1955–79 and 1980–2009.

Code	Name	River	Regime	Measure period		Mean 1955–1979 ( $\text{m}^3 \text{s}^{-1}$ )	Missing years	Mean 1980–2009 ( $\text{m}^3 \text{s}^{-1}$ )	Missing years	Evolution in %
				Begins	Ends					
5002	Guadalquivir	Guadalquivir	Altered	1912	1994	12.92	12	6.11	15	–52.75
5003	Pedro Marin	Guadalquivir	Altered	1911	2009	26.84	13.5	11.39	14	–57.55
5004	Mengibar	Guadalquivir	Altered	1912	2009	47.09	6	23.88	10	–49.29
5023	Guadiana menor	Guadiana menor	Altered	1911	1990	16.78	7	3.59	28	–78.60
5024	Horno del vidrio	Jandulilla	Natural	1932	2009	0.18	24	0.46	7	+150.57
5029	Mengibar	Guadalbullon	Natural	1912	2009	5.43	2	2.22	5	–59.10
5044	Cacin	Cacin	Natural	1930	1969	1.44	10	—	—	—
5061	Guadalquivir	Guadalquivir	Altered	1949	1995	26.49	4	12.21	14	–53.91
5062	Mengibar	Guadalquivir	Altered	1949	1995	50.38	2	20.15	14	–60.00
5083	Puente Nuevo	Guadalbullon	Natural	1970	2009	5.06	15	1.44	4	–71.55
5084	Puente Jontoya	Quiebrajano	Natural	1974	2009	1.82	21	0.95	1.5	–48.13



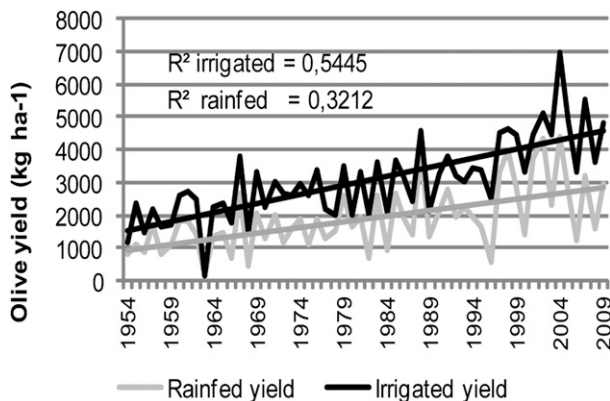


FIG. 6. Evolution of irrigated (black line) and rainfed (gray line) yields during the period 1954–2009. Linear trends (black thin lines) are represented as well as the coefficients of determination ( $r^2$ ) between yields values and time. Source is MAGRAMA.

to identify break points in time series (Pettitt 1979; Mann 1945).

We select by photo interpretation and compute with a GIS (Arcgis 10.0) the percentage of high-density olive groves surface in 2004 in a sample area (northwest grid cell; Fig. 1). In this region, the increase in planting density is supposed to be the most probable. Indeed, the size of olive groves is rather large [mean of 0.75 ha; standard deviatin (SD) of 2.45], and the area is located in the Guadalquivir valley, where irrigation is very easy. In comparison, the average size of groves is 0.6 ha in Jaén Province (SD of 2.55). In this cell, where 20.71% of the olive groves of our study area are located, high-density

groves represent 5.76% of the olive groves surface (MAGRAMA 2006). We also built water resources maps, overlaying thematic information (Fig. 5). We compared the evolution of river flow and regional rainfall during two periods: 1955–79 and 1980–2009.

2) SOCIOLOGICAL APPROACH

(i) Overview of the sociological method

A detailed analysis of rural reality leads us to understand its complexity (Weber 1978). With this purpose, we first built a typology according to Weber’s “ideal types” method (Weber 1949), within the framework of interpretative sociology. Then, we compiled perceptions, decisions, and personal trajectories of both farmers and stakeholders to establish a relation between their profile and their views on climate change.

(ii) Semistructured interviews on the strategies and climate perceptions of farmers and stakeholders

In November 2009, we interviewed nine institutional representatives, here referred to collectively as stakeholders. We asked them about the farming system, the key climatic parameters for olive growth, and their views on climate change and the natural resources. We analyzed these semistructured interviews qualitatively.

In March 2010, we interviewed 15 farmers on the following main topics: the farmer and the farm, decision-making process, opinion about climate change (present and future), decision according to climatic projections, and other information. We arranged the collected

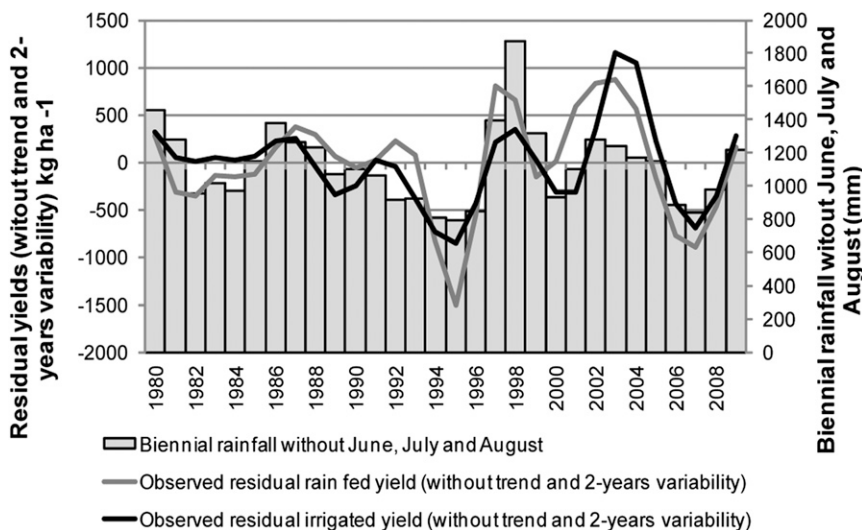


FIG. 7. Biennial regional rainfall in 15 stations without the JJA totals (bars) and annual residual (without trend and biennial bearing) irrigated (gray line) and rainfed (black line) yields. 1980 rainfall value is the sum of 1978 and 1979 rainfall (without JJA rainfall). The 1980 yield values corresponds to the November 1979 to January–February 1980 crop. Sources are MAGRAMA and AEMET.

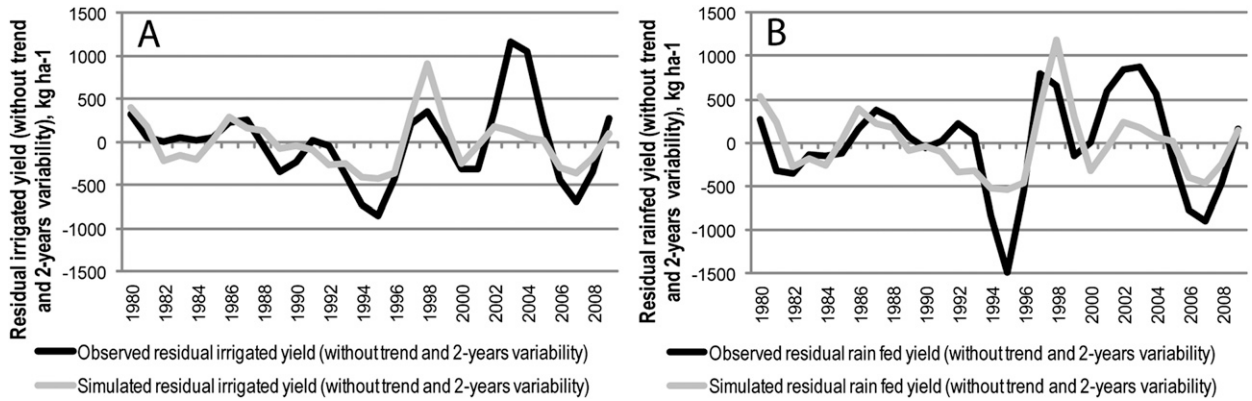


FIG. 8. Observed (black line) and simulated (gray line) residual yields, that is, detrended and without the biennial bearing, during the period 1980–2009, for (a) irrigated yield and (b) rainfed yield. Estimated yields are function of the biennial rainfall without the summer rainfall (JJA) in 15 stations. Sources are MAGRAMA and AEMET.

information in a table in order to facilitate the sharing of information with other scientists and cross analyzed the interviewees and their opinions about the main topics. Then, we analyzed the information qualitatively and built a cognitive scheme (Fig. 9) in order to display the logical relations established by farmers between processes, their causes, and their consequences (Cohen et al. 2009).

(iii) Interviews on local knowledge about the relationship yield–climate

In May 2012, we conducted semistructured interviews to compile the experience of six olive oil professionals and one representative NGO on the relationship between climate and olive yield and their views about the discrepancies of our yield–climate model. We also compiled agronomic data to confirm the consistency of their views (Table 4; Fig. 10).

3. Main results

a. Climate and water resources evolutions

1) THE CLIMATE IN THE SIERRA MÁGINA AND ITS EVOLUTION SINCE THE 1950S

(i) Mean climate

Mean monthly rainfall and temperature data (1988–2008; see the appendix; Table A1) show that in the Sierra Mágina, as in many Mediterranean regions, annual-mean daily maximum temperatures are high (between 20° and 23°C, up to 25°C in Guadalquivir valley), summers are dry and very hot (up to 40° in the valley), and maximum rainfall is observed in October–January (winter) and April–May (spring). Annual rainfall varies from 450 to 900 mm yr<sup>-1</sup> on the western side of Sierra Mágina, exposed to the westerlies, and from 400 to 600 mm yr<sup>-1</sup> on the lee side of the mountain,

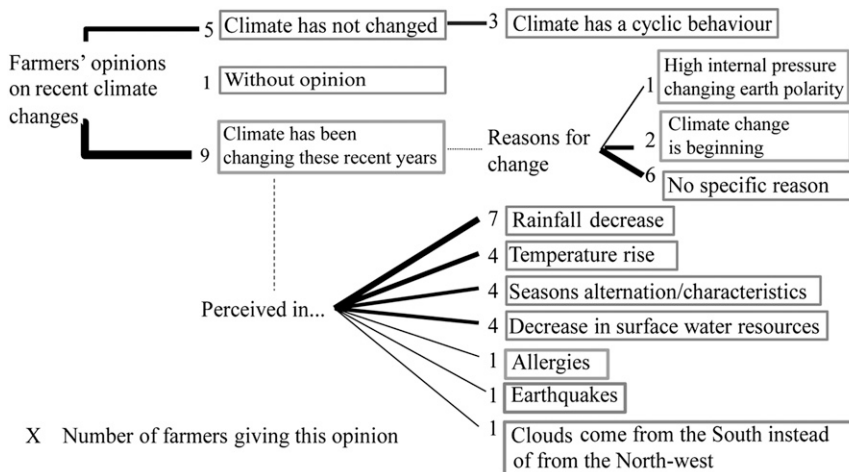


FIG. 9. Farmers' opinions and perception on changes in climate.

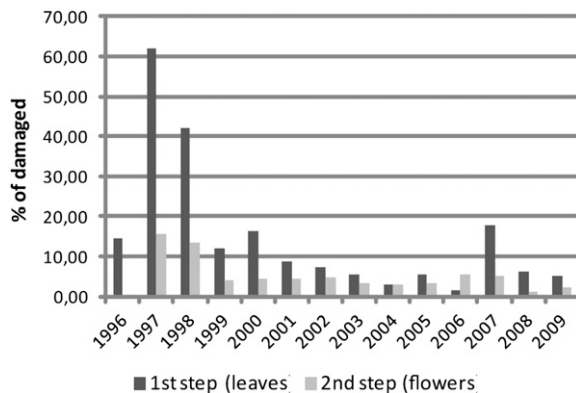


FIG. 10. Damages of *P. oleae* in 1996–2009. Source are Memorias Atrias and DPO (denominación de origen protegida) Sierra Mágina, (2012 unpublished data).

as shown by Gimenez Martinez (1982). We took this spatial rainfall variability into account when we selected the sample villages where we conducted the farmer's interviews (section 2b).

### (ii) Rainfall evolution since 1955

The first PCA (PC1) on annual rainfall (15 stations, during the period 1955–2009) summarizes 80% of the total rainfall variance and reveals an important spatial consistency of rainfall variability in the Sierra Mágina region. The presence of this feature allowed us to construct an annual regional rainfall index by averaging the rainfall of the 15 stations (Fig. 4). This regional rainfall index is strongly correlated with the time series of PC1 ( $r = 0.99$ ,  $p < 0.00001$ ).

Figure 4 shows a strong interannual variability of rainfall with, for instance, a regional rainfall index as low as 400 mm in the mid-1990s and as high as 1000 mm in 1996 and 1997. This irregularity is a characteristic of Mediterranean climate (Gimenez-Martinez 1982).

During the period 1955–2009, the annual regional rainfall index is correlated negatively and significantly ( $r = -0.31$ ,  $p = 0.05$ ) with time, indicating a negative rainfall trend. Moreover, different break tests applied to the regional rainfall index highlight a break point ( $p = 0.05$ ) in 1979 (Fig. 4). Rainfall decreased by 18% between the first period (1955–79: 731 mm yr<sup>-1</sup>) and the second one (1980–2009: 598 mm yr<sup>-1</sup>). Considering seasonal rainfall time series at individual stations, the drop varied from 10% to 30%, principally in winter.

The rainfall decrease in the region of the Sierra Mágina is consistent with the pattern reported by Rodrigo et al. (2000) and Rodrigo (2010) for the entire Andalusian autonomous region and with the findings of Rodrigo and Trigo (2007) and González-Hidalgo et al.

(2010), who described a decrease of rainfall intensity in Spain along with a shortening of the wet season. The long-term variability is probably due to a long-term phase change of the North Atlantic Oscillation (Rodríguez-Puebla et al. 1998, 2001; Trigo et al. 2004).

Most of the farmers and stakeholders interviewed reported the rainfall decrease (section 3c).

### (iii) Temperature evolution since the 1970s

PCA analysis on annual minimum and maximum temperature time series (7 and 8 stations, respectively, during the period 1974–2009) shows that the time–space variations in temperatures is less uniform than the variation in rainfall. PC1 captures 58% and 55% of the total variance of maximum and minimum temperatures, respectively, and highlights some spatial differences in the timing temperature changes. The correlation between time and the minimum temperature PC1 time series is significant and positive ( $r = +0.79$ ,  $p < 0.00001$ ), indicating a trend of increasing nighttime temperatures. Trend analysis on seasonal values in individual stations shows that the strongest increases in minimum temperature occur in spring and summer, consistent with Del Río et al. (2011). Break tests on individual series show breaks in four stations out of seven at the end of the 1970s and at the beginning of the 1990s.

In contrast, the maximum temperature PC1 time series is not significantly correlated with time; two stations out of eight exhibit a positive trend, one shows a negative trend, and the others show no change. This result is not consistent with findings of increase in both maximum and minimum temperatures by many authors, among them Brunet et al. (2007), or perceptions of stakeholders and farmers (section 3c).

The number of frost days diminished consistently, as observed in the Iberian Peninsula by Fernandez-Montes and Rodrigo (2011), while the number of very hot days, with a maximum temperature over 40°C, remained unchanged in the Sierra Mágina region (40°C is a critical temperature for olive trees; Loussert and Brousse 1978).

## 2) USE AND SITUATION OF WATER RESOURCES IN SIERRA MÁGINA

Water resources are a key factor for the olive-growing sustainability within the context of climate change. Drip irrigation for olive groves does not require much water; in 2010, CHG recommends to use 1290 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>, equivalent to a third of the lowest annual rainfall value (400 mm); according to some interviewees, 500 to 800 m<sup>3</sup> ha<sup>-1</sup> yr<sup>-1</sup>—50 to 80 mm—are sufficient. However, the average water consumption for drip irrigation in olive grove is currently higher in the Guadalquivir

TABLE 3. Inflow and outflow of the main dams in the study area.

River dam	Built	Full capacity	In ( $\text{m}^3 \text{s}^{-1}$ )	Out ( $\text{m}^3 \text{s}^{-1}$ )
Pedro Marin–Guadalquivir	1969	1975–76	14.5	14.5
Quiebrajano	1976		0.3	0
Alto Guadiana Menor	2000		3.4	3.4

basin ( $1837 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$ ; 183.7 mm; Argüelles 2010). This difference may partly be due to the existence of illegal wells or pools. Nevertheless, we must have in mind that in 1995 the water allocation for olive trees irrigation was up to  $3000 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$  (300 mm) and that the amount has been reduced by the basin authority (CHG) (Berbel 2008) in order to mitigate the agrarian water deficit in the upper basin ( $-25$  to  $-30\%$ ; CHG 2010). Water used for olive groves' drip irrigation is currently extracted either from surface or/and ground-water bodies (CHG 2010; Fig. 4).

#### (i) Groundwater resources

Sierra Mágina is a karstic mountain with numerous groundwater bodies, most of them with high permeability and productivity. Despite the groundwater control policy, half of the aquifers are overexploited (Fig. 4a). Water storage has decreased in four aquifers. Generally, the decline happened after the severe drought of the mid-1990s (Fig. 10; IGME 1997; González-Hernando and González-Ramón 2002; CHG 2010). For this reason, drip irrigation, mainly based on surface water resources, replaced the ancient irrigation system, based on the utilization of springs, canals (*acequias*), and ditches. Nevertheless, because of the high water demand, groundwater is also increasingly exploited (10% of the total amount of water in 1992, 21% in 2007, and  $726 \text{ hm}^3$  in the Guadalquivir basin), mostly for agriculture (84%; CHG 2010) by individual farmers (64% of the users; Corominas-Masip 2002). Most of the springs used for agriculture have a low flow, particularly those from overexploited aquifers (Fig. 4a; J. Salamé 2010, unpublished manuscript). Local people confirmed these observations (section 3c).

Drip irrigation increase and winter rainfall decrease are the main reasons for groundwater decline (e.g., Úbeda aquifer; Corominas-Masip 2002). The growing demand for freshwater may also have had a negative influence on aquifers located around cities [e.g., Mancha Real–Pegalajar (González-Ramón 2008) and Bedmar–Jódar aquifers].

#### (ii) Surface water resources

The main water resource used for olive groves drip irrigation is surface water. Almost the entire river

network is used for irrigation. A band 10 to 15 km wide along the Guadalquivir River is irrigated by pumping water from the river (points 2–4 and 61–62, Fig. 5b). The same thing happens in Larva, where farmers use a diversion (not mapped) of the Guadiana Menor River (point 23, Fig. 5b). The Guadalbullón River (points 83 and 84, Fig. 5b) supplies water for irrigated olive groves, replacing the dried springs from the Mancha Real–Pegalajar aquifer (Fig. 5a; González-Ramón 2008). The most important rivers of the region, the Guadalquivir, Guadiana Menor, and Quiebrajano (near point 153, Fig. 5b), are highly regulated. Surface water is generally used by the irrigation communities, which comprise 69% of the users (Corominas-Masip 2002). Surface water is highly exploited, exceeding the rate of 60% in most of the small rivers (Bedmar, Torres, and Jandulla Rivers, which flow from Sierra Mágina to the Guadalquivir River) and also in large parts of the large ones (e.g., Guadalbullón, Guadiana Menor, and Guadalquivir; CHG 2010).

When comparing two periods, 1955–79 and 1980–2009, during which rainfall decreased by 18%, we observe that the streamflow decrease has been double or even triple (Table 2) the rainfall decrease. The streamflow decrease may be due to dams (Lorenzo Lacruz et al. 2012). In our case study, the most important dam was built during the first period of our study (Table 3). We assume that, besides and because of the rainfall decrease, the intense extraction of water for olive grove irrigation has contributed to the discharge decrease since the 1980s. These results are consistent with other studies on the effects of rainfall decrease and of land use change on water resources degradation (Duran et al. 2006; Perez and Andreo 2006; Rodríguez-Díaz et al. 2007; Lorenzo-Lacruz et al. 2012).

#### b. Olive oil yield variability since the 1950s and its relationship with climate

##### 1) HISTORICAL, ECONOMIC, PHYSIOLOGICAL, AND TECHNICAL COMPONENTS OF YIELD VARIABILITY

Olive yields increased significantly since the 1950s in Jaén Province, from  $1000$  to  $3000 \text{ kg ha}^{-1}$  and from  $2000$  to  $4000 \text{ kg ha}^{-1}$ , for rainfed and irrigated yields, respectively (Fig. 6). This trend is due to multiple factors

explained in [section 1b](#). The Bravais–Pearson coefficients of correlation between yield and time are positive and significant ( $r = 0.73$  and  $p < 0.00001$  for irrigated yield and  $r = 0.57$  and  $p = 0.00001$  for rainfed yield). A high-frequency variability of both rainfed and irrigated olive groves, due to the biennial bearing ([section 1a](#)), is also clearly noticeable in [Fig. 5](#).

## 2) RELATIONSHIP BETWEEN YIELD AND CLIMATE INDICES

We subtracted both the historical trend ([section 1b](#)) and the biennial bearing ([section 1a](#)) from the observed yield values and obtained residual yields values that can be considered as mainly related to climate ([Fig. 6](#)). The influence of planting density on residual yield is considered low; indeed high-density groves cover only 5.76% of olive groves surface, in large plots of land (mean 6.04 ha), in our sample area located in Jaén Province in 2004. Because of the mechanical or chemical weed control, the role of interspecific competition on yield is also considered as insignificant as explained above ([section 1b](#)). Since rainfall is not stationary and shows a break in 1979, we examined the relationship between rainfall and residual yields during the period 1980–2009.

### (i) Dependence of yield on rainfall

Bravais–Pearson coefficients of correlation are calculated between residual yields and regional rainfall indices computed on various periods of time in order to find the best relationship between rainfall and yields. The best result is observed between the residual yields of year  $Y$  (corresponding to the harvest occurring from November year  $Y - 1$  to January–February year  $Y$ ) and the accumulated biennial rainfall [without the summer values, June, July, and August (JJA)] of the two previous years (years  $Y - 2$  and year  $Y - 1$ ; [Fig. 6](#)). The result that the rainfall during the previous 2 yr is important was expected because of the biennial bearing ([section 1a](#)). But, the fact that summer rainfall does not contribute much to the explanation of the yields variability is partly inconsistent with [Galán et al. \(2008\)](#), who found that the spring and summer period rainfall is correlated with fruit production, and with [Doupis et al. \(2013\)](#), who show that the lack of irrigation in summer favors stomata closure and the limitation of photosynthesis.

The coefficients of correlation between yields values and rainfall are 0.64 ( $p = 0.0001$ ) and 0.68 ( $p < 0.0001$ ) for irrigated and rainfed yields, respectively. This means that drip irrigation does not mitigate the lack of rainfall as much as might be expected ([Loussert and Brousse 1978](#); [Moriana et al. 2003](#)).

Simulated residual yields, dependent on rainfall, are computed using linear regression models. The equations of the models are as follows:

$$\text{SRRY} = 1.6054 \text{ RR} - 1817.38, \quad (1)$$

$$\text{SRIY} = 1.2266 \text{ RR} - 1393.25. \quad (2)$$

SRRY is the simulated residual rainfed yield, SRIY is the simulated irrigated yield, and RR is the biennial rainfall without summer values. The goodness of fit of the models and the significance of the estimated parameters are assessed by F tests and  $t$  tests. Their results are presented in [Table A2](#) and confirm the quality of the models.

These results mean that residual yield increases by  $160 \text{ kg ha}^{-1}$  each time biennial rainfall (without summer) values increase by 100 mm for rainfed crops and by  $120 \text{ kg ha}^{-1}$  for irrigated crops.

Some discrepancies between observed and simulated residual series are highlighted in [Fig. 8](#), with overestimated values during the dry period of the mid-1990s (especially for rainfed values) and after some rainy years, at the end of the 1990s. Also, underestimated values characterize the beginning of the twenty-first century. Agronomic information gathered by semistructured interviews with farmers and stakeholders helps understanding of the differences between observed and simulated yields ([section 3c](#)).

Finally, a wavelet analysis on rainfall and yields series presented in [Fig. 8](#) reveals a 6-yr pattern since the 1990s (not shown); this is consistent with the 7–9-yr rainfall variability observed in the Iberian Peninsula and related to the North Atlantic Oscillation variability ([Rodríguez-Puebla et al. 1998, 2001](#); [Rodrigo et al. 2000](#)).

### (ii) Dependence of yield on temperature

We do not assess the relationship between temperatures and yields because it is difficult to obtain a reliable index of regional temperature. Indeed, temperature data lack homogeneity as seen in [section 3a](#). This is a limitation of our work as temperature has an influence on olive yield ([Galán et al. 2008](#)).

### c. Understanding the farming system and the perception of climate variability

We constructed a typology of the different farmers and farming systems of Sierra Mágina, characterized by the role that farming income plays within the household economy. This role can be the main income source, a complement to the main income source, or capital investments (M. Alonso-Roldán 2010, unpublished manuscript). This typology is helpful in understanding farmers' interpretations about climate change and variability.

## 1) TYPOLOGY OF SIERRA MÁGINA'S FARMERS

The typology covers three target groups (small-, medium-, and large-scale farmers), using different olive production systems among those described by [Stroosnijder et al. \(2008\)](#).

### (i) Type 1: Small-scale farmers

In small farms (less than 5 to 10 ha, depending on the production and on the market), the income from olive groves is an additional (secondary) income. Farmers cultivate their own olive groves in their spare time, and they usually invest in small equipment and drip irrigation systems. They harvest the olives with the help of the family and then mill the olives in a local cooperative, so they obtain olive oil for self-consumption and extra revenues. All farming systems are present in this group: from traditional olive groves (<200 trees ha<sup>-1</sup>; [MAGRAMA-SGT 2013](#)) to one intensive olive grove (>400 trees ha<sup>-1</sup>, in the same place), rainfed or irrigated, in high or low slope areas. Olive groves are partially mechanized (pruning, fertilization, or weed control are done manually, especially in rainfed olive groves).

### (ii) Type 2: Medium-scale farmers

In this group, the farmers are professional, and they make a living from the revenues that their holding generates. They follow a strategy based on competitive investments to increase the farm size and the farm machinery. However, as with small-scale farmers, they depend on market prices. The farming system consists of traditional or intensive olive groves, with drip irrigation systems located in low slope areas. Harvesting, pruning, pest control, fertilizing, irrigation, mechanical, or chemical weed controls are carried out with farming machinery.

### (iii) Type 3: Large-scale farmers

The property is big enough (more than 50 ha, according to the interviewees) to have wage earner(s) full time. Their farm is a capital investment, and they rely on other professional farmers to manage it. The farming systems within this group may be traditional or intensive olive grove, all of them with drip irrigation, located in low slope areas and completely machine operated.

## 2) LOCAL PERCEPTIONS OF CLIMATE AND WATER RESOURCES

The survey responses from our interviews show different opinions on the climate. While all institutional stakeholders acknowledge the existence of climate change, and consider it a future threat, the farmers' views are more varied.

### (i) Institutional stakeholders' perception about climate

The stakeholders interviewed in November 2009 considered climate change a true phenomenon, a recent and a drastic process, and they are aware of the dangerous effects associated with it. They reported observed changes in climate, that is, rainfall decrease, particularly during winter and spring, more frequent extreme events (storms), higher temperatures in winter and in summer, as well as drastic seasonal changes. Our study has partly confirmed their statements ([section 3a](#)). Their opinions are based on their own experience or on elders' or farmers' testimonies. However, only one person mentioned the relationship between higher temperature and CO<sub>2</sub> concentration. Stakeholders regret that farmers have little awareness of climate change, despite the increasing importance given to this phenomenon in the mass media.

### (ii) Farmers' perceptions of climate

Most of the farmers (9/15) considered that climate has changed during the past years, while some others (3/15) interpreted these changes as a demonstration of the usual climate irregularity of Sierra Mágina ([Fig. 9](#)). A larger proportion of medium- and large-scale farmers (6/9) than small-scale farmers (3/6) acknowledged changes in climate during the last 10 to 20 yr. Nearly half of the farmers (7/15) have noticed a rainfall decrease. Three out of seven farmers described a period of reduced rainfall that is consistent with our results. Four of them also mentioned an increase in temperature, which our data partially confirm. Most of the farmers who mentioned a change in climate did not give an explanation (6/9). Surprisingly, these perceptions do not depend on the village or on the olive-growing system, although the Larva farmers changed their crop system partly because of the drought.

### (iii) Farmers, and stakeholders, perceptions of water resources

Despite the dramatic decrease during the last decades ([section 3a](#)), a water resources decline was mentioned in the same proportion as a water resources improvement (4/15). In addition, the groundwater issue was debated locally. Some farmers considered that the capacity of groundwater bodies is sufficient for drip irrigation. One local NGO [[Asociación vecinal "Fuente de la Reja" de Pegalajar \(Jaén\) 2002](#)] considered that Pegalajar spring is a collective and cultural legacy to be preserved, while hydrogeologist [González-Ramón \(2008\)](#) found that the corresponding aquifer is not overexploited. This spring dried up in 1988 and flowed again after

TABLE 4. Annual regional rainfall and water consumption of the irrigation community Santa Potenciana (1000 ha of olive groves in Villanueva de la Reina, in the course of the Guadalquivir River). Period 2002–11. Source is V. Gallego (xxxx, unpublished data).

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
Rainfall (mm)	570	654	541	377	525	522	735	826	1111	No data
Water use (m <sup>3</sup> ha <sup>-1</sup> )	1090	1100	835	1580	900	900	600	850	275	430

heavy rains in 2010 and 2013, filling occasionally the ancient basin (*charca*) used for the gravity irrigation of orchards. Other stakeholders were aware of the water resource scarcity, but they thought that technical improvements and better water management were appropriate solutions.

### 3) LOCAL KNOWLEDGE ABOUT THE RELATIONSHIP BETWEEN CLIMATE AND YIELD

Farmers and stakeholders interviewed in November 2009 and March 2010 mentioned the same climatic parameters favoring olive growth: sufficient rainfall for branch development and mild, maximum temperatures the following year to avoid flowers falling in spring; and sufficient rainfall for olive growth and mild maximum temperatures to avoid olive fall in autumn. Those statements are, to some extent, similar to previous literature (Loussert and Brousse 1978; Lavee 1996; Moriana et al. 2003; Galán et al. 2008) and to our findings on the relationships between climate and yields (section 3b).

Most farmers related good harvests to temperatures (12/15) and to rainfall (11/15), six of them, regardless of the use of irrigation. Considering longer time periods, almost half of them (7/15) explained the olive yield increase with the use of irrigation, but the same proportion attributed the increase to other factors (e.g., technical practices; only one person refers to climate). These latter statements are rather close to our results on the relationships between irrigated yields and rainfall (section 3b).

The stakeholders we interviewed in May 2012 about the models between rainfall and yields were quite surprised by the relatively poor efficiency of irrigation shown by our model. They agreed with our results that show concomitant decreases in rainfall and in yields during the years 1993–95 and 2005 (Fig. 7). Some of them explained lower than expected yields observed in 1998 and 1999 (after 1996 and 1997 rainy years) by high temperatures, others by the impact of parasites or by the saturation of olive roots in the deep and clayish soils near Guadalquivir River. Indeed, data supplied by the Denomination of Protected Origin Office technicians (Memorias Atrias, 1995–2009, unpublished data) demonstrate that the damages of the most virulent olive groves parasite, *Prays oleae*, were significant in 1997 and

1998 (Fig. 10). Local data (Table 4) suggest that the farmers do adjust irrigation practices based on rainfall. In such cases, soil saturation occurring during rainy years might not be due to overirrigation. Last, stakeholders attributed higher than expected yields during the period 1999–2005 (Fig. 8) to the maturity of the olive trees, which were planted from the mid-1980s to the end of the 1990s, when farmers received European subsidies for these new plantations.

## 4. Discussion and conclusions

The study of the past and present conditions of olive groves and climate in Sierra Mágina has contributed to our knowledge of this Mediterranean agrarian region. In this section, we summarize our main results and discuss a key point: does past experience provide a basis for adaptation to climate change?

### a. Main results on climate, water resources, and yield

Our study documents the different changes in rainfall, water resources, and olive yields in the mountainous region of Sierra Mágina (Andalucía, Spain) since the 1950s and points out the relationships between yields and rainfall since 1980. In this region, the record of rainfall is highly variable and exhibits a step function decrease of 18% after a break point in 1979. Notably, available water resources also decreased, dropping 2 or 3 times more than rainfall since 1955. Meanwhile, in the Jaén Province that includes Sierra Mágina, olive yields increased considerably since the middle of the twentieth century, from 1000 to 3000 kg ha<sup>-1</sup> and from 2000 to 4000 kg ha<sup>-1</sup> for rainfed and irrigated yields, respectively. The yield increase can be related to economic, social, and technical factors, and the increased proportion of irrigated groves is considered an adaptation to the decreasing rainfall and an effort to increase profits (Adams et al. 1998; Adger 2000).

Nevertheless, we have proved that yield still depends on rainfall regardless of irrigation. Indeed, the rainfall of the 2 yr (without summer totals) preceding the crop explains 41% of the variability of residual (without trend and biennial bearing) irrigated olive tree yields and 46% of residual rainfed yields. This is an unexpected result compared to previous studies (Loussert and Brousse 1978; Moriana et al. 2003).

TABLE A1. Codes, names, locations, availability period of rainfall or temperature, and mean annual rainfall (in mm) and temperatures (in °C) in the stations used in this work. The mean annual rainfall, minimal temperature (Tmin), and maximal temperature (Tmax) are computed on the data availability period. Different sets of stations are used to analyze first the local climate (1988–2008) and second the rainfall evolution and its relation with yields (1955–2009).

AEMET code	Name	Longitude (W)	Latitude (N)	Altitude	Beginning	End	Climatic variables	Mean annual		
								Rainfall	Tmin	Tmax
5032	Iznatoraf	03°02'02"	38°09'20"	1039	1944	2009	P (mm)	400		
5039	La Iruela	02°59'37"	37°55'10"	933	1955	2009	P (mm)	496		
5089	Pozo Alcon	02°55'07"	37°46'30"	1020	1911	2009	P (mm)	568		
5138	Cabra de Santo Cristo	03°17'17"	37°42'10"	938	1985	2009	P (mm)/T (°C)	402	9.7	22.2
5149	Belmez de la Moraleda	03°22'47"	37°43'30"	887	1985	2009	P (mm)	543		
5163	Jimena	03°28'37"	37°50'30"	590	1950	2009	P (mm)/T (°C)	516	12	19.8
5165	Torres	03°29'57"	37°46'20"	1030	1985	2009	P (mm)	587		
5169	Jaen Los Racioneros	03°37'17"	37°56'50"	260	1945	2009	P (mm)	496		
5220	Canena	03°28'52"	38°02'50"	546	1955	2009	P (mm)/T (°C)	540	12	22.7
5252	Linares, Torrubia	03°39'47"	38°01'15"	290	1945	2009	P (mm)/T (°C)	544	10	24.3
5255	Campillo de Arenas (B. Monasterio)	03°38'57"	37°35'50"	1160	1985	2009	P (mm)	672		
5263	Pegalajar	03°38'55"	37°44'17"	827	1985	2009	P (mm)	509		
5266	La Guardia de Jaen	03°41'27"	37°44'30"	645	1985	2009	P (mm)	403		
5271	Torre del Campo	03°53'52"	37°46'18"	640	1954	2009	P (mm)	642		
5272	Torre del Campo (el termino)	03°51'27"	37°49'10"	460	1956	2009	P (mm)	494		
5334	Higuera de Arjona	03°59'27"	37°58'20"	380	1985	2009	P (mm)	485		
5349	Arjona "Santo Tomas"	04°09'17"	37°58'00"	340	1955	2009	P (mm)	544		
5418	Valdepenas de Jaen	03°49'02"	37°35'15"	927	1944	2009	P (mm)	764		
7045	Pontones C. H. Segura	02°40'11"	38°07'13"	1350	1934	2009	P (mm)/T (°C)	900	3.5	17.5
7054	Salto de Miller	02°27'35"	38°13'18"	750	1961	2009	P (mm)/T (°C)	597	7.3	20.6
7056	Santiago de la Espada	02°33'10"	38°06'44"	1340	1934	2009	P (mm)	757		
5166A	Torres	03°30'32"	37°47'10"	885	1978	2009	P (mm)	568		
5166i	Baeza (las Escuelas)	03°30'42"	37°52'20"	535	1989	1993	T (°C)		11	22.8
5171A	Villatorres-Villargordo	03°43'37"	37°56'35"	345	1974	2009	P (mm)/T (°C)	428	11	24.7
5180E	Beas de Segura (Las Perales)	02°52'27"	38°17'20"	345	1974	2009	T (°C)		8.6	20.8
5250O	Lupion	03°32'50"	37°59'53"	503	1983	2009	P (mm)	459		
5262B	Pegalajar (la Cerradura)	03°38'17"	37°41'32"	560	1977	2009	P (mm)	451		
5269A	Los Villares	03°48'56"	37°41'17"	640	1950	2009	P (mm)	547		
5270A	Jaen (CHG)	03°47'17"	37°46'00"	570	1985	2009	P (mm)/T (°C)	497	11	22.8
5279U	Linares "Vor"	03°37'57"	38°09'25"	520	1974	2009	T (°C)		11	22.8
5330A	Torredonjimeno	03°57'25"	37°45'54"	591	1956	2009	P (mm)/T (°C)	612	abs	21.7
5334B	Higuera de Aarjona	03°59'34"	37°58'37"	360	1985	2009	P (mm)	460		

We confirm the increase in minimum temperature found by Brunet et al. (2007), Del Río et al. (2011), and Fernandez-Montes and Rodrigo (2011) but, due to the lack of reliable data, we could not confirm the negative influence of maximum temperature on olive yield, as shown by Galán et al. (2008).

#### b. Consistency between our results and local knowledge and perception

The knowledge of local stakeholders and farmers is partly consistent with our results on the evolution of climate and water resources during the last decades and on the relationships between climate and yields. The awareness about climate issues varies according to the

two groups of interviewees. For the stakeholders, recent changes in climate are warning signs of future climate change. They are unanimous on that matter, while farmers' opinions vary according to the importance of farm income relative to the total household income. The large- and medium-scale farmers are the most aware of climate change. Indeed, most of them (five out of nine) are relying exclusively on their farming activity, while in small farms, olive growing is a secondary activity for five out of six farmers. Our typology is different from Stroosnijder et al. (2008), which is based on the type of olive-growing systems; nevertheless, it seems relevant to understand differences in farmers' perceptions and strategies related to climate change.



TABLE A2. Significance of statistical tests.

(a) Irrigated yield vs rainfall				
	Value	Standard error	T statistics	P
b	-1393.245 84	319.659 457	-4.358 531 58	0.000 159 63
a	1.226 638 97	0.279 371 57	4.390 707 97	0.000 146 27
Variance analysis				
	Degree of freedom	Sum of squares	F	P
Regression	1	2 383 596.05	19.278 316 5	0.000 146 27
Residuals	28	3 461 956.31		
Total	29	5 845 552.36		
(b) Rainfed yields vs rainfall				
	Value	Standard error	T statistics	P
b	-1817.384 87	373.625 051	-4.864 194 37	$4.0204 \times 10^{-5}$
a	1.605 405 09	0.326 535 68	4.916 476 86	$3.4849 \times 10^{-5}$
Variance analysis				
	Degree of freedom	Sum of squares	F	P
Regression	1	4 082 896.89	24.171 744 7	$3.4849 \times 10^{-5}$
Residuals	28	4 729 535.01		
Total	29	8 812 431.9		

Differences in local climate and agricultural systems do not seem to explain the farmer's views, contrary to the findings of other authors (Diggs 1991; Australian Bureau of Statistics 2009; Seres 2010; Merot et al. 2012). A larger survey would be useful to confirm this result.

*c. Is past experience useful for adaptability to future climate change?*

In our study, the experience of declining rainfall (after 1979) and of drought (mid-1990s, 2005) does not always “solidify people's perception about certainty of [future climatic] change,” as found by Diggs (1991, p. 129). The farmers base their interpretations of the recent climatic changes on their own experience and on the limited information they have. This could be the reason for their low degree of awareness—or even skepticism—about future climate change, particularly among the small-scale farmers who represent the largest group overall. Most stakeholders also refer to their own experience of climate change, but their awareness may be explained by a better access to information.

Stakeholders and some of the farmers view drip irrigation as the technique that “saved” the olive yields after the long-lasting drought in the mid-1990s. Indeed, the relatively high yields of irrigated olive groves during the period 1993–95 is seen as convincing evidence of the usefulness of irrigation. Two decades later, as shown by our results and other authors' (Gómez-Limón et al. 2012; Lopez-Gunn et al. 2012), drip irrigation is not as effective at increasing yields as expected. Some farmers have always known about the dependence of irrigated

groves on rainfall, but other farmers and all the stakeholders still believe in irrigation. Those farmers interviewed appeared to be less aware than stakeholders about the decline of water resources.

According to Heltberg et al. (2009) “climate change will cause some climatic variables to deviate from their historical range [...]. Traditional approaches to decision making in risky climates based on communities' historic experience could lose value” in the future.

This seems to be the case in Sierra Mágina. Past experience is not a valuable asset in formulating future adaptation strategies. During the 1990s, after the decline of groundwater resources, irrigation benefited from the possibility of exploiting surface water; now all the water resources, from the ground and from the rivers, are already divided between users. In addition the European subsidies, a substantial support in past times, are decreasing. Moreover, if local farmers are connecting olive growing to the climate influence on yields, their perception of past climate still depends on personal interpretations, which obviously remains diverse. Our companion paper (Part II) discusses the paradoxical relationships between climate predictions, their consequences for water resources, and olive yields and farmers' doubts about climate change.

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## APPENDIX

### Station Data and Significance Tables

Codes, names, locations, availability period of rainfall or temperature, and mean annual rainfall (in mm) and temperatures (in °C) in the stations used in this work (Table A1) and the significance of statistical tests (Table A2).

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