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Climate Change in Spain: Phenological Trends in Southern Areas

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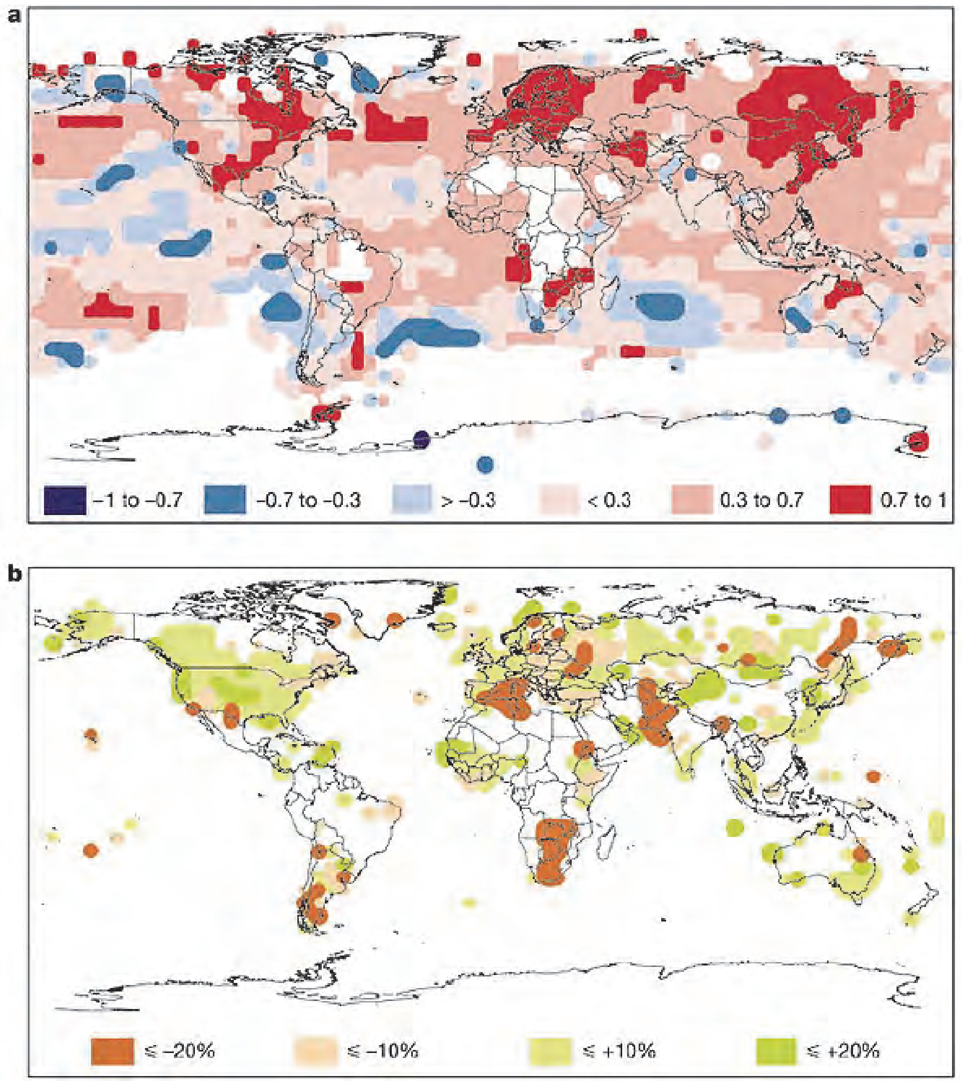
1. Introduction

Global average surface temperatures increased by 0.6±0.2ºC over the twentieth century, and a further increase of 1.4 to 5.8ºC is projected by 2100 (Figure 1). Europe recorded its warmest decade from 1990 to 1999 (IPCC, 2001; IPCC, 2007). The rate of warming during this period has been approximately double that the previous one and, greater than at any other time during the last 1,000 years. Organisms, populations and ecological communities do not, however, respond to approximated global averages. Rather, regional changes, which are highly spatially heterogeneous (Figure. 1), are more relevant in the context of ecological response to climatic change. In many regions there is an asymmetry in the warming that undoubtedly will contribute to heterogeneity in ecological dynamics across systems. Diurnal temperature ranges have decreased because minimum temperatures are increasing at about twice the rate of maximum temperatures. As a consequence, the frost-free periods in most mid- and high-latitude regions are lengthening and satellite data reveal a 10% decrease in snow cover and ice extent since the late 1960s. Changes in the precipitation regime have also been neither spatially nor temporally uniform (Figure 1). In the mid- and high latitudes of the Northern Hemisphere a decadal increase of 0.5–1% mostly occurs in autumn and winter whereas, in the sub-tropics, precipitation generally decreases by about 0.3% per decade (IPCC, 2007).

The impact of climate change, and particularly of climate warming, is being tracked in many physical and biological systems. Phenology—the timing of seasonal activities of animals and plants—is perhaps the simplest process in which to track changes in the ecology of species in response to climate change. Birds, butterflies and wild plants, in particular, include popular and easily identifiable species and thus have received considerable attention from the public. Plant phenology is seen as one of the most important bio-indicators, since trends can provide considerable temporal and spatial information regarding ongoing changes (Menzel et al., 2006). As a result many long-term phenological data sets have been collected. Studies in Europe and North America have revealed phenological trends that very probably reflect responses to recent climate change. Common changes in the timing of spring activities include earlier breeding or first singing of birds, earlier arrival of migrant birds, earlier appearance of butterflies, earlier choruses and spawning in amphibians and earlier shooting and flowering of plants. In general, spring activities have occurred progressively earlier since the 1960s. Plant reproductive phenology is controlled by temperature, especially in tree species, and precipitation and photoperiod, especially in herbaceous ones (García-Mozo et al., 2000; 2009; Galán et al., 2005). It has been shown that plants flowering early in spring are more affected by warming than species flowering later in the year (Ahas et al., 2002; García-Mozo et al., 2002; Galán et al., 2005).



Source: IPCC 2007.

Fig. 1. Spatial variability of annual trends in temperature and precipitation since 1976 relative to 1961 to 1990 normals. a, Temperature (°C per decade); b, precipitation (% per decade).

In Spain, temperatures, especially minimum temperature, have increased over the last century by around 1.5ºC the annual average (Fernández-González et al., 2005). Climate change has had a particularly marked effect on southern Spain, increasing temperatures and reducing rainfall. Rainfall has also become increasingly torrential in recent years (Pita, 2003; De Castro et al., 2005).

Most long-term phenological studies to date have focussed on northern Europe, while comparatively few have addressed the Mediterranean region (Gordo & Sanz, 2005; Peñuelas et al., 2002). The projections proposed by the Intergovernmental Panel on Climate Change (IPCC) and confirmed by the Spanish Meteorology Agency (AEMET) for the future Spanish climate, point to a continuing increase in temperatures and a decrease in annual rainfall (IPCC, 2007).

The present study, carried out by the University of Córdoba Aerobiology Research Group and the AEMET, sought to chart phenological trends in response to climate in the Andalusia region of southern Spain, and to compare *in-situ* phenological data with airborne pollen counts in the same area. For this purpose, special attention was paid to the reproductive phenophases of anemophilous species.

2. Materials and methods

2.1 Phenological data

Andalusia boasts considerable climatic and topographical diversity. Regular phenological data series dating back to the mid-1980s from four sites were selected for this study, on the basis of unbroken data series availability, presence of anemophilous species and distance from pollen traps: Bujalance and Pozoblanco, in the province of Cordoba, central Andalusia; Charcones and Huescar, in the province of Granada, a more elevated area of eastern Andalusia (Table 1).

Province	*Localities*	*Distance*	*Altitude*	*Coordinates.*	*Tº*	*Rf*
Córdoba	Córdoba		123	37º 50' N, 4º 45' W	18.0	674
	Bujalance	42	222	37º 54' N, 4º 23' W	17.5	550
	Pozoblanco	86	649	38º 23' N, 4º 51' W	16.0	505
Granada	Granada		685	37º 11' N, 3º 35' W	15.5	462
	Charcones	62	1280	37º 40' N, 2º 94' W	13.9	300
	Huescar	100	1115	37º 48' N, 2.33' W	14.8	367

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Table 1. Characteristics of the study sites including distance to the province capital (km) where pollen monitoring was performed, altitude (m.a.s.l.), latitude & longitude coordinates, annual mean temperature (Tº) and annual mean cumulated rainfall (Rf).

The following species were studied in the indicated dates: 2 oak species: holm oak *(Quercus ilex* subsp. *ballota* (Desf.) Samp.) from 1989 to 2008 and gall oak *(Quercus faginea* Lam.) from 1989 to 2000; olive tree (*Olea europaea* L.) from 1986 to 2008; grape *(Vitis vinifera* L.) from 1986 to 2007; and 3 Poaceae crop species: rye (*Secale cereale* L.) from 1989 to 2008, wheat *(Triticum vulgare* L.) from 1987 to 2008, and common barley *(Hordeum vulgare* L.) from 1987 to 2008. Studied periods varied depending on the site and phenophase.
The analysed species were chosen given their ecological or agricultural importance to the region. Typical vegetation of southern Spain is basically formed by Mediterranean forest and dehesas where the main arboreal genus is *Quercus* (estenopalynous genus), and specially holm-oak. This species is the first flowering oak in Andalusia, being the main species contributing to the pollen curve where there are included pollen grains from all the *Quercus* species (García-Mozo et al., 2002; Gómez-Casero et al., 2004; Gómez-Casero et al., 2007). Apart from its ecological importance, in Iberian Mediterranean ecosystems holm-oak acorn production is of vital economic importance due to acorns are the major component in the feeding systems of high-quality Iberian domestic pigs. Regards to olive tree, Spain produces 33% of the world's olive oil, and Andalusia accounts for 80% of total Spanish output being the world's leading olive-oil-producing region. The largest olive-growing areas are concentrated in the provinces of Jaén and Cordoba. Another economically important species analysed in this work is the grape. Spain is the third worldwide winemaker country counting with the largest surface devoted to vineyards, being Andalusia the sixth region in Spain. The analysed variety was "Garnacha", one of the most abundant in the region, which has a medium range flowering time. Finally, although cultivated grass species contribute in a lower percentage than wild species to the grass pollen curve (estenopalynous family), the analysed grass species selected for the present work were indicated as the crop species more represented in the Poaceae airborne pollen curve in Spain (Muñoz et al., 2000).
The following phenophases, taken directly at the field, were analysed once a week: flowering (appearance of first flowers in some individuals), fruit ripening (several ripe fruits present in several individuals), leaf unfolding (appearance of first leaves in some individuals) and leaf falling (branches have lost half their leaves).
Daily airborne pollen counts were monitored in the cities of Córdoba and Granada (Table 1). Hirst volumetric traps were used (Hirst, 1952). Daily samplings were stained and analysed by using optical microscopy following the rules laid down by the Spanish Aerobiological Network (REA) (Galán et al., 2007, http://www.uco.es/rea/infor_rea/manual_eng.pdf). Two important dates of the pollen season were analysed in the present work as indicators of the flowering period from the aerobiological data. The Pollen season Start date (PS) defined as the first day on which 1 pollen grain/m^3 was recorded and the 5 following days recorded 1 or more pollen grains/m^3 (García-Mozo et al., 2000), and the Pollen season Peak day (PP) defined as the day when the maximum concentration was recorded.

2.2 Climate data

Daily temperature and rainfall data (1986-2008) from the study sites were used to evaluate the impact of climate on phenology, these variables being considered the most relevant for this purpose (Peñuelas et al., 2002; Gordo & Sanz, 2005). The warming index, anomalies from average temperature, for both cities from the start of the 20th century (Figure 2) reveals a progressive rise in temperature, especially over recent years. During the study period (1986-2008), mean annual temperature increased by 4ºC in Córdoba and 3.2ºC in Granada.

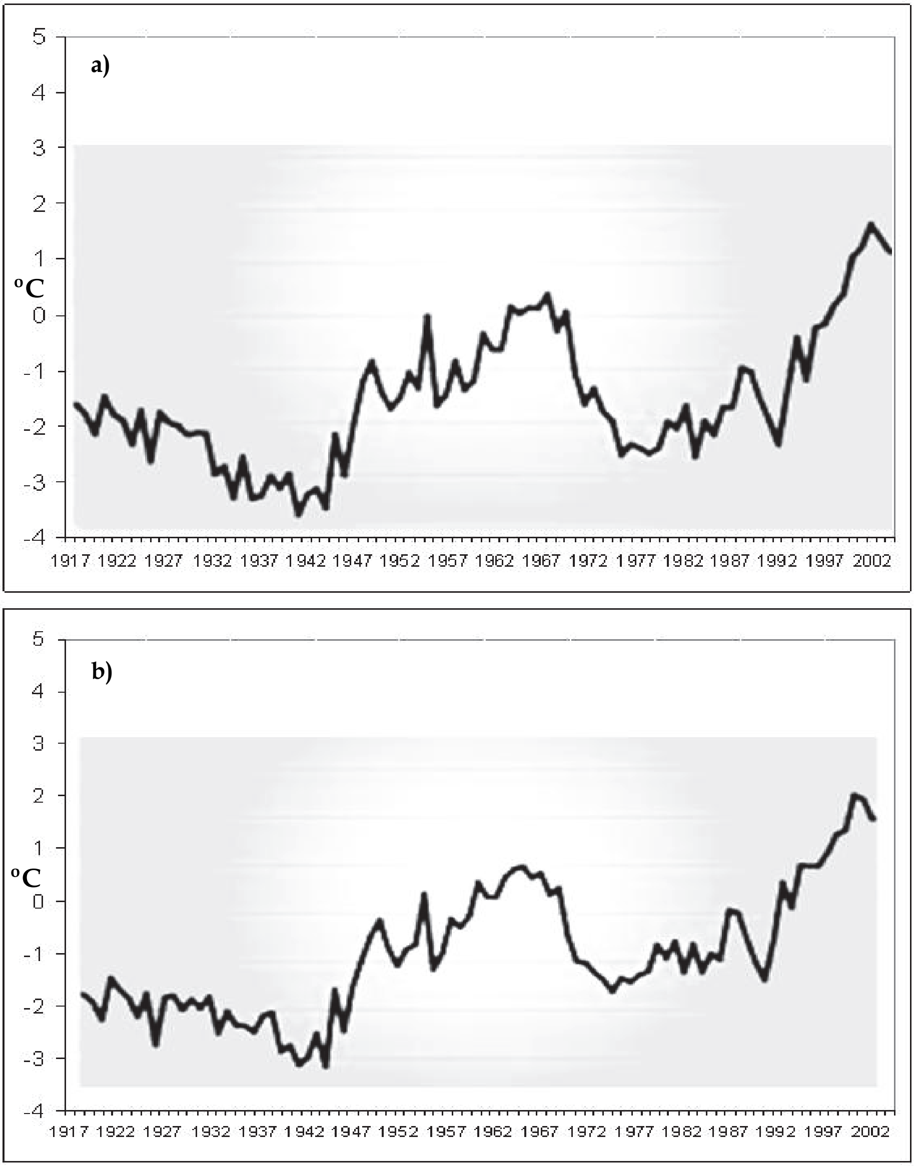

Fig. 2. Warming Index, anomalies from average temperature, in Cordoba (a) and Granada (b) from 1917 to 2005.

2.3 Statistical analysis

Phenological events and weather data were subjected to a Spearman correlation test. Linear regression analysis was performed to calculate trend lines where R^2 values were given and also p values in order to estimate the significance of these trend lines. The Excel Microsoft

2007 and STATISTICA 6.0 software packages were used. Results were considered significant at a 95% confidence interval.

3. Results

Phenological trends for the study species are shown in Table 2. Through the studied period, the flowering dates of holm oak varied up to 60 days, with a significant average advance of 1.6 days per year (27 days during the studied period). The PP in Córdoba city better matched field data at study sites in Córdoba province than the PS date. Although the PP trend line does not show a significant statistics due to the high variability in the data, both aerobiological dates are occurring increasingly earlier, with an overall advance of 7 and 12 days respectively over the period. In this species, fruit ripening advanced by 24 days at Pozoblanco and 36 at Huescar (significant trend gradient, $p<0.05$), leaf unfolding advanced by 25 days in *Quercus faginea* at Huescar (significant trend gradient).

In situ observations of olive flowering advanced at the three studied sites, being significant in the two last ones (Table 2): Pozoblanco (6 days), Bujalance (40 days) and Huescar (40 days). Airborne pollen data suggested a less marked advance, nevertheless the PP curve better matched field data at study sites in Córdoba province than the PS dates, except for the years 1998 to 2001 in Pozoblanco. In the case of Huescar (Granada) phenological data trend was more similar to PS dates. Also olive fruit ripening advanced significantly in the sites located in the province of Córdoba although no significant trend gradient was revealed in Huescar (Granada).

Over the period 1989-2000, *Vitis vinifera* leaf unfolding advanced an average of 10 days, and leaf life was extended up to 20 days in the case of Huescar; although an advance in the fruit ripening time was observed in Charcones (40 days) there was no significant change in the timing of fruit ripening in Huescar. Regarding herbaceous species, *Secale cereale* flowering advanced an average of 16 days between 1989 and 2006 at the Granada province sites. Field data suggested a great delay with regard to pollen dates, although the trend was similar and significant except for the Start date values. Fruit ripening in *Secale cereale* did not display any noteworthy trend between 1989 and 2008. Results for *Triticum vulgare* in Córdoba province revealed a general advance in flowering, significant in the case of field data of Pozoblanco whereas no significant trends were detected in fruit ripening. Finally phenological data for *Hordeum vulgare* indicated a flowering delay of 7 days in Pozobanco and 31 days in Bujalance. By contrast, flowering in Charcones (Granada) showed a slight advance and fruit ripening at all sites appeared largely unchanged over the study period. It is noticeable that the herbaceous species showed the less coincident trends of field phenological data and aerobiological data and the lower significance values for both types of data. In the case of *T. vulgare* and *H. vulgare* the aerobiological phase most coinciding with field phenological data was the PS curve.

Spearman analysis results showed in Table 3 indicated a negative correlation between various cumulative sums of average daily temperature and most of the flowering and fruiting events, especially in tree species. *Vitis vinifera* leaf fall displayed significant positive correlation with temperature (Tables 3b and 3c). Temperature over the preceding autumn correlated positively with most phenological phases in tree species. For some herbaceous species, there was also some correlation with temperature over the preceding months, as well as a weak but still-significant correlation with rainfall over previous months.

Site	Species	Phenophase	Gradient	R^2	*p*	N
Cordoba	*Quercus* spp.	Pollen season start	-0.77	0.21	0.05	17
		Pollen season peak	-0.41	0.04	0.41	17
	Olea europaea	Pollen season start	-0.31	0.03	0.49	20
		Pollen season peak	-0.34	0.04	0.38	20
	Poaceae	Pollen season start	-0.42	0.02	0.45	22
		Pollen season peak	-0.9	0.15	0.07	22
Pozoblanco	*Quercus ilex*	Flowering	-1.58	0.24	0.04	17
		Fruit ripening	-1.17	0.15	0.08	20
	Olea europaea	Flowering	-2.04	0.18	0.06	20
		Fruit ripening	-1.25	0.72	0.03	22
	Triticum vulgare	Flowering	-0.71	0.33	0.01	21
		Fruit ripening	-0.24	0.06	0.51	21
	Hordeum vulgare	Flowering	0.49	0.10	0.17	20
		Fruit ripening	0.07	0.00	0.74	21
Bujalance	*Olea europaea*	Flowering	-1.63	0.37	0.00	20
		Fruit ripening	-1.86	0.81	0.00	22
	Vitis vinifera	Leaf fall	0.16	0.00	0.74	15
	Triticum vulgare	Flowering	-0.12	0.00	0.74	21
		Fruit ripening	-0.13	0.05	0.32	21
	Hordeum vulgare	Flowering	1.59	0.55	0.00	21
		Fruit ripening	-0.14	0.00	0.20	21
Granada	Olea europaea	Pollen season start	0.43	0.19	0.07	19
		Pollen season peak	-0.08	0.00	0.57	19
	Poaceae	Pollen season start	-0.13	0.00	0.88	16
		Pollen season peak	-1.70	0.29	0.04	16
Huescar	*Quercus faginea*	Foliation	-2.30	0.46	0.01	11
		Fruit ripening	-1.79	0.84	0.00	20
	Olea europaea	Flowering	-1.99	0.66	0.00	19
		Fruit ripening	0.07	0.00	0.00	22
	Vitis vinifera	Foliation	-0.40	0.31	0.07	11
		Leaf fall	1.16	0.46	0.01	15
		Fruit ripening	-0.25	0.09	0.19	19
	Secale cereale	Flowering	-0.99	0.92	0.00	16
		Fruit ripening	-0.04	0.00	0.70	20
Charcones	*Vitis vinifera*	Foliation	-1.26	0.17	0.19	11
		Fruit ripening	-0.09	0.00	0.49	19
	Secale cereale	Flowering	-0.95	0.42	0.01	15
		Fruit ripening	-0.01	0.00	0.99	20
	Hordeum vulgare	Flowering	-0.29	0.06	0.32	20
		Fruit ripening	-0.18	0.00	0.87	20

Table 2. Trends for different phenological stages. Site, species, phenological stages, gradient, R2, significance (p value) and number of years (N) are represented.

	Phase	Tmx	T	Tmn	T_{j-a}	T_{j-jn}	T_{s-n}	T_{s-n}^{-1}	Rf	Rf_{j-a}	Rf_{j-jn}	Rf_{s-n}	Rf_{s-n}^{-1}
Quercus ilex	Fl	**-0.35**	0.22	0.03	0.18	0.07		**0.50**	0.29	-0.10	0.03		-0.12
	PS	-0.12	-0.20	-0.14	-0.08	-0.16		-0.15	0.17	-0.19	**-0.33**		**-0.46**
	PP	**-0.24**	**-0.38**	**-0.27**	**-0.23**	**-0.24**		**0.15**	0.03	0.01	0.00		**-0.47**
	FR	**-0.62**	**-0.41**	**-0.34**	**-0.26**	**-0.54**	-0.15	**0.34**	**-0.35**	**-0.46**	**-0.28**	**-0.42**	-0.13
Olea europaea	Fl	**-0.38**	**-0.22**	**-0.33**	**-0.20**	**-0.44**		**0.37**	-0.29	**-0.55**	**-0.49**		**-0.48**
	PS	**-0.53**	**-0.53**	**-0.54**	**-0.38**	**-0.51**		-0.14	0.19	**-0.24**	**-0.32**		**-0.62**
	PP	**-0.46**	-0.17	-0.09	0.10	**-0.35**		0.09	0.22	**0.32**	**0.33**		0.08
	FR	**-0.54**	**-0.47**	**-0.37**	**-0.31**	**-0.35**	-0.01	**0.17**	**-0.37**	**-0.56**	**-0.46**	-0.08	-0.21
Triticum vulgare	Fl	**-0.28**	**-0.21**	-0.02	0.02	**-0.15**		**0.47**	0.20	**-0.26**	-0.10		-0.25
	PS	0.18	0.14	-0.04	-0.15	-0.05		-0.14	**-0.26**	**-0.25**	**-0.33**		-0.02
	PP	**-0.19**	-0.08	-0.04	0.19	0.06		-0.08	0.17	-0.02	0.04		0.09
	FR	**-0.21**	0.28	0.04	-0.05	**-0.19**		-0.05	-0.05	-0.04	0.01		-0.02
Hordeum vulgare	Fl	0.29	-0.02	-0.11	0.29	-0.03		0.03	0.30	**0.23**	0.07		-0.18
	PS	0.18	0.14	-0.04	-0.15	-0.05		-0.14	**-0.26**	**-0.25**	**-0.33**		-0.02
	PP	**-0.19**	-0.08	-0.04	0.19	0.06		-0.08	0.17	-0.02	0.04		0.09
	FR	-0.02	0.35	0.16	0.16	-0.09		-0.05	0.06	-0.04	0.09		0.21

Table 3. a.

	Phase	Tmx	T	Tmn	T_{j-a}	T_{j-jn}	T_{s-n}	T_{s-n}^{-1}	Rf	Rf_{j-a}	Rf_{j-jn}	Rf_{s-n}	Rf_{s-n}^{-1}
Olea europaea	Fl	**-0.40**	**-0.45**	**-0.32**	**-0.23**	**-0.37**		0.26	0.17	0.04	0.04		0.24
	PS	-0.17	-0.16	-0.06	-0.08	-0.18		**-0.30**	0.02	0.22	0.11		0.01
	PP	-0.13	0.03	**0.32**	0.21	0.22		0.30	0.16	0.05	0.11		-0.02
	FR	**-0.57**	**-0.62**	**-0.38**	**-0.32**	**-0.38**	**-0.56**	**0.56**	0.24	0.09	0.06	0.13	0.11
Triticum vulgare	Fl	0.04	-0.11	**-0.35**	**-0.30**	**-0.30**		-0.18	**-0.27**	**-0.24**	-0.20		0.23
	PS	-0.21	**-0.27**	**-0.24**	0.06	**-0.23**		**-0.33**	-0.11	**-0.25**	**-0.30**		0.22
	PP	-0.13	-0.02	0.21	0.12	0.09		**0.37**	0.15	-0.20	-0.12		0.03
	FR	-0.17	-0.02	**-0.29**	-0.03	-0.09		0.21	**-0.33**	-0.11	-0.19		0.17
Hordeum vulgare	Fl	**-0.38**	**-0.33**	-0.07	-0.12	-0.22		-0.32	-0.11	0.11	-0.02		-0.04
	PS	-0.21	**-0.27**	**-0.24**	0.06	**-0.23**		**-0.33**	-0.11	**-0.25**	**-0.30**		0.22
	PP	-0.13	-0.02	0.21	0.12	0.09		**0.37**	0.15	-0.20	-0.12		0.03
	FR	-0.05	0.09	-0.29	-0.25	-0.19		**0.51**	-0.05	0.28	-0.08		0.07
Vitis vinifera	LF	**0.63**	**0.34**	**0.16**	0.09	0.04	**-0.22**	0.09	0.21	0.06	0.03	**0.30**	0.10

Table 3. b.

	Phase	Tmx	T	Tmn	T_{j-a}	T_{j-jn}	T_{s-n}	T_{s-n}^{-1}	Rf	Rf_{j-a}	Rf_{j-jn}	Rf_{s-n}	Rf_{s-n}^{-1}
Quercus faginea	FO	**-0.33**	**-0.40**	**-0.41**	**-0.75**			0.17	**-0.33**	-0.13			0.03
Quercus ilex	PS	-0.11	-0.08	-0.04	-0.10	**-0.33**		0.01	**0.33**	0.07	-0.05		**-0.61**
	PP	**-0.52**	**-0.42**	-0.25	0.02	-0.22		-0.07	**0.48**	**0.52**	**0.44**		0.29
	FR	**-0.70**	**-0.72**	**-0.64**	**-0.58**	**-0.69**	-0.60	-0.31	-0.16	-0.08	-0.12	-0.03	-0.28
	Fl	**-0.74**	**-0.71**	**-0.59**	**-0.73**	**-0.78**		-0.18	-0.25	-0.08	-0.01		-0.05
	PS	0.09	0.15	0.18	-0.01	**-0.39**		**0.33**	**0.47**	**0.28**	**0.36**		**-0.47**
Olea europaea	PP	-0.08	**-0.27**	**-0.47**	**-0.36**	**-0.27**		-0.36	**-0.34**	-0.18	-0.12		**-0.26**
	FR	-0.10	-0.04	0.06	0.12	-0.03	0.15	**0.66**	0.20	0.24	**0.33**	**-0.31**	0.12
	Fl	**-0.59**	**-0.57**	**-0.44**	-0.63	-0.67		**-0.46**	0.03	0.02	0.03	-0.02	-0.17
	PS	**-0.36**	**-0.44**	**-0.46**	**-0.26**	-0.19		**-0.39**	-0.34	-0.41	-0.43	0.08	0.21
Secale cereale	PP	-0.17	**-0.31**	**-0.44**	-0.36	-0.16		-0.27	-0.23	-0.28	-0.33	0.13	-0.25
	FR	**-0.52**	**-0.42**	-0.25	0.02	-0.22		-0.07	**0.48**	**0.52**	0.44	0.20	0.29
	LF	**0.27**	0.21	0.09	0.18	0.20	**0.25**	**-0.39**	-0.18	-0.42	-0.45	-0.18	0.17
Vitis vinifera	FR	**-0.32**	**-0.30**	-0.24	-0.14	**-0.39**	-0.16	0.23	0.00	0.11	0.12	-0.24	-0.25
	FO	**-0.63**	**-0.62**	**-0.48**	-0.53	**-0.57**		**0.36**	-0.07	0.05	0.22		-0.04

Table 3. c.

	Phase	Tmx	T	Tmn	T_{j-a}	T_{j-jn}	T_{s-n}	T_{s-n}^{-1}	Rf	Rf_{j-a}	Rf_{j-jn}	Rf_{s-n}	Rf_{s-n}^{-1}
	Fl	-0.01	-0.20	**-0.38**	**-0.50**	**-0.24**		0.17	0.31	0.12	**0.33**		**0.28**
	PS	0.21	-0.01	**-0.23**	0.05	0.03		0.21	0.10	**0.31**	0.11		0.09
Hordeum vulgare	PP	-0.03	-0.07	-0.08	-0.13	0.02		0.16	0.10	-0.13	0.31		**0.34**
	FR	**-0.37**	**-0.43**	**-0.39**	**-0.38**	**-0.39**		-0.30	**0.42**	**0.38**	0.22		**0.28**
	Fl	**-0.81**	**-0.80**	**-0.70**	-0.28	**-0.82**		-0.03	-0.04	**0.37**	0.14		0.26
	PS	0.21	-0.01	**-0.23**	0.05	0.03		0.21	0.10	**0.31**	0.11		0.09
Triticum vulgare	PP	-0.03	-0.07	-0.08	-0.13	0.02		0.16	0.10	-0.13	0.31		**0.34**
	FR	-0.11	-0.19	-0.23	0.12	-0.35		-0.08	**0.52**	**0.34**	**0.34**		0.06
	Fl	**-0.36**	**-0.45**	**-0.43**	-0.07	-0.16		0.17	0.14	-0.05	0.11		0.11
	PS	0.21	-0.01	**-0.23**	0.05	0.03		0.21	0.10	**0.31**	0.11		0.09
Secale cereale	PP	-0.03	-0.07	-0.08	-0.13	0.02		0.16	0.10	-0.13	0.31		**0.34**
	FR	**-0.36**	**-0.41**	**-0.36**	-0.25	**-0.39**		-0.24	**0.43**	**0.40**	0.19		0.19
Vitis vinifera	FR	**-0.29**	**-0.24**	-0.17	0.39	0.12	**-0.77**	**-0.53**	0.12	0.19	0.05	**0.33**	0.11
	FO	**-0.32**	**-0.09**	-0.17	-0.46	-0.32		-0.04	**0.60**	-0.19	0.27		-0.01

Table 3. d.

Phases: Fl, flowering; PP, Pollen Start; PP, Pollen Peak; FR, Fruit Ripening; FO, Foliation; LF, Leaf Fall. **Meteorological factors**: Tmx, Annual Maximum Temperature; T, Annual Mean Temperature; Tmn, Annual Minimum Temperature; Tj-a, Mean Temperature from January to April; Tj-jn, Mean Temperature from January to June; Ts-n, Mean Temperature from September to November; Ts-n-1, Mean Temperature from previous September to November; Rf, Annual Cumulated Rainfall; Rfj-a, Cumulated Rainfall from January to April; Rfj-jn, Cumulated Rainfall from January to June; Rfs-n, Cumulated Rainfall from September to November; Rfs-n-1, Cumulated Rainfall from previous September to November.

Table 3. Spearman correlation values for each species and phenophases in Pozoblanco (a), Bujalance (b), Huescar (c) and Charcones (d). p values < 0.05 are highlighted in bold.

4. Discussion

Although with some delay, probably due to the distance between field phenological stations and aerobiological stations, field phenological and aerobiological data showed similar patterns in the study species, especially in tree species. The higher differences in the herbaceous species patterns are probably influenced because cultivated grass species (as the observed in the present work) contribute in a lower percentage than wild species to the grass pollen curve (Muñoz et al., 2000; Subiza et al., 1992). In general the results indicated a general trend towards earlier onset of phenological phases, except for *Hordeum vulgare*. Shifts in leaf phenology were stronger than those previously reported for Europe by Menzel & Fabian (1999), who noted a 6-day advance in leaf unfolding and a 4.8-day delay in leaf fall over a 30-year period. The increase in growing-season length due to the earlier start recorded here also exceeds the 7 days reported for Europe between the 1960s and the 1990s, but largely coincides with the effect reported from the 1980s onwards (Keeling et al., 1996). The observed advance was also more marked than that found in North America by Bradley et al. (1999) and Abu-Asab et al. (2001). Also the observed trends are stronger that those reported in other Mediterranean areas such as California and Australia (Denisson & Roberts, 2003; Sadrasa & Monzon, 2006). The findings of the present study agree with those reported for other areas of southern Europe, in pointing to a bringing-forward of pollen-season start-dates and peak pollen counts in *Olea europaea* and *Quercus* species, and to a lesser extent in Poaceae (García-Mozo et al., 2008a; 2008b; 2009).

Although we must take into account the low significance in some of the results due to a high degree of variability in the analysed dates, the data recorded here suggest a more marked advance in southern than in north-eastern Spain, where Peñuelas et al. (2002) report during 1952-2000, an advance of 7.8 days for *Quercus ilex* flowering and 17 days for *Vitis* leaf unfolding, while flowering for *Olea europaea* and *Quercus faginea* displayed no significant trends. Data for a north region of Spain, show a lack of any apparent trend in the phenology of herbaceous crops, similarly to the results obtained in the present work.

The increase in mean annual temperatures over the study period appears to be the most marked since the mid-1970s, thus matching Mediterranean and global trends (Jones et al., 1999; IPCC, 2001). The detected increment of temperature in Spain (1.5ºC) during the last century has been greater than those calculated for the world global average (0.6±0.2ºC) or for Europe (0.5ºC). (IPCC, 2001; IPCC, 2007). Climate change has had a particularly marked effect on southern Spain, increasing temperatures up to 4ºC in last years (INM, 2002; De Castro, 2005; Ayala-Carcedo, 2004). Changes in rainfall patterns have been less pronounced, although a slight drop in annual rainfall was recorded for Andalusia over the last few years. Also during this period rainfall has also become increasingly torrential (Pita, 2003; De Castro et al., 2005).

Phenological changes displayed a strong correlation with temperature changes and especially with temperature over the months prior to the reproduction phase. The months preceding any given phenological event appeared to be the most important for the majority of the species. It was noteworthy that the previous autumn temperature influenced flowering in tree species, probably due to temperature in this period is related to vernalisation and to chilling requirements; the amount of chilling the plant receives in autumn is related to heat accumulation in spring. The correlations between flowering and fruit ripening and rainfall were mostly slight, although the correlation was more marked for grass species – which displayed fewer phenological changes over the study period – than for tree species. The shift towards more arid conditions, owing to increased temperatures and to the slight drop in rainfall recorded in Andalusia, may strengthen this correlation in the near future (Peñuelas et al., 2002).

At the same time, the potential effects of airborne CO_2 levels on phenological phases such as flowering and fruiting cannot be ruled out (Peñuelas et al., 1995). Global climate warming seems to be the main cause of phenological changes, but other factors - including less rainfall and CO_2 enrichment – may also affect them. Field phenological and aerobiological data are important bio-indicators of the ongoing ecosystem change, and can provide a general idea of how future climate change may be the major driver of changes in biodiversity.

5. Conclusions

Flowering patterns matched aerobiological data for the study species, and particularly for trees. Preliminary results suggested a general advance in flowering, foliation, and fruit ripening for most of the species examined in this study, especially significant for flowering dates. That general advance was more marked in trees than in herbaceous species, in which flowering dates – more closely determined by water availability – displayed little change. The advance of phenological phases in trees was more evident than in the rest of the studied species. Increased temperature was the main factor affecting the advance in foliation, flowering and fruit ripening and the delay in leaf fall dates. Potential effects of the change in phenology on the growth and yield of these species can lead to an increase of crop size. Herbaceous species were more affected than tree species by changes in rainfall patterns. In conclusion, field phenological data and aerobiological data are important bio-indicators of ongoing ecosystem changes, and can provide a general idea of how future climate change may be the major driver of changes in biodiversity.

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