ORIGINAL ARTICLE

Impacts of climate change on airborne *Quercus* pollen trends in Andalusia region (southern Spain)

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Abstract

Quercus species are the most frequent autochthonous arboreal taxa in the natural areas of Andalusia region (southern Spain). Due to their abundance and anemophilous character, high airborne pollen concentrations are detected in natural and urban areas of the region. Variations in its reproductive phenology can be considered an important bio-indicator regarding the impacts of climate change on vegetation in the Mediterranean region. This study aims to analyze trends in flowering patterns using airborne pollen concentrations from the capital cities of the 8 provinces of Andalusia region and to study its relationships with meteorological parameters and climate change over decades. Variations in time and intensity of flowering have been studied using different methods for defining the pollen season. This study demonstrates that for comparing results, it is relevant to choose the right definition to calculate the pollen season. The analysis of historical databases of *Quercus* airborne pollen in Andalusia showed variations in the floral phenology with an increase in the intensity of the pollen season throughout the studied period and an advance in the start trends due to the increase of temperature. Nevertheless, this increase might have been smoothed by the decrease of precipitations in some sampler locations, a limiting factor in the area. It has been also observed a delay in the end dates that caused a lengthening of the season. Climate change could be provoking longer and more intense pollen seasons that will lead to more intense and persistent symptoms in sensitive patients.

Keywords *Quercus* · Climate change · Airborne pollen · Trends · Andalusia

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Introduction

Quercus is a common tree being a genus of importance in forests of Europe. Former studies on trends in *Quercus* pollen in 10 European sites from Spain to Sweden found higher *Quercus* pollen levels and longer seasons in South Spain. Long *Quercus* seasons were observed in different regions due to several *Quercus* species flowering at different times that add complexity to the study of this pollen type (Grundström et al. 2019). In the region of Galicia (NW Spain), a study of airborne *Quercus* pollen counts found a significant trend towards rising *Quercus* pollen indices and higher maximum daily mean pollen counts was observed in Ourense, linked to the more marked temperature increase (Jato et al. 2014). Similar studies have been conducted in Northern Europe. In Benelux, *Quercus* has most likely been tending to emit and disperse more pollen over time (Weger et al. 2021). In UK, most of the changes identified were caused by climate drivers of increasing temperature and sunshine total. *Quercus* pollen season is starting earlier and lasting

longer (Adams-Groom et al. 2022). In Stockholm region of Sweden, the pollen season of *Quercus* was found to start earlier and has an earlier peak date. Also, a significant trend towards an earlier end date was found but the length of the season was unaffected. The trend of increasing yearly mean air temperatures in the Stockholm area may be the reason to changed phenological patterns of pollen seasons. Finally, a trend towards an increase in yearly concentrations of pollen was observed (Lind et al. 2016).

Quercus species are the most frequent autochthonous arboreal taxa in the natural areas of Andalusia region (southern Spain). Due to their abundance and anemophilous character, high airborne pollen concentrations are usually detected in natural and urban areas of the region. Climate change is rising global temperatures, which has an impact on ecosystems causing variations in plant phenology that may provoke changes in flowering timing (Lee et al. 2020). Moreover, the increase in the CO_2 atmospheric concentrations and the changes in water availability are affecting plant biomass, and thus flowering intensity (Ziska 2020).

Andalusia, in the western Mediterranean Basin, can be considered a vulnerable area due to the stressful weather conditions that characterize its climate. A temperature increase, together with a decrease in precipitation, would intensify extreme weather events in this climate change hotspot (Giorgi 2006).

For the Mediterranean Basin, the Six Assessment Report (6AR, 2022) of the Intergovernmental Panel on Climate Change (IPCC) projected future annual and summer warming rates 20% and 50% larger than the global average, respectively, with longer and more intensive heat waves. In addition to high temperatures, the main risk factor identified is more severe, frequent, and longer droughts. Precipitation is projected to decrease by around 4% per 1 °C of global warming in the southern Mediterranean basin. Climate change is projected to intensify throughout the entire Mediterranean region. The projected annual mean temperature increase at the end of the century will be in the range of 0.9–5.6 °C, while precipitation will decrease in most areas by 4–22%. These changes will imply severe and irreversible impacts on vegetation and thus on human beings. One of these impacts would concern the wildfire risk: temperature increases are expected to rise the probability of wildfires. In fact, it is estimated that the burnt surface of forests may increase by 96–187% under 3 °C depending on fire management.

Plant reproductive phenology is controlled by temperature, especially in tree species. It has been also proved that plants flowering in early spring, such as *Quercus species* in Andalusia, are more affected by warming than species flowering later in the year (García-Mozo et al. 2010). For this reason and given the vast coverage that *Quercus* formations have in the region, variations in its reproductive phenology can be considered an important bio-indicator

regarding the impacts of climate change on vegetation in the Mediterranean region. On the other hand, although *Quercus* pollen is an allergen source of medium importance in Andalusia, it presents Phl p4–like molecules as a predominant IgE-reactive structure, which supports cross-sensitization with grasses (Egger et al. 2008). Recio et al. (2018) also cited *Quercus* as a moderate allergy cause in many areas of Europe, pointing out cross-reactivity with other pollen types besides grasses, such as *Alnus*, *Betula*, *Castanea*, and *Olea*. In Korea, *Quercus* pollen is also cited as a major respiratory allergen (Kim et al. 2018). Due to the proven presence of allergens in *Quercus* pollen, an increase in airborne *Quercus* pollen concentrations, caused by a rise in CO_2 concentrations and higher temperatures, could lead to an exacerbation of symptoms. Reid and Gamble (2009) pointed out that the fertilizing effects of CO_2 and rising temperatures increase pollen production and the allergen content of pollen grains. These changes in aeroallergen production and thus in human exposure could influence the prevalence and severity of symptoms in patients with allergic diseases. Also, Nielsen et al. (2002) found that increased exposure to aeroallergens increases the risk in the allergic airway diseases. Increases in CO_2 could directly increase the allergenicity of pollen and consequently the prevalence and/or severity of seasonal allergic disease (Singer et al. 2005).

Weger et al. (2021) found that in long-term studies in Benelux, current climate changes are affecting the presence of airborne allergenic pollen with respect to exposure intensity, timing, and duration. In this study, *Quercus* showed a trend towards an increase in the annual pollen integral and peak values and earlier start and end of the pollen season. These dynamics in the observed trend can impact allergenic patients by increasing the severity of symptoms, upsetting the habit of timing of the season and the emergence of new symptoms due to allergens that were weak at first. Adams-Groom et al. (2022) pointed out that important changes in the UK *Quercus* pollen seasons will impact on the health of respiratory allergy sufferers due to longer *Quercus* pollen seasons.

Although many studies focused on the impact of climate change on plant reproductive phenology (Fernández-González et al. 2020; Fernández-Rodríguez et al. 2016; García-Mozo et al. 2010; Galán et al. 2016; López-Orozco et al. 2021; Recio et al. 2018), it is also important to pay attention to the methods used for defining the pollen season (Bastl et al. 2018; Gehrig and Clot 2021; Pfaar et al. 2017) since they are crucial for the study of trends in airborne pollen. The election of the method that suits better the data is conditioned by the purpose of the study, e.g., environmental studies, or clinical trials and it is essential for comparing results (Glick et al. 2021). Grundström et al. (2019) tested 4 common definitions of season start finding that the most accurate definition for *Quercus* pollen start in Europe was

cumulative daily average pollen count reached 50 grains per cubic meter.

This study sought to study possible variations in *Quercus* floral phenology thanks to the historical databases of *Quercus* airborne pollen concentrations that allow detecting variations in both time and intensity of flowering, using different methods for defining the pollen season. The study aims to analyze possible trends in flowering patterns using airborne pollen from the capital cities of the 8 provinces of Andalusia region and to study its relationship with meteorological parameters and climate change over decades.

Material and methods

Study area

Airborne pollen information was obtained from the capital cities of the 8 provinces of Andalusia (southern Spain). Andalusia is the southernmost Spanish region of the Iberian Peninsula; it is the first Spanish autonomous region in population and the second in surface with 87,598 km^2.

Bioclimatic data for the studied cities are shown in Table 1. Cádiz, Huelva, Málaga, and Almería are coastal cities with mild winters and temperate summers due to the proximity of the sea. Sevilla, Córdoba, Jaén, and Granada display a higher degree of continentality, with colder winters and hotter summers. Figure 1 presents the location of the 8 capital cities and the different species of *Quercus* distribution in Andalusia, the most representative arboreal taxon in the Mediterranean forest.

Pollen data

Airborne pollen concentration databases were obtained from sampling stations of the Andalusia Aerobiology Network (RAA) belonging to the Spanish Aerobiology Network (REA). Sampling was performed from 1989 to 2020 (with

variations depending on the studied site; Table 1), using volumetric suction samplers based on the impact principles of Hirst-type spore traps (Hirst 1952), which is currently the prevalent monitoring method in Aerobiology (Buters et al. 2018). This sampler allows continuous monitoring of the atmosphere and produces daily pollen concentrations (daily average of pollen grains per cubic meter of air). Data were obtained following a standardized methodology published in the Spanish Aerobiology Network Management and Quality Manual (Galán et al. 2007), the minimum requirements of the European Aerobiology Society (Galán et al. 2014), and the European standard (EN 16868 2019). Silicone fluid was the adhesive applied for pollen capture and the mounting media was glycerin gelatin with fuchsin. The magnification of the microscope for pollen identification and quantification was 400×, and in each sample, 4 longitudinal transects were counted. The quality of the data was ensured by means of internal training and REA quality control exercises (Oteros et al. 2013).

In this study, both variations in timing and intensity of the *Quercus* flowering were analyzed. The first was studied by means of the start, peak, and end dates of the main pollen season (MPS), while the flowering intensity was indirectly measured using the Seasonal Pollen Integral (SPIn) (Galán et al. 2017). Pollen season parameters were calculated using different methods usually applied in Aerobiology (Table 2). In this study, 6 different MPS definitions were used to find possible variability in trend studies as some authors suggested (Gehrig and Clot 2021; Glick et al. 2021; Pfaar et al. 2017), all of them based on thresholds. More information about the methods and their parameters can be consulted in Table 2 and in Rojo et al. (2019). Percentage definitions were not considered as they are not recommended for trend studies due to the annual pollen integral can change significantly. On the contrary, threshold definitions of the MPS indicate regular occurrence above certain concentrations and are independent of the APIn, thus being recommended for trend analysis (Gehrig and Clot 2021).

Table 1 Characteristics of the study sites. Pollen season data (start date, integral pollen, peak concentration, peak day, and PSD) obtained as an average of the study years and the different used methods. *PSD*, pollen season duration

|	Sampling period	Coordinates	Altitude m a.s.l	Mean temp PS (°C)	Annual rainfall (mm)	PSD	Start date	Integral pollen	Peak concentration	Peak day
Almería	1998/2010	36°50′N, 2°28′W	23	18.72	185.45	55	10/04	1677	168	26/04
Cádiz	1999/2010	36°32′N, 6°18′W	7	18.60	483.97	88	21/03	3895	347	16/04
Córdoba	1995/2020	37°50′N, 4°45′W	123	18.59	586.81	132	07/03	13732	1266	09/04
Granada	1992/2019	37°11′N, 3°35′W	685	15.85	378.66	72	29/03	4075	320	24/04
Huelva	1989/2019	37°16′N, 6°75′W	20	18.34	528.65	87	16/03	4821	523	06/04
Jaén	1993/2020	37°46′N, 3°47′W	550	17.17	473.32	64	28/03	5138	512	20/04
Málaga	1991/2020	36°47′N, 4°19′W	5	18.99	498.88	92	21/03	4661	491	17/04
Sevilla	1993/2020	37°25′N, 5°54′W	10	19.32	522.44	91	13/03	6206	760	09/04
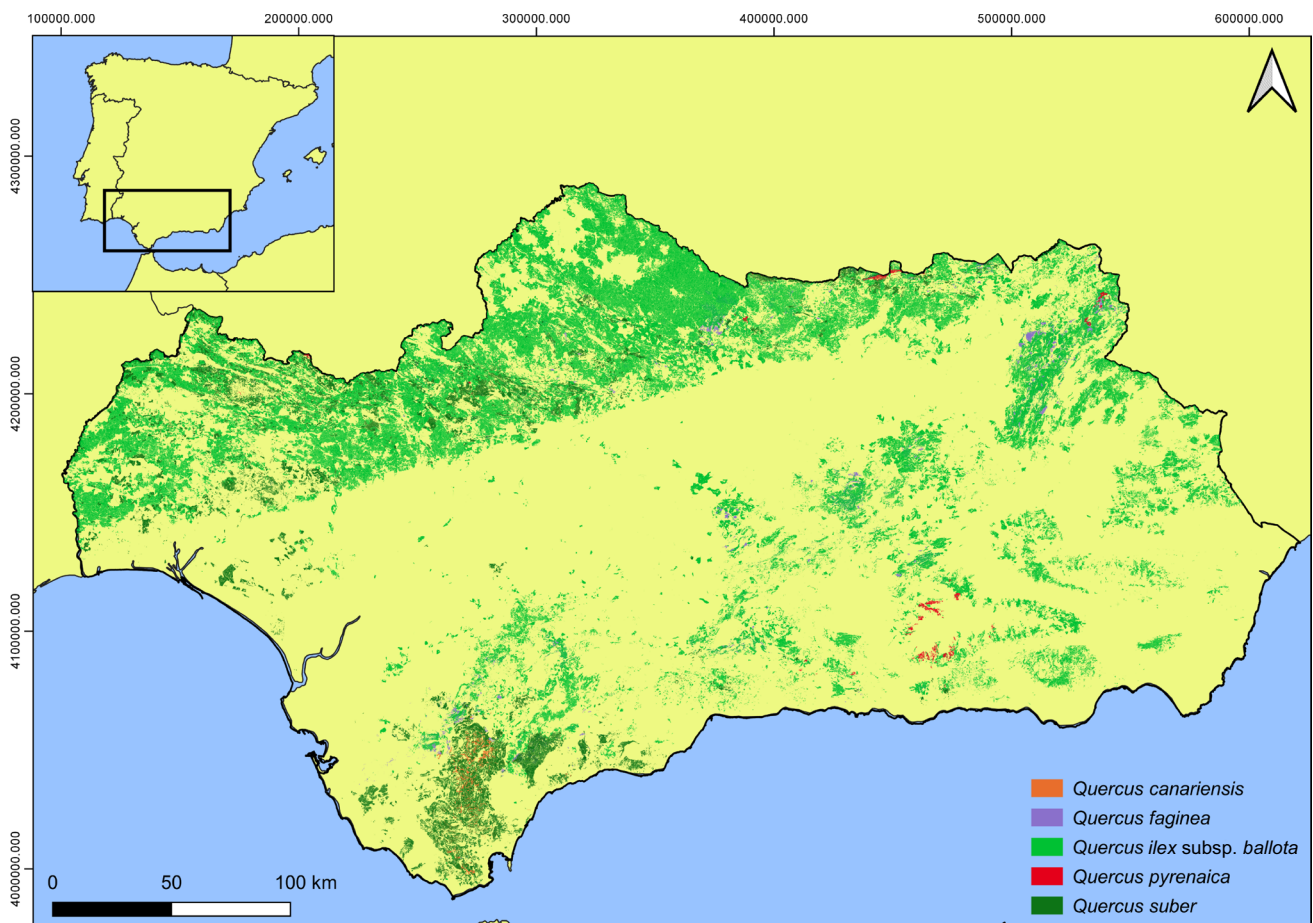
Fig. 1 Location of Andalusia region in Spain and distribution of different species of *Quercus* (CRS ETRS89/UTM zone 30N; geographical information obtained from Junta de Andalucía (2023)). Datos Espaciales de Referencia de Andalucía. https://www.junta deandalucia.es/institutodeestadisticaycartografia/DERA/ Consulted: 22/02/2023

Table 2 List of the six definitions used to determine the start and end dates of the main pollen season (MPS)

MPS definition	Definition type	Pollen season start	Pollen season end
TR20	Threshold	First day ≥ 20 pollen/m^3	Last day ≥ 20 pollen/m^3
3d10	Threshold	First day of 3 consecutive days of pollen with ≥ 10 pollen/m^3	Last day of 3 consecutive days of pollen with ≥ 10 pollen/m^3
3d20	Threshold	First day of 3 consecutive days of pollen with ≥ 20 pollen/m^3	Last day of 3 consecutive days of pollen with ≥ 20 pollen/m^3
5d1	Threshold	First day of 5 consecutive days of pollen with ≥ 1 pollen/m^3	Last day of 5 consecutive days of pollen with ≥ 1 pollen/m^3
5d10	Threshold	First day of 5 consecutive days of pollen with ≥ 10 pollen/m^3	Last day of 5 consecutive days of pollen with ≥ 10 pollen/m^3
Moving	Threshold	First day of 11-day period when moving average pollen concentration is ≥ 5 pollen/m^3	Last day of 11-day period when moving average pollen concentration is ≥ 5 pollen/m^3

To complete the few days with missing data, a linear interpolation was performed by using the "interpollen" function of the AeRobiology R-package (Rojo et al. 2019).

Linear trends of the different characteristics of the MPS (timing and severity) and meteorological variables (mean, maximum, and minimum temperature, and precipitation) were calculated using the Mann-Kendall trend tests. The meteorological variables used for the study were obtained from the historical database of the European Climate Assessment & Dataset (ECA&D, www.ecad.eu) (Tank et al. 2002).

Additionally, Spearman's correlation tests were performed between the MPS parameters obtained with the different definitions and the meteorological data.

Results

Characteristics of the pollen season in Andalusia

The analysis showed that the MPS starts earlier in western Andalusia (early to mid-March) than in eastern Andalusia (from the end of March to the beginning of April) (Table 1). The peak date is also reached first in the western part of Andalusia. The highest *Quercus* SPIn are generally reached in Córdoba, Sevilla, Jaén, and Huelva, in order of intensity. These cities are located in the south of Sierra Morena, a mountain range that crosses the north of Andalusia from east to west, and which is characterized by the dominance of *Quercus* species in their arboreal and shrub stratum, being the most relevant *Q. ilex*, *Q. suber*, and *Q. coccifera* (Gómez-Casero et al. 2007). These species are part of protected natural forests (some converted into "dehesas") of great ecological and economic importance.

Trends in pollen season timing and intensity

As shown in Fig. 2, the intensity (SPIn) of the *Quercus* pollen season generally increased throughout the studied period in the provinces of Andalusia with all the MPS definitions. The trends were significant in Córdoba and Granada for all the MPS definitions, in Cádiz for most of them, and in Jaén with the 3d10 method. In Almería, Huelva, Málaga, and Sevilla trends were not statistically significant. The absolute increases in the SPIn during the studied period were 889 pollen*day/m^3 in Almería, 5440 in Cádiz, 16113 in Córdoba, 2864 in Granada, 1217 in Huelva, 3570 in Jaén, 1077 in Málaga, and 1809 in Sevilla.

In general, there is temporal variability in the onset of MPS between locations and methods used. Cádiz and Granada are the locations that show equivalent trends between the different methods analyzed, negative and positive, respectively. Regarding the MPS start (Fig. 2), trends showed an advance in most provinces. In Cádiz, Córdoba, Málaga, and Sevilla, trends were negative (i.e., significative earlier MPS start dates) when using the 5d1 method. Only Granada presented significant positive trends that imply a delay in the MPS start. In Cádiz, trends were always
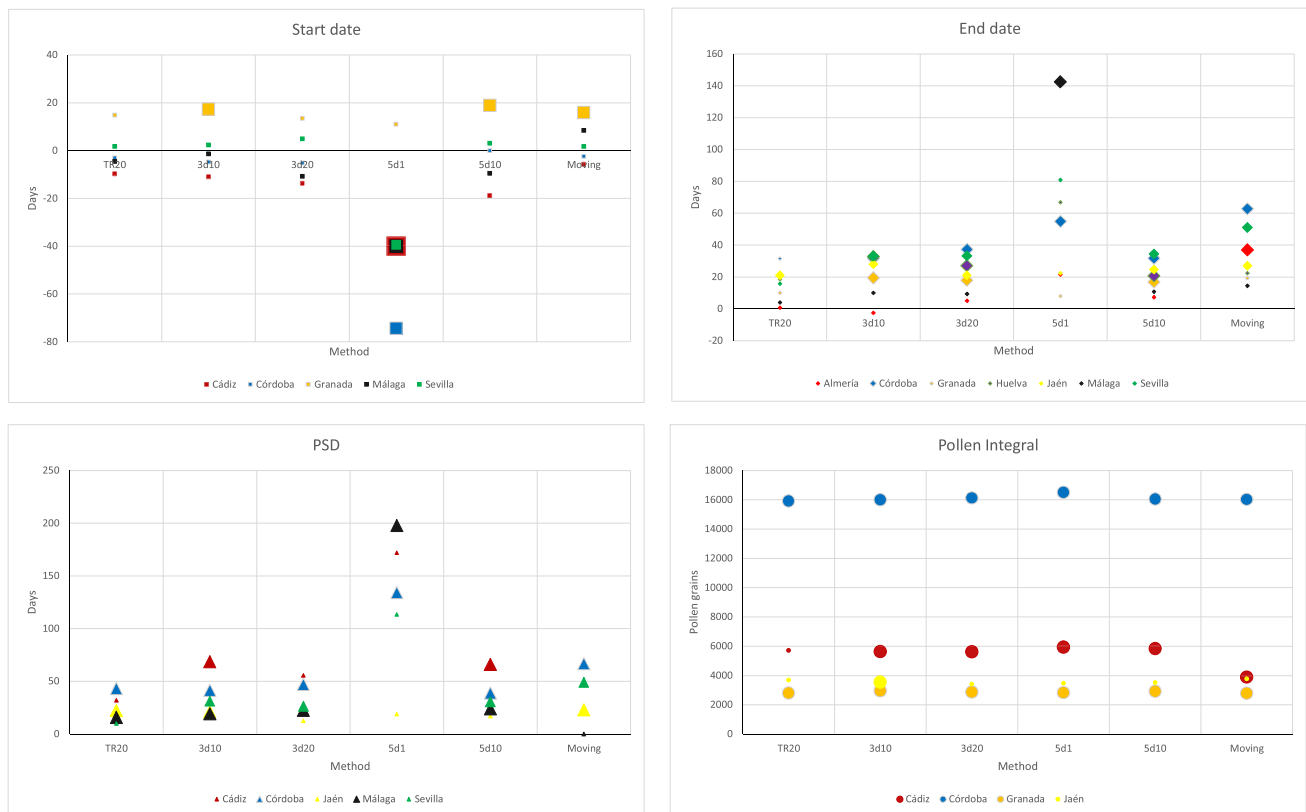

Fig. 2 Absolute trends (pollen grains) of integral pollen and absolute trends (days) of the start dates, end dates, and PSD with six different pollen season definitions for the period 1989 to 2020 in Andalusia. PSD, pollen season duration. Big points show significant trends (*p*-value ≤ 0.05); small points show non-significant trends

negative but only significant with the 5d1 MPS definition, which showed an advance of 40 days. In Córdoba, trends towards earlier start dates were detected with 5 definitions, although only significant when using the 5d1 methods, with an advance of 74 days. In Granada, the MPS start was delayed with all methods, but only significant for the 3d10, 5d10, and moving definitions, with delays ranging from 16 to 19 days. In Málaga, negative trends were detected with all methods except the moving definition. The advance was significant for the 5d1 method, recording an advance of 40 days. Lastly, in Sevilla, results were only significant with the 5d1 definition, detecting an advance of 40 days during the study period.

In the case of the MPS end, results were similar in all sites with a clear delay (significant positive trends) in all the cities (Fig. 2). Almería had a significant delay of 37 days according to the moving MPS definition. In Córdoba, positive trends were significant for all the methods except TR20, with delays ranging from 32 to 63 days. In Granada, positive trends were significant for half of the pollen season definitions, with delays ranging from 8 to 19 days. Also, Huelva and Jaén had significant delays according to most of the methods (from 19 to 67 days, and 21 to 28 days, respectively). In Málaga, a significant delay of 143 days was recorded with the 5d1 MPS definition. In Sevilla, significant delays were detected for the majority of the methods, ranging from 16 to 81 days.

This marked delay observed at the end of the MPS was the cause of the lengthening of the MPS in Cádiz (an increase of 32–172 days during the study period), Córdoba (39–134 days), Málaga (0–198 days), Jaén (13–23 days), and Sevilla (10–144 days) (Fig. 2). In Huelva, Almería, and Granada, trends were non-significant.

The main result of this research was the fact that pollen season definitions have an impact on trends of pollen season parameters. Therefore, it is an important factor to consider on studies analyzing the impact of climate change. In this study, percentage definitions were rejected as they depend on the annual pollen integral. This type of definition is not useful for long-term trend studies of pollen types with high inter-annual variations although they could be useful for pollen types with low airborne pollen concentrations as suggested by Gehrig and Clot (2021). In Andalusia, trend studies would obtain more robust results with threshold definitions given that high *Quercus* airborne pollen concentrations are usually detected. First day with a certain concentration (e.g., TR20) is less stable over time because this level could be reached by chance. Several consecutive days with a given concentration (e.g., 3d10, 3d20, 5d1, 5d10) offer more consistent results. The definition selected depends on the objective of the study. Research focused on allergy studies works better with definitions considering low concentrations while for climate change studies definitions with higher thresholds work better, giving

more stable pollen season parameters. These methods need a regular presence of relevant pollen concentrations. Also moving average showed adjusted results.

Correlation with meteorological variables

A significant increase in temperature (mean, maximum, and minimum) was detected in most sampling locations with the exceptions of the mean temperature in Sevilla during March, the maximum temperature in Almería during winter, and the minimum temperature in Almería for March. Concerning precipitation, it has reduced in Córdoba during December, in Huelva during September, in Granada and Jaén during June, and in Sevilla during May (Table 3). According to our results, the MPS start date and the SPIn were the parameters of the MPS mostly affected by the meteorological variables (Tables 4, 5, 6, and ESM 1).

The MPS start delayed in Granada when raining during pre-flowering periods or at the beginning of flowering (significant positive correlation). On the contrary, the temperature during the previous month to flowering and the flowering period showed a negative significant correlation with the MPS start date, i.e., higher temperatures advanced the MPS start (Table 4).

Negative correlations were detected in some cases between the end of the MPS and precipitation during the MPS, with pollen seasons finishing earlier when higher precipitations were recorded. Temperatures showed, in general, negative correlations with the end of the MPS, i.e., the MPS finishing later with warmer temperatures and earlier with colder ones (Table 5).

In the case of the MPS duration (Table 6), no clear pattern was detected in the correlations for all the study sites. Precipitation caused a shortening of the pollen season in some cases but in others not. Similarly, higher temperatures seemed to produce a shortening in the MPS.

Regarding the SPIn (ESM 1), precipitation recorded during the MPS had a negative correlation, decreasing the total annual concentration recorded while precipitations during the prior month to flowering (February) had a positive correlation with the SPIn. Similarly, the temperatures had a positive correlation during the flowering period, i.e., higher temperatures increase the SPIn. The temperatures of October also had a positive effect on the SPIn in some cases, probably due to high temperatures during that month causing a second flowering in autumn, which increases the SPIn.

Discussion

Regarding the timing of the MPS in the eight provincial capitals of Andalusia, the *Quercus* pollen season started earlier in western Andalusia (near the Atlantic Ocean), than in eastern

Table 3 Meteorological parameters trends during the studied period with significant results. Mean, Max and Min Temp are referred to mean, maximum and minimum daily temperatures. Trend abs shows the absolute linear change of the parameter during the studied period. Trends were calculated with Mann-Kendall trend test and Theil-Sen linear trend slope

	Mean Temp (°C)		Max Temp (°C)		Min Temp (°C)		Precipitation (mm)	
	Trend abs	p-value	Trend abs	p-value	Trend abs	p-value	Trend abs	p-value
Almería 1997–2010								
Annual							110.70	0.029
Winter			−1.57	0.038				
February								
March					−1.21	0.032		
July							0.38	0.026
Córdoba 1994–2020								
Annual			1.35	0.004				
Summer	1.51	<0.001	2.08	0.007	1.14	0.006		
Autumn								
January								
April							32.83	0.012
June								
July								
August	1.16	0.020	1.91	0.033				
September	2.23	0.006	2.36	0.013				
October								
December							−89.91	0.024
Huelva 1989–2019								
Annual								
Spring	1.20	0.030	1.45	0.049	1.16	0.023		
Summer								
Autumn			1.42	0.004				
January			1.07	0.008				
April					1.72	0.019		
May								
June								
August	1.61	0.023	2.22	0.005				
September	1.49	0.041					−12.92	0.045
October	1.70	0.038	2.42	0.023				
December			1.28	0.022				
Málaga 1991–2020								
Annual	1.40	<0.001	1.13	0.000	1.61	<0.001		
Spring	1.49	0.001	0.99	0.031	2.07	<0.001		
Summer	1.91	<0.001	1.57	<0.001	2.19	<0.001		
Autumn	1.40	0.004	1.49	0.011	1.39	0.042		
Winter	1.13	0.037			0.97	0.041		
January			1.59	0.021				
February								
March	1.11	0.008			1.25	0.009		
April	1.33	0.039			2.48	<0.001		
May	1.54	0.009			1.95	0.002		
June	1.94	0.001	2.01	0.010	1.90	0.002		
July	2.16	0.000	1.91	0.007	2.12	<0.001		
August	1.79	0.001	1.18	0.007	2.38	<0.001		
September	2.08	<0.001	1.54	0.009	2.33	<0.001		
October	2.47	0.004	2.69	<0.001				

Table 3 (continued)

	Mean Temp (°C)		Max Temp (°C)		Min Temp (°C)		Precipitation (mm)	
	Trend abs	p-value	Trend abs	p-value	Trend abs	p-value	Trend abs	p-value
Cádiz								
1999–2010								
Annual								
Winter								
February								80.61	0.013
March								
July								
Granada								
1992–2020								
Annual								
Summer	2.09	<0.001	2.77	0.001	1.49	0.003		
Autumn			2.78	0.017				
January			1.33	0.028				
April								
June			2.52	0.038			−5.25	0.033
July	1.35	0.036	1.99	0.020			0.00	0.005
August	2.37	0.002	2.78	0.004	1.61	0.038		
September	2.32	0.001	3.19	0.007	1.81	0.048		
October			4.80	0.014				
December								
Jaén								
1993–2020								
Annual	1.18	0.037	2.04	<0.001				
Spring	1.78	0.036	2.53	0.015				
Summer	2.32	<0.001	3.40	<0.001				
Autumn			2.35	0.011				
January								
April								
May			4.05	0.019				
June							−7.43	0.022
August	2.32	0.002	3.64	<0.001				
September	2.85	0.001	4.02	<0.001	1.62	0.020		
October			3.61	0.008				
December								
Sevilla								
1993–2020								
Annual								
Spring								
Summer								
Autumn								
Winter								
January								
February								
March	−1.85	0.019						
April								
May							−47.44	0.021
June								
July								
August	1.74	0.033	2.50	0.003				
September	2.31	0.005	2.56	0.009	1.83	0.033		
October								

Table 4 Correlation coefficients between meteorological parameters and start dates of the pollen season. Correlation coefficients for all pollen season definitions were averaged. Correlations are significant with $p < 0.05$. Months without significant correlations are not listed

	Jan	Feb	Mar	Apr	May	Jul	Sep	Oct	Nov	Dec
Precipitation										
Almería										
Cádiz	−0.669									
Córdoba				−0.460				0.389		
Granada		0.394	0.416							
Huelva										
Jaén										
Málaga					−0.404		−0.420			
Sevilla										
Max Temp										
Almería										
Cádiz								−0.610		
Córdoba										
Granada		−0.652				0.397				
Huelva									−0.437	
Jaén		−0.605	−0.587							
Málaga		−0.508	−0.620							
Sevilla								−0.558		
Min Temp										
Almería										
Cádiz										
Córdoba										
Granada										
Huelva										
Jaén		−0.465	−0.490							
Málaga		−0.580								
Sevilla		−0.602								0.542
Mean Temp										
Almería										
Cádiz										
Córdoba										
Granada		−0.593								
Huelva										
Jaén		−0.570	−0.572							
Málaga										
Sevilla		−0.475								0.559

Andalusia (near the Mediterranean Sea), which matched the overall flowering pattern reported for other species in the region (Alcázar et al. 2011). Additionally, the distance of the pollen trap to the main *Quercus* vegetal formations in the area might have influenced the start date of the MPS. Long distances seemed to produce a delay in the MPS start date, such as in the case of Almería. A delay trend in the *Quercus* MPS when the main producing source is located at medium or large distance also has been reported by Fernández-Rodríguez et al. (2016) in southwest of the Iberian Peninsula, although the pollen season was calculated with defined percentage.

The increase detected in the airborne pollen concentrations can be provoked by the increase in CO_2 emissions in Andalusia reported by the National Government for Ecological Transition and the Demographic Challenge in their National Inventory Data (Ministerio Transición Ecológica y Reto Demográfico 2020). According to this report, CO_2 emissions to the atmosphere increased from 38,514 Kt in 1990 to more than 50,000 in 2018. Increases in atmospheric CO_2 enhance photosynthesis and growth, which can induce more intense flowering increasing the APIn (Reid and Gamble 2009). However, according to our results, not all the Andalusian provinces presented an increase in the SPIn. Guerrieri et al. (2019) pointed out that the availability of water can limit the effect of increasing CO_2, which can be a determining factor in the Mediterranean area. This might be the case of Sevilla, where a decrease in precipitations was recorded during decisive months for *Quercus* flowering.

Table 4 (continued)

	Jan–Feb	Feb–Mar	Mar–Apr	May–Jun	Jan–Mar	Feb–Apr	Mar–May	Jan–Apr	Feb–May	Jan–May	Feb–Jun	Jan–Jun
Precipitation												
Almería												
Cádiz												
Córdoba												
Granada		0.489				0.415						
Huelva												
Jaén												
Málaga												
Sevilla												
Max Temp												
Almería												
Cádiz												
Córdoba												
Granada	–0.535	–0.590										
Huelva												
Jaén	–0.519	–0.708			–0.654	–0.617		–0.595		–0.429		
Málaga	–0.529	–0.585	–0.432		–0.614	–0.594	–0.413	–0.617	–0.526	–0.546	–0.482	–0.473
Sevilla												
Min Temp												
Almería												
Cádiz												
Córdoba												
Granada												
Huelva												
Jaén	–0.461	–0.579			–0.589	–0.439		–0.413		–0.415		
Málaga	–0.527	–0.552			–0.523	–0.552		–0.600	–0.509	–0.564	–0.466	–0.509
Sevilla	–0.457	–0.505			–0.468		0.978	–0.476				
Mean Temp												
Almería												
Cádiz												
Córdoba												
Granada	–0.491	–0.584			–0.509							
Huelva												
Jaén	–0.528	–0.665			–0.667	–0.557		–0.539		–0.445		–0.409
Málaga	0.473											
Sevilla	–0.524				–0.446			–0.446				

According to our results, the temperatures have significantly increased during spring, summer, and, to a lesser extent, autumn in most sampling locations. Analogously, in Europe, all temperature indices indicate intense warming during the whole year. This temperature rise was more noticeable during winter than in summer (Moberg et al. 2006). Cano et al. (2019) already found important increases in May and June temperatures in Andalusia, while more moderate increases were detected during April and July. Additionally, the annual temperature has significantly increased from 0.15 to 0.4 °C per decade in most locations. The Andalusian Regional Environmental Information Network (Regional Government of Andalusia) found that the Global Warming Index has increased in the last 3 decades when compared to previous data (1961–1990). Additionally, according to the investigations of some authors, the temperature during the hot months could increase by around 4 °C (Giorgi and Lionello 2008; Giannakopoulos et al. 2009; Gabaldón-Leal et al. 2017).

In most of our sampling locations, an advance in the MPS start date was observed although trends were significant or not depending on the definition applied to calculate the MPS start. Higher temperatures have a positive effect on the onset of flowering and, thus, on the MPS start date, causing an early blooming that provokes an advance of the pollen season. In accordance with our results, most of the previous studies dealing with the influence of climate change on pollen season trends detected an advance in the MPS start dates (Ziska

Table 5 Correlation coefficients between meteorological parameters and end dates of the pollen season. Correlation coefficients for all pollen season definitions were averaged. Correlations are significant with $p < 0.05$. Months without significant correlations are not listed

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation												
Almería												
Cádiz												
Córdoba												−0.396
Granada	−0.492						−0.432					
Huelva												
Jaén												
Málaga								−0.382	0.390			
Sevilla												
Max Temp												
Almería						−0.615						
Cádiz			−0.664									−0.627
Córdoba					0.487							
Granada				−0.458							−0.385	
Huelva		−0.412										
Jaén								0.618				
Málaga	0.495		0.449					0.377	0.467			
Sevilla												
Min Temp												
Almería								0.745				
Cádiz												−0.745
Córdoba	−0.430	−0.394										
Granada				−0.446						−0.434		
Huelva												
Jaén												
Málaga								0.423	0.590			
Sevilla							0.679					
Mean Temp												
Almería												
Cádiz												−0.745
Córdoba		−0.530				0.393						
Granada			−0.407	−0.475							−0.393	
Huelva				0.404								
Jaén								0.466				
Málaga												
Sevilla												

2016; Ziska et al. 2019; Anderegg et al. 2021; Rojo et al. 2021). Also, a previous study carried out in different localities of the Iberian Peninsula from 1992 to 2004 showed earlier *Quercus* flowering seasons due to the increased temperatures during the pre-flowering period (García-Mozo et al. 2006).

In our study, there were some sampling locations, such as Sevilla, where a delay in the MPS start was detected for the majority of MPS definitions. It also matched a lack of significant temperature trends during months prior to flowering, which might explain these results. Higher precipitations at the beginning of flowering could also be responsible for the observed delay in the MPS start. A previous study also detected a delay in the *Quercus* MPS start in the North-Western part of the Iberian Peninsula where temperatures

have decreased in the months before flowering (Fernández-González et al. 2020).

According to our results, the temperature in the first month of the MPS and the previous one obtained the highest correlations with the MPS start. Similar findings were observed by Gehrig and Clot (2021), who detected a strong relationship between the MPS start and the temperatures registered during the MPS start month and during the 2 or 3 months before.

A lengthening of the pollen season was observed in the region caused by a marked delay at the end of the pollen season coinciding with many previous studies (Recio et al. 2018; Ziska et al. 2019; Anderegg et al. 2021); a general increase in observed pollen intensity may have also affected

Table 5 (continued)

	Jan–Feb	Feb–Mar	Mar–Apr	Apr–May	May–Jun	Jan–Mar	Feb–Apr	Mar–May	Apr–Jun	Jan–Apr	Feb–May	Mar–Jun	Jan–May	Feb–Jun	Jan–Jun
Precipitation															
Almería															
Cádiz															
Córdoba															0.464
Granada	−0.525														
Huelva															
Jaén															
Málaga									−0.440						
Sevilla															
Max Temp															
Almería					−0.731				−0.736			−0.571			
Cádiz	−0.733						−0.794			−0.733					
Córdoba				0.439					0.506						
Granada			−0.461	−0.382											
Huelva									0.421						
Jaén															
Málaga									0.368			0.374			
Sevilla															
Min Temp															
Almería															
Cádiz		−0.682													
Córdoba	−0.504	−0.571				−0.584	−0.467			−0.469	−0.452		−0.452	−0.454	
Granada			−0.441	−0.469				−0.469			−0.416		−0.409		
Huelva									0.505						
Jaén		−0.409	−0.452				−0.435	−0.410			−0.477		−0.436	−0.540	−0.535
Málaga															
Sevilla															
Mean Temp															
Almería					−0.588				−0.709						
Cádiz						−0.710				−0.648					
Córdoba	−0.563	−0.608				−0.621			0.396	−0.421					
Granada			−0.578	−0.445				−0.462			−0.477	−0.420			
Huelva									0.472						
Jaén															
Málaga															
Sevilla															

this event, but in contradiction with Gehrig and Clot (2021) where a prolongation of the whole pollen season could not be observed. An earlier end of arboreal taxa was also reported by Rojo et al. (2021). Gehrig and Clot (2021) found that trends for pollen season end dates and duration are diverse due to different geographical locations and species presence. On the other hand, differences in data series must be also considered as longer analysis with a higher set of decades can smooth out the variability of pollen data. All these factors can explain contradictory results as Gehrig and Clot (2021) study was carried out in North Europe with different *Quercus* species and different climate than our study, developed in South Europe, predominating woody perennial *Quercus* species. Moreover, in Mediterranean areas,

Quercus species could be adapting their flowering phenology with longer phases and their geographical distribution, increasing in altitude, because of climate change, as concluded by Recio et al. (2018).

The general increase in temperatures together with higher CO_2 atmospheric concentrations could have caused the increase observed in the SPIn. On the other hand, precipitations during the prior month to flowering (February) had a positive correlation with the SPIn causing an increase in it due to more intense flowering. Nevertheless, this increase might have been smoothed by the decrease of precipitations in some sampling locations, a limiting factor in the area that could have diminished the influence of higher temperatures on the MPS start and the flowering intensity.

Table 6 Correlation coefficients between meteorological parameters and duration of the pollen season. Correlation coefficients for all pollen season definitions were averaged. Correlations are significant with $p < 0.05$. Months without significant correlations are not listed

	Jan	Feb	Mar	Apr	May	Jul	Aug	Sep	Oct	Nov	Dec
Precipitation											
Almería											
Cádiz											
Córdoba											–0.484
Granada		–0.393									
Huelva											
Jaén				0.506							
Málaga								0.500			
Sevilla		0.461									
Max Temp											
Almería											
Cádiz											
Córdoba					–0.415					0.405	
Granada		0.476		–0.437							
Huelva											
Jaén							0.404				
Málaga	0.545						0.486	0.434			
Sevilla											
Min Temp											
Almería											
Cádiz											–0.736
Córdoba			–0.415								
Granada				–0.450							
Huelva											
Jaén											
Málaga							0.438	0.607			
Sevilla						0.639					
Mean Temp											
Almería											
Cádiz											–0.682
Córdoba						0.399					
Granada		0.399		–0.444							
Huelva				0.396							
Jaén											
Málaga											
Sevilla											

Many other studies on pollen intensity for arboreal taxa have found clear trends towards more intense pollen seasons (Lind et al. 2016; Hoebeke et al. 2018; Rojo et al. 2021; Anderegg et al. 2021; Gehrig and Clot 2021). López-Orozco et al. (2021) found similar results in Córdoba for the period 1995–2019 with significant rising trends for the intensity and lengthening of the MPS due to a delay in the pollination of *Q. suber*. They also reported warmer springs, summers, and autumns, as well as a decrease in winter and autumn rainfall. In Málaga, Recio et al. (2018) related the increase in the pollination intensity of *Quercus* with increases in the spring temperature. Fernández-González et al. (2020) also detected increases in the APIn in the atmosphere of Ourense during the last decade.

As reported in other studies, *Quercus* pollen type is a good proxy for early-spring flowering taxa, providing the opportunity to detect variations induced by climate warming (Gehrig and Clot 2021). In addition, the importance of investigating this taxon lies in its role in forest conservation, its economic value, and its implication in health due to high rates of sensitization in allergy sufferers as suggested by Fernández-González et al. (2020). The increase in flowering

Table 6 (continued)

	Jan–Feb	Mar–Apr	Apr–May	Jan–Mar	Feb–Apr	Mar–May	Apr–Jun	Jan–Apr	Feb–May	Mar–Jun	Jan–May	Feb–Jun	Jan–Jun
Precipitation													
Almería		–0.622			–0.605	–0.564		–0.599	–0.729	–0.533	–0.713	–0.729	–0.663
Cádiz													
Córdoba													0.517
Granada	–0.493												
Huelva			–0.450			–0.398							
Jaén													
Málaga													
Sevilla													
Max Temp													
Almería													
Cádiz	–0.709			–0.733				–0.709			–0.697		
Córdoba													
Granada	0.462		–0.459										
Huelva													
Jaén													
Málaga	0.411	0.413		0.450	0.404	0.471	0.405	0.511	0.415	0.488	0.527	0.468	0.533
Sevilla													
Min Temp													
Almería													
Cádiz													
Córdoba				–0.402									
Granada			–0.393										
Huelva													
Jaén													
Málaga										0.370			
Sevilla													
Mean Temp													
Almería													
Cádiz													
Córdoba													
Granada		–0.393	–0.499			–0.405							
Huelva													
Jaén													
Málaga													
Sevilla													

intensity and longer pollen seasons will enhance the impact on allergy sufferers. Therefore, studies like this, in which several monitoring sampling locations are analyzed simultaneously, provide stable results that can be useful for estimating the possible implications of climate change (Gehrig and Clot 2021).

Many pollen season definitions are currently used without there being a recommended definition for aerobiological studies since it depends on the aim of the study (Jato et al. 2006). Coinciding with Gehrig and Clot (2021), this study shows the importance of the method selected on trends studies of the pollen season characteristics. Grundström et al. (2019) found the most accurate definition for *Quercus* pollen start in Europe is the cumulative daily average pollen count of 50 grains per cubic meter. Our study found more suitable 3d10, 3d20, 5d1, and 5d10 methods. These methods suit better the data obtained in all provinces of Andalusia. Nevertheless, the use of these methods is suitable for Andalusia but other methods could be more suitable in other areas.

In Andalusia, as in many other areas of the USA and Europe (Barnes 2018; Katelaris and Beggs 2018), increasing CO_2 levels and higher temperatures contribute to the increase of pollen production and the extension of pollen seasons. Also, rising pollution in cities is increasing pollen potency and together with the exposure to particles from wildfires, increased by more and more frequent heat waves in Andalusia, will contribute to the increase in respiratory diseases as pointed out by Barnes (2018). Kim et al. (2018) found that under elevated CO_2 levels, oak trees produced significantly higher amount of pollen and allergenic proteins, contributing to the worsening of the sensitive population.

Conclusions

In Andalusia, the trends obtained by applying different MPS definitions had usually the same direction but were significant or not depending on the method. This study demonstrates that for comparing results from different studies, it is important to pay attention to the definition used to calculate the MPS. Moreover, results are much more robust if several MPS are considered.

The analysis of historical databases of oak airborne pollen concentrations in Andalusia showed variations in the floral phenology with an increase in the intensity of the *Quercus* pollen season throughout the studied period and an advance in the MPS start trends due to the increase of temperature in the previous months to flowering. It has been also observed a clear delay in the MPS end dates in all the cities that caused a lengthening of the MPS.

Climate change with rising temperatures and atmospheric CO_2 concentrations could be provoking longer and more intense pollen seasons that will lead to more intense and persistent symptoms in sensitive patients.

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