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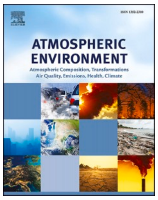

Long-term trends in atmospheric *Quercus* pollen related to climate change in southern Spain: A 25-year perspective

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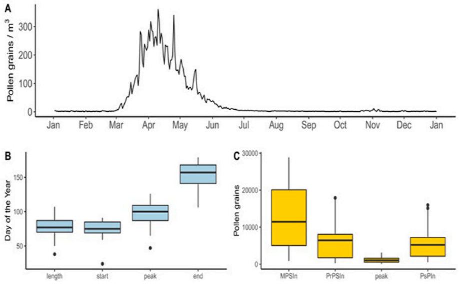
HIGHLIGHTS

- Oaks are bioindicators of the impact of Climate Change on Mediterranean forest.
- Analysis of airborne *Quercus* pollen concentration measured for a 25-year period.
- Strong correlation of meteorological fluctuations on oaks species.
- Increase of oak pollen concentration and pollen season.

GRAPHICAL ABSTRACT



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ABSTRACT

Long-term trends of atmospheric *Quercus* pollen recorded for 25 years (1995–2019) in southern Spain (Cordoba city, Andalusia region) have been studied to determine the influence of climate fluctuations and other anthropogenic factors on Mediterranean oak vegetation areas. Atmospheric pollen analysis revealed different changes on reproductive *Quercus* phenology through the study period. Pollination intensity showed an average cumulated value of the Main Pollen Season Integral of 12,832 Pollen * day/m^3, with a high variability among years (±SD 8,048) and a significant rising trend of 771 pollen grains per year, being stronger in recent years (2014–2019). It was remarkable the high quantity of *Quercus* pollen grains detected out of the Main Pollen Season (703 Pollen * day/m^3 ± SD 431), also increasing in recent years.

Regarding *Quercus* phenology, results indicated as the main *Quercus* species in the area, *Quercus ilex* subsp. *ballota* (holm oak), *Q. coccifera*, *Q. faginea* and *Q. suber,* presented a gradually pollination during spring (from mid-March to early June), although a lengthening of the pollination season is observed in recent years. This phenomenon could be explained by the progressive delay in the pollination of *Q. suber*. Regarding climate factors, a decrease in rainfall, especially during winter and autumn was recorded, along with colder winters but warmer springs, summers, and autumns. These changes were significantly correlated with pollination timing and intensity. The climate parameters most affecting were those related to temperature and sunshine. However, the total annual pollen showed a significant negative correlation with the annual recorded rainfall. Results show that

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recent climatic change, among other factors, are leading to changes in the timing and intensity of the *Quercus* pollen season in the Mediterranean area.

1. Introduction

The present study analyzes atmospheric *Quercus* pollen data from a long-term database comprising 25 years (1995–2019) recorded in southern Spain. The vegetation of the study area is characterized by Mediterranean forest and “dehesa” formations dominated by *Quercus* arboreal species. Both ecosystems are the ecological and economical basis for a 20% Europe territory, providing a high diversity of ecosystem services, and economically, since they are a source of wood, firewood and cork, and their fruits can be used to feed livestock (Cavender-Bares et al., 2016; Kremer and Hipp, 2020; Chețan and Dornik, 2021). The large surface areas of this sort of vegetation involve high concentrations of *Quercus* pollen in the atmosphere. Apart from the allergy interest of this pollen type, indicated as allergenic in different parts of Europe, including Spain (Ianovici, 2009; Skjøth et al., 2013; Pedrosa et al., 2020), the monitoring of this pollen gives a valuable information regarding the behavior and health of this important Mediterranean ecosystem highly threatened by climate change, fragmentation, pollution and anthropization, among other factors (Lee et al., 2016; MacDicken et al., 2016; FAO 2018). Furthermore, the study of long-term pollen databases of anemophilous species provides useful information to understand the impact that changes in ecosystems, biodiversity or land cover can have on plant phenology (Damialis et al., 2007; García-Mozo et al., 2016; Schramm et al., 2021). Nevertheless, this sort of database is scarce due to the difficulty of uninterrupted daily sampling because of the economical and human resource cost related to the continuous optical analysis (Galán and Thibaudon, 2020).

The *Quercus* genus is well represented in the study area in which are dominant the Mediterranean forest and “dehesa” ecosystems, being holm oak especially abundant. In regard to the floral biology of the genus studied herein, all the *Quercus* species are monoecious with unisexual wind pollinated flowers (Tucker et al., 1980), and share pollen with similar morphological characteristics, although they flower at different times throughout the season (Gómez-Casero et al., 2007). Male oak flowers usually produce large amounts of pollen grains that are released into the atmosphere in order to ensure pollination and fertilization (Gómez-Casero et al., 2004), and the aerobiological analysis of *Quercus* pollen grains is, therefore, a valuable bioindicator of seed production (García-Mozo et al. 2007, 2012, 2012; Bogdziewicz et al., 2017).

In the case of *Quercus* aerobiological studies, previous ones have revealed that the climate change is causing variations in phenology and pollination intensity (Galán et al., 2016). In the case of deciduous species, the observed trend indicates that oak pollination tended to occur earlier (Bruffaerts et al., 2018; Gehrig and Clot, 2021). On the other hand, it has been observed in other European areas with perennial *Quercus* species, that the main *Quercus* pollen season dates are changing, especially because pollination is tending to occur later (Damialis et al., 2007; Recio et al., 2018; Fernández-González et al., 2020). These changes can have consequences not only on human pollen exposure, but also on the success of acorn fruiting, and consequently on the local economy and ecology related to the regeneration of these ecosystems (García-Mozo et al. 2007, 2012, 2012; Ziska et al., 2019). Nevertheless, the use of oaks’ airborne pollen data as a useful bioindicator of the response of ecosystems to climate change must be related to the analysis of long-term series as the study performed in the present work, in order to obtain objective and valid conclusions. Concerning other factors that could affect pollen production and release, some studies have demonstrated that atmospheric CO_2 favors the biological activity of plants and photosynthesis, even increasing, floral and pollen intensity (Rogers et al., 2006; Ziello et al., 2012; Galán et al., 2016; Anderegg et al., 2021).

In short, the present study analyzes the dynamics of airborne *Quercus* pollen trends and its relationship with the meteorological parameters during the study period. To achieve this purpose, our study focused on the following three objectives: (1) analyzing the *Quercus* pollen season trends, (2) studying the meteorological parameter trends, and (3) identifying the correlations between the features of the pollen season and meteorological conditions.

2. Materials and methods

2.1. Study area

Pollen data were monitored in the city of Cordoba, (37°53′ N, 4°47′ W, 111 m above sea level -m.a.s.l-), which is located in the Central Andalusia region (southern Spain) of the Iberian Peninsula (Fig. 1), in an aerobiological study that covered 25 years of pollen data (1995–2019). Cordoba is located in the valley of the Guadalquivir River, and is surrounded in the north by the Sierra Morena mountains (200–600 m.a.s.l.), in which the dominant ecosystems are Mediterranean oak forest and ‘dehesa’. The main woody species in this area are four *Quercus* species which are, therefore, the principal contributors to the *Quercus* pollen. These are: *Q.ilex* subsp. *ballota (*Desf.) Samp. *(*holm oak*)*, the most dominant, followed by *Q. suber* L. (cork oak), the best represented in the Atlantic influenced areas of western Iberian Peninsula, *Q. coccifera* L. (kermes oak), which is found in the sunniest areas with poor soils, and *Q. faginea* Lam. (Portuguese oak), which grows in humid ecosystems. All of them are perennial species, except *Q. faginea,* which is a marcescent species.

2.2. Airborne pollen monitoring

A continuous daily pollen sampling from 1995 to 2019 was performed by using a pollen trap placed 20 m above ground level in the city of Cordoba. It was carried out by a volumetric Hirst-type spore trap (Hirst, 1952). Airborne pollen concentration data (pollen grains/m^3) were managed and analyzed following the standard protocol of the Spanish Aerobiology Network (REA) (Galán et al., 2007), which complies with the quality and terminology requirements of the European Aerobiology Society (EAS) (Galán et al. 2014, 2017).

Several parameters defining the pollen dynamics are analyzed in this study. The Main Pollen Season (MPS) was defined as the period in which significant pollen concentrations are recorded in the atmosphere. MPS start was defined as the first day of 5 consecutive days with $\geq$10 pollen grains/m^3, and MPS end was defined as the last day of 5 consecutive days with $\leq$10 pollen grains/m^3. Other parameters analyzed in relation to the MPS were its length in number of days; the Peak value (Peak), as the maximum daily pollen concentration (pollen grains/m^3); and the Peak date as the day of the year when the peak value is recorded. Moreover, the length of the pre-peak season, as number of days from the pollen season start up to the Peak date, and the length of the post-peak season as number of days from the Peak date up to the pollen season end.

In the case of the pollination intensity, other features were analyzed: Annual Pollen Integral (APIn), as the sum of daily pollen concentrations from the whole year (Pollen * day/m^3), and Main Pollen Season Integral (MPSIn), Pre-Peak Season Integral (PrPSIn) and Post-Peak Season Integral (PsPSIn) as the sum of daily pollen concentrations (Pollen * day/m^3) for the corresponding period. The quantity of pollen grains detected outside the MPS, it means the difference between APIn and MPSIn, was also considered. Finally, the number of days recorded that exceeded different thresholds during a year were also analyzed in order to obtain another idea of the intensity of the seasons (Galán et al., 2007): null< 1; low: 1–50 pollen grains/m^3; moderate: 51–200 pollen grains/m^3; high:

>200 pollen grains/m^3.

2.3. Climate and meteorological data

Cordoba has a Mediterranean climate with certain continental features, which are characterized by high temperatures in summer and low temperatures in winter, with alternating wet and dry periods. The annual average temperature is 18.2 °C, and the mean annual rainfall is 605 mm (data from 1981 to 2010, AEMET—State weather agency). Daily meteorological data were provided by the European Climate Assessment & Dataset pertaining to the weather station located at Cordoba airport (37° 50′39″ N, 4° 50′45″ W,90 m.a.s.l.) (https://www.ecad.eu/dailydata/).

The meteorological parameters analyzed were daily mean cloud cover (CC, octa); potential evapotranspiration (ETo), which was determined by employing Hargreaves' formula (Hargreaves y Samani, 1985) and expressed in mm/day; daily precipitation (P), expressed in mm; rainfall days (Pdays, day); relative humidity, expressed as a percentage (RH, %); duration of sunshine, expressed in hours (Sun, h); daily maximum temperature, expressed in degrees Celsius (Tmax, °C); daily mean temperature, expressed in degrees Celsius (Tmean, °C); daily minimum temperature, expressed in degrees Celsius (Tmin, °C); daily maximum wind speed, expressed in meters per second (WG,m/s); and daily mean wind speed, expressed in meters per second (WS, m/s).

2.4. Data analysis

The Shaphiro-Wilk normality test was first performed on the data regarding both the pollen and the meteorological parameters, after which temporal trends of the main aerobiological and meteorological parameters were calculated by considering the normality results. The statistical method selected was the non-parametric Mann-Kendall trend test with Sen's slope estimation (McLeod, 2011). The year 1995 was excluded from the trends analysis as it was extremely dry "*The drought of '95*" and out of long-term range. The pollen data were analyzed and managed by employing the "AeRobiology" package developed for R software (Rojo et al., 2019).

Finally, Spearman correlation analysis was calculated as a non-parametric test in order to evaluate the relationship between aerobiological and meteorological parameters using raw values in both cases.

Separated parts of the MPS (full MPS, pre-peak season and post-peak season) were considered, including even previous months before pollination. The correlations were also run in R software version 4.0.3 (R Core Team, 2020). The correlations of all the aerobiological variables described in section 2.2 with the meteorological ones described in section 2.3 of 'Materials and Methods' were both monthly and seasonal analyzed. Only correlation results presenting highest values, 25% of the whole analyses, were showed in section 3.4 of 'Results' to focus on the main information about meteorological influence.

3. Results

3.1. Main aerobiological features

Fig. 2 shows the main features on the pollen curve, and different variables of the MPS. The average APIn was 13,535 ± SD 8,128 Pollen * day/m^3 with strong variations ranging from 2,555 in 2005 to 28,851 in 2014. MPSIn had an average value of 12,832 ± SD 8,048 Pollen * day/m^3, with a high variability from 2,339 in 2005, to 27,676 in 2014. In the case of the Pre-Peak (PrPSIn) and Post-Peak Season Pollen Index (PsPSIn), they had similar values per year, with 6,723 ± SD 5,457 Pollen * day/m^3 and 6,109 ± SD 4,552 Pollen * day/m^3, respectively.

Regarding the timing of the MPS, it usually started around mid-March and finished around late May, although in some years it extended into the first fortnight of June. Nevertheless, date variations among years were revealed by the standard deviation analysis. The average start date was recorded on 17th March ± SD 9 days; a higher variation has been observed for end dates on 2nd June ± SD 20 days. In the case of pollen season length, it had an average duration of 78 ± SD 18 days. Regarding pollen Peak date, it usually occurred in early-April (8th April ± SD 16 days) (Fig. 2B), with a daily average of 1,287 ± SD 898 pollen grains/m^3 (Fig. 2C). One outstanding event is the fact that, in some specific years, a second pollination took place in autumn, usually

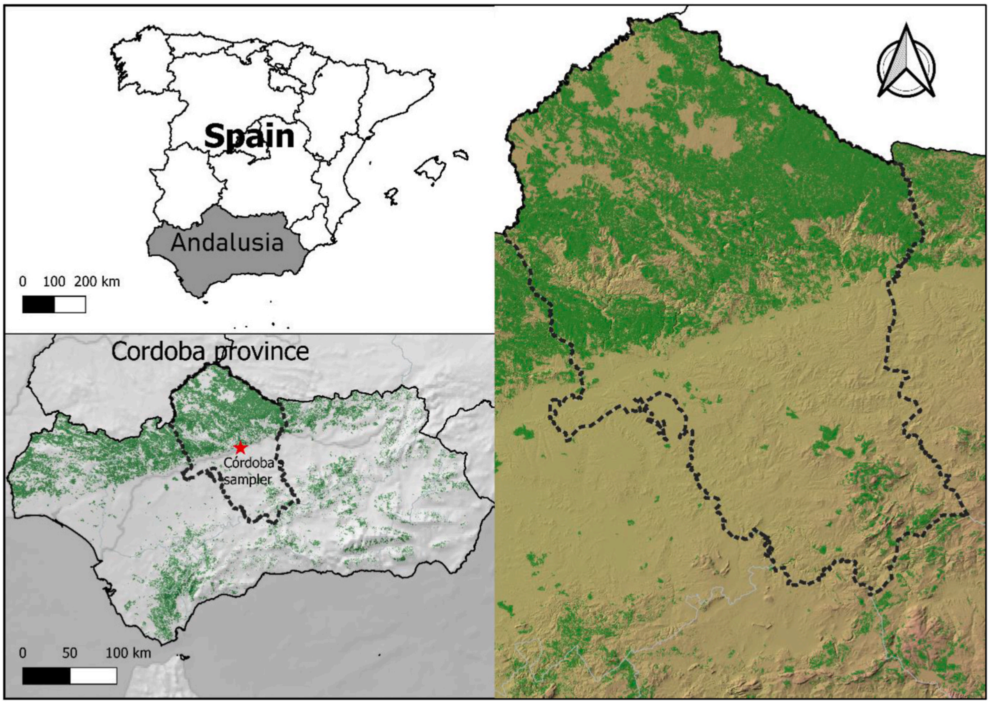

Fig. 1. Study area: Distribution of *Quercus genus* in Andalusia region and Cordoba province (Data source: SIPNA10, "*Plan forestal Andaluz*").

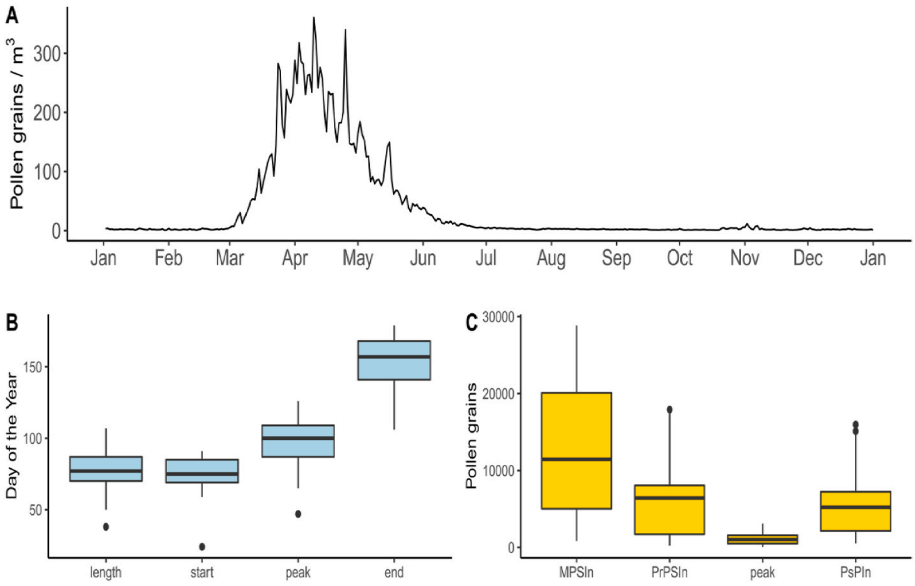

Fig. 2. Seasonal *Quercus* pollen average behavior from 1995 to 2019 in the city of Cordoba (southern Spain). (A) Average daily values of airborne *Quercus* pollen concentration. (B) Characteristics of the Main Pollen Season (MPS): start, end and peak date, and its length. (C) Main Pollen Season Integral (MPSIn, Pollen * day/m^3), pollen peak value (pollen grains/m^3), Pre-Peak and Post-Peak Season Integral (PrPSIn and PsPSIn, Pollen * day/m^3).

in November, although lower pollen concentrations were registered (Fig. 2A). In this respect, pollen grains detected outside the MPS were analyzed, and an average of 703 ± SD 431 Pollen * day/m^3 was detected. The highest APIn results coincided with those years in which a second pollination took place in autumn.

In relation to the number of days recorded that exceeded different thresholds during a year, the results were: 108 ± SD 64 days (null< 1), 195 ± SD 59 days (low: 1–50 pollen grains/m^3), 26 ± SD 9 days (moderate: 51–200 pollen grains/m^3), and 18 ± SD 12 days (high>200 pollen grains/m^3).

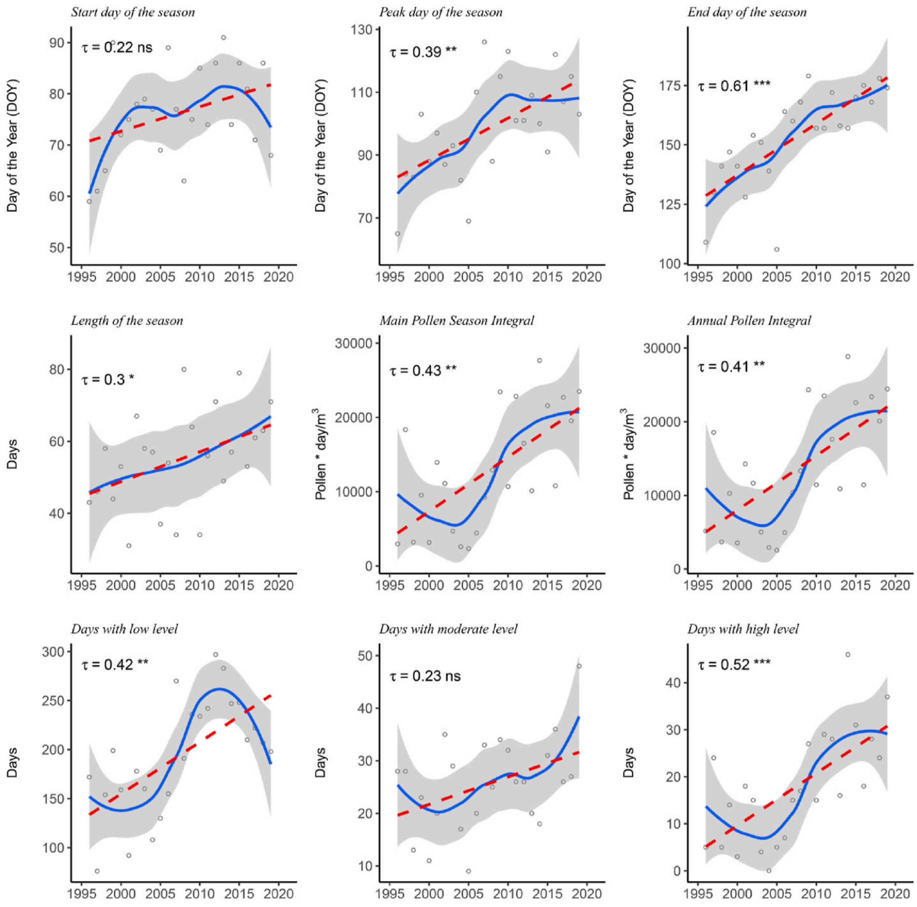

Fig. 3. Trends of the main aerobiological parameters analyzed from 1995 to 2019 in the city of Cordoba (southern Spain). Each graph shows: the regression line (red dashed line); the smoothed trend line LOESS (blue line), and the confidence interval 95% (grey area). Kendall tau and p-value of the Mann-Kendall trend: non-significant (ns), 0.05*, 0.01** and 0.001***. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.2. Aerobiological parameter trends

Fig. 3 shows the trends of the aerobiological features analyzed using the Mann-Kendall trend test with Sen's slope estimation. In regard to pollen concentration parameters, an average increase in cumulated *Quercus* pollen can be observed for both APIn (785 Pollen * day/m^3) and MPSIn (771 Pollen * day/m^3). Nevertheless, if these features are studied in detail, it is possible to observe two different trends: a decreasing trend during the first years of the study, and an increasing trend during the last ones. In the case of pollen grains detected outside the MPS, there was an average increase annually of 27 Pollen * day/m^3.

Significant rising trends were also observed for the number of days with the presence of airborne *Quercus* pollen in the atmosphere. The highest increase was detected for the low level days being an average of 5.5 days per year.

In relation to *Quercus* pollen season dates, an elongation of the MPS was observed (1.4 days per year). All the main dates of the pollen season underwent significant delays: the start date (0.8 days per year), peak date (1.5 days per year) and end dates, (2.2 days per year). The greatest delay was observed on the end of the season date, especially in the recent years. It was, therefore, observed that in the first study years (1995–1999), the average end date was 7th May ± 18 days, while during the following years, 2000–2014, it occurred around the 2nd June ±18 days, and finally, in the last years (2015–2019), the average end date was delayed until 22nd June ± 4 days.

3.3. Meteorological parameter trends

Meteorological parameter trends were estimated by applying the Mann-Kendall test and Sen's slope estimation per season for the 1995–2019 period in the city of Cordoba (Fig. 4). In this Figure, the x-axis represents each season, while the y-axis represents the units per year of the different parameters. It is important to note that the y-axis scale is different depending on the trend range that each variable attains. The values are displayed above or below zero, depending on whether the trend is positive or negative in each case.

The most remarkable trend during the study period was a decrease in rainfall, especially during autumn (−3.5 mm/year) and winter (−4.7 mm/year). A decrease in the number of rainy days in those seasons was also observed: -0.22 and −0.06 days/year, respectively. Relative humidity consequently underwent a general and significant decrease, even in the already dry Mediterranean summer (−0.5% per year).

In the case of temperature, the maximum temperature showed a general increase, except during winter. This increase was more significant in summer, with an average increase of +0.1 °C/year. These trends on maximum temperature followed the same pattern as that obtained for

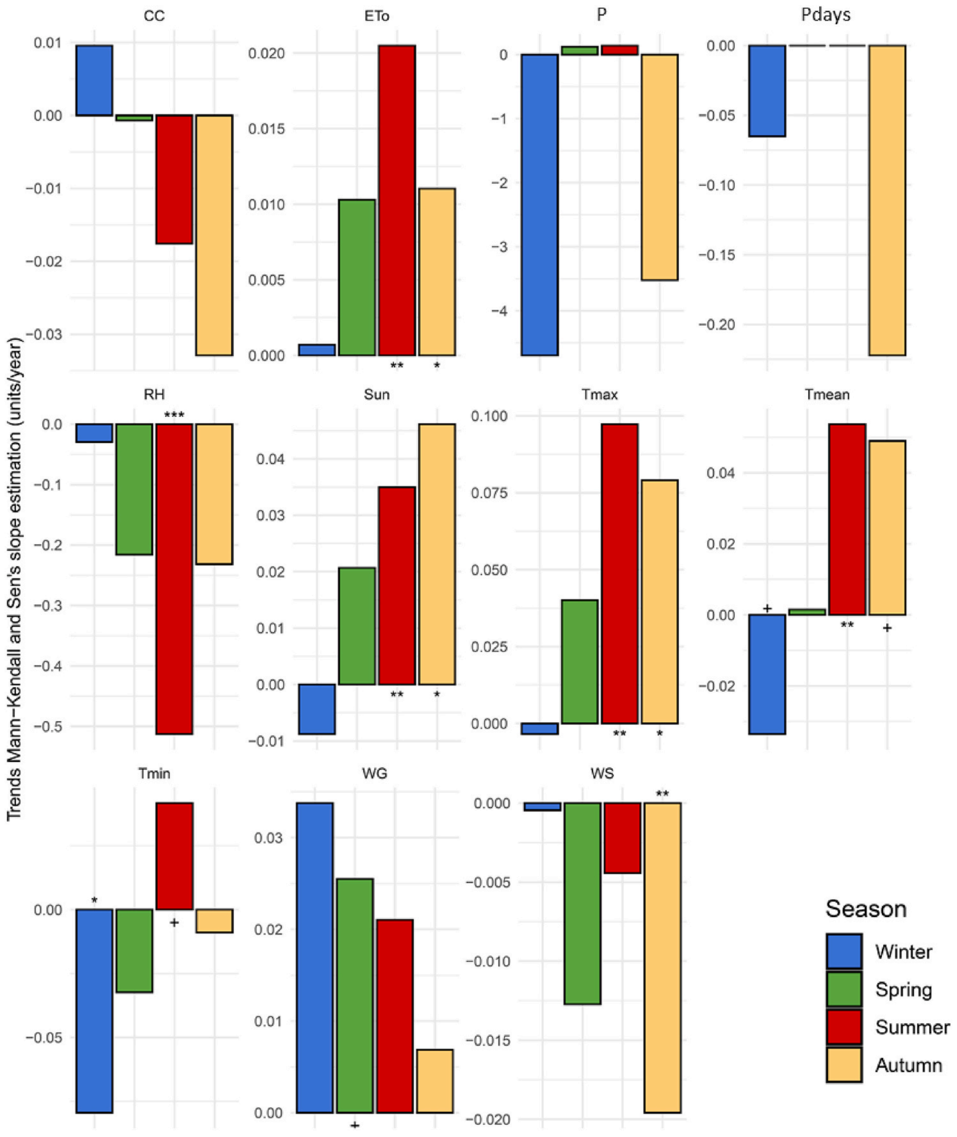

Fig. 4. Trends of meteorological parameters obtained using Mann-Kendall test and Sen's slope estimation (units/year) per season in the city of Cordoba (1995–2019). Parameters: cloud cover (CC, octa); potential evapotranspiration (ETo, mm/day); amount of daily precipitation (P, mm); rainfall days (Pdays, day); relative humidity (RH, %); duration of sunshine (Sun, h); daily maximum temperature (Tmax, °C); daily mean temperature (Tmean, °C); daily minimum temperature (Tmin, °C); daily maximum wind speed (WG, m/s); and daily mean wind speed (WS, m/s).p-value: 0.1+, 0.05*, 0.01** and 0.001***.

evapotranspiration and hours of sunshine. A general decrease was, meanwhile, detected in the case of the minimum temperature, with the exception of summer (+0.04 °C/year).

The study period was generally characterized by a decrease in rainfall, especially during winter and autumn, in addition to colder winters but warmer springs, summers and autumns.

3.4. *Aerobiological-meteorological parameter correlations*

Spearman correlations were calculated not only among the aerobiological features and meteorological data recorded during the pollination season, but also for those recorded during previous months. Regarding the analyses of the pollination season, three different periods were considered: the MPS, and the pre-peak and post-peak periods.

The results obtained for the pre-pollination months indicated low and weak correlations between aerobiological features and meteorological winter conditions. The only remarkable results were related to the MPS start, which was positively correlated with the rainfall in March, signifying that more rainfall led to delayed start dates. The mean temperature in February also affected this but in a negative manner, signifying that a higher temperature led the pollen season to start earlier.

Furthermore, most of the results obtained during the pollination period were quite high and statistically significant. These results are shown in Figs. 5 and 6. In these figures, the correlation values are indicated on the second y-axis, in which the blue circles represent negative correlations, meanwhile, red circles represent positive correlations. Ellipses encompass point clouds, therefore the narrower the ellipse and the more intense the coloration, the higher the absolute correlation. Fig. 5 shows the results related to temperature and wind parameters, while Fig. 6 depicts the correlation results regarding rainfall, relative humidity, cloud cover, evapotranspiration, sunshine, and atmospheric pressure.

Temperature generally had a positive correlation with all the aerobiological parameters analyzed. The end day had a strong positive relationship with the maximum and mean temperatures of the post peak period. There was a similar relationship with respect to season length.

Moreover, cumulated pollen features, such as APIn and MPSIn, had a positive relationship with temperature, being especially significant with the maximum temperature. It was also possible to observe that the higher the temperatures, the fewer the days with less than one pollen grain/m^3 during the MPS.

Regarding the hydric variables, the influence on cumulated pollen values, APIn and MPSIn, was mostly negative, with the exception of evapotranspiration (Fig. 6). In this respect, the major significance and negative correlation was found for relative humidity. In the case of the results regarding temporal phenological features, the end date had a high and positive correlation with evapotranspiration. The rainfall recorded during the pre-peak period also had a positive influence about delaying the peak day, which additionally affected the pre-peak length. Furthermore, relative humidity had a negative influence on the end and peak day.

Finally, hours of sunshine positively affected the APIn and MPSIn values, which attained very high Spearman correlation coefficients. The number of days >200 pollen grains/m^3 was also higher in those springs in which more hours of sunshine were registered, while the cumulated pollen variables decreased during seasons in which there were more cloudy days.

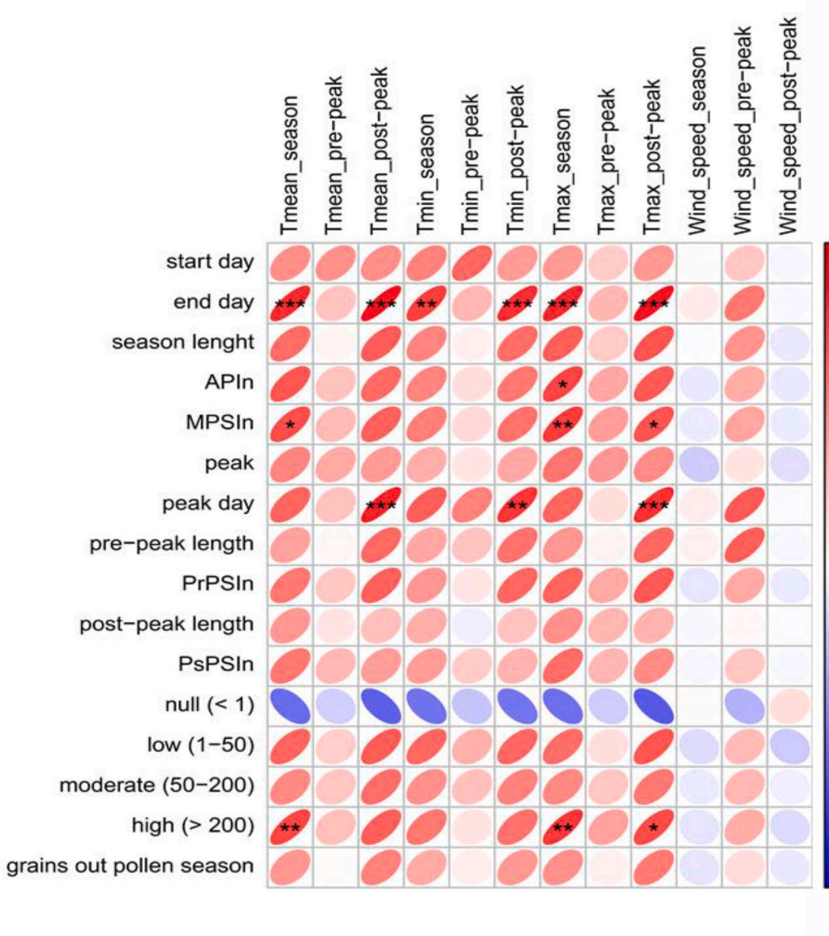

Fig. 5. Spearman correlations between thermal & wind variables and aerobiological parameters for the Main Pollen Season (MPS), pre-peak and post-peak pollen season. Each box represents a point cloud: blue circles (negative correlations); red circles (positive correlations). Ellipses encompass the point clouds. The narrower the ellipse and the more intense the coloring, the higher the absolute correlation. p-value: 0.05*, 0.01** and 0.001***. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

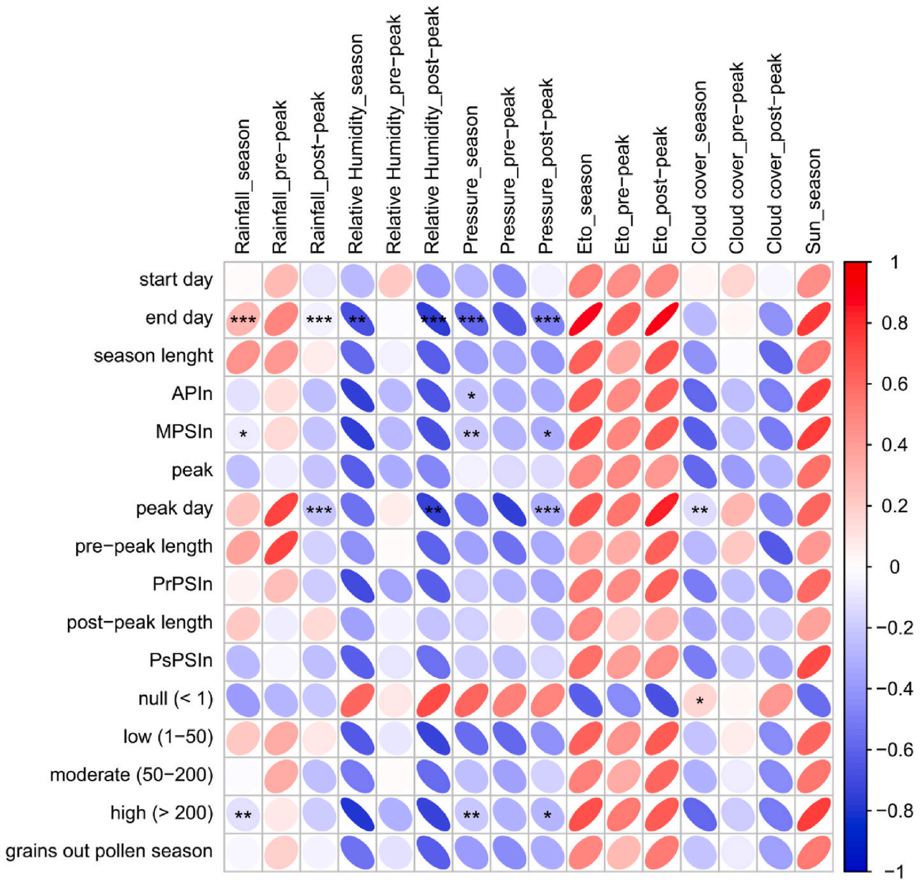

Fig. 6. Spearman correlations between meteorological and aerobiological parameters for the Main Pollen Season (MPS), pre-peak and post-peak pollen season. Each box represents a point cloud: blue circles (negative correlations); red circles (positive correlations). Ellipses encompass the point clouds. The narrower the ellipse and the more intense the coloring, the higher the absolute correlation. p-value: 0.05*, 0.01** and 0.001***. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

Long-term airborne pollen records are useful bioindicators on reproductive phenology of wind pollinated plants in relation to environmental and climate change (García-Mozo et al., 2010; Galán et al., 2016; De Linares et al., 2017). In this sense, arboreal species, and especially those that flower in early spring, would appear to be the most sensitive to these changes. This is the case of the *Quercus* genus in southern Spain. The study of their airborne pollen trends during the recent 25 years provides an excellent opportunity to obtain a better understanding of the state of conservation and evolution of both the Mediterranean forest and the 'dehesa' ecosystems in this area, which are greatly affected by anthropization and climate change (Gea-Izquierdo and Canellas, 2014; Camarero et al., 2016; López-Sánchez et al., 2016).

Our data reveal that *Quercus* pollen is recorded over a long period in the atmosphere of this area, and that this period has even lengthened in recent years. The average length of the MPS detected is slightly higher than that found in other studies carried out in nearby areas (Recio et al., 2018; Ruiz-Valenzuela and Aguilera, 2018), and even higher than those observed in other Mediterranean areas (Puljak et al., 2016; Ciani et al., 2020). An analysis of pollen data in conjunction with local field phenology surveys on this genus has revealed that the contribution as regards pollen made by the different oak species in the area occurs gradually. *Q. ilex* subsp. *ballota* is the first to flower around mid-March, followed by *Q. coccifera*, after which the pollination of *Q. faginea* begins, while the season ends with the pollination of *Q. suber* towards the month of June (Gómez-Casero et al., 2004).

In relation to the total pollen registered during the MPS even during the whole year, results revealed higher values of APIn and MPSIn in recent years, as also evidenced by other studies carried out in nearby areas (e.g. Recio et al., 2018; Ruiz-Valenzuela and Aguilera, 2018). Moreover, the cumulated pollen detected outside the MPS is remarkable, and is particularly high in those recent years in which holm oaks undergo a second pollination during autumn. This behavior has been previously described by other authors in the Iberian Peninsula, and would appear to be an occasional phenomenon for some populations, although the factors controlling it remain unknown (Vázquez, 1998; Costa et al., 2015).

Another characteristic of the total pollen figures was its high interannual variability, which does not follow any clear pattern, as occurs with other anemophilous Mediterranean species, e.g. the strong biannual pollination intensity for olive trees (Rojo et al. 2015, 2016). This asynchronous pollen release observed in our data has already been described by different authors for caducifolious and perennial *Quercus* species (Corden and Millington, 1999; García-Mozo et al., 2002; Spieksma et al., 2003; Skjøth et al., 2013; Recio et al., 2018). This behavior is characterized by years in which pollen records are so high that it can be related to mast seeding years producing large acorn crops, a typical feature of the ecology of oak trees (García-Mozo et al., 2007; Kasprzyk et al., 2014; Tanentzap and Monks, 2018). Studies on oak species in the Iberian Peninsula have shown high levels of intra-population genetic diversity that could explain this high interannual variability of pollen production and release (Ortego et al., 2014; Ramírez-Valiente et al., 2019; Shibata et al., 2020). In this respect, it is widely documented that the maintenance of fitness and the evolutionary potential of species in changing environments is mainly due to this intraspecific diversity (Reed and Frankham, 2003; Jump et al., 2009; Pautasso, 2009).

Notwithstanding their high variability, the trend analysis of the cumulated pollen showed a general increase throughout the study period, which has become stronger in the last few years. A similar increase in *Quercus* pollen concentrations is being reported in last years in different areas of Spain (Jato et al., 2015; Galán et al., 2016; Fernández-González et al., 2020). Different factors could be responsible for explaining this trend, one of which may be related to the increase in temperature and CO_2, detected in last years in the Iberian Peninsula (Fonseca et al., 2016; Pérez et al., 2019) that can provoke higher pollination intensity in anemophilous plants. In this sense, several studies have found that the atmospheric CO_2 from anthropogenic emissions favors the biological activity of plants and photosynthesis, thus increasing biomass production and affecting, for example, floral intensity (Rogers et al., 2006; Kim et al., 2018; Galán and Thibaudon, 2020).

Furthermore, it is known that temperature has a positive effect on airborne pollen concentrations by increasing it (Majeed et al., 2018; Ziska et al., 2019). During our study period, there was an increase in temperature in spring, while winters were characterized by lower temperatures. In fact, our results as regards the Spearman correlations between meteorological factors and aerobiological variables showed that the cumulated pollen variables are associated with an increase in the maximum temperature. Moreover, years in which there was a greater intensity of sunshine and low relative humidity during the pollen season favored higher pollen concentrations.

Another factor that may influence this increasing *Quercus* pollen trend is the anthropic influence. In this sense, during the last few years, the regeneration of Mediterranean forests has been favored by the abandoning of crop areas and by reforestation actions that have recently begun to use more and more autochthonous *Quercus* species. In the case of the main *Quercus* species, holm oak, its use in reforestation plans in Spain has risen from 30.23% in 1990 to 63.75% in 2020 (FAO, 2020).

In the case of timing phenological trend parameters, a general delay in the MPS has been observed. Although this was detected for all the main dates (start, peak and end), it was more significant for the end date, signifying that the pollen season has undergone a significant lengthening in recent years. A similar trend of the *Quercus* pollen season has been detected in other Iberian areas (Jato et al., 2015; Fernández-Rodríguez et al., 2016; Recio et al., 2018; Ruiz-Valenzuela and Aguilera, 2018; Fernández-González et al., 2020). In our case, the meteorological analysis revealed a decrease in rainfall and colder winters in the Cordoba area, which could be responsible for the delay in the start of the pollination of the *Quercus* species. The decrease in the minimum temperatures detected during spring could also be affecting the later peak and end dates, and this lengthening and delay in the peak and end dates could, in turn, be due to a later pollination of *Q. suber*. Furthermore, Grundström et al., (2019) have showed how oak pollen seasonality might be driven by temperature patterns. In this respect, if climate is changing the biogeographical regions in Europe, oak seasonality might also be altered.

The present work overviews main features of atmospheric *Quercus* pollen in a Mediterranean area for 25 years and reveals that in our area they are undergoing changes. The most evident changes are the increasing rise of airborne pollen together with the lengthening of the pollen season, so more pollen availability for pollination and a major exposure to this pollen would be two of the main consequences of the climate change and other anthropogenic related impacts on the behavior of this atmospheric pollen due to the response of the Mediterranean forest and "dehesa" ecosystems.

5. Conclusions

Our results reveal that *Quercus* pollination in the Mediterranean area is undergoing changes. To detect these changes is essential to understand the phenological, ecological and distribution variations of Mediterranean forests and 'dehesas' ecosystems. Furthermore, the gradual pollination of the main 4 oak species results in high pollen concentrations during the Main Pollen Season, although presenting a remarkable variability. Even the values recorded outside the MPS were significant mainly due to the occurrence of occasional second pollination in autumn in the study area. In the case of temporal *Quercus* phenology, there is a delay in the start and end, and even a longer length of the main *Quercus* pollen season. Moreover, regarding climate factors a decrease in rainfall, especially during winter and autumn was recorded, along with colder winters but warmer springs, summers, and autumns. These changes were significantly correlated with pollination timing and intensity, especially those related to temperature and sunshine. Apart from other factors, results would indicate a clear effect of climate change in the Mediterranean forests and "dehesa" phenology that cannot be considered negative for the ecology of oak trees. An increasing availability of pollen and longer pollen seasons are valuable attributes, which could indicate a good adaptation of Mediterranean oaks to the new climatic scenario and environmental conditions.

CRediT authorship contribution statement

R. López-Orozco: Writing – original draft, Formal analysis. **H. García-Mozo:** Conceptualization, Writing – review & editing. **J. Oteros:** Software, Validation, Formal analysis, Writing – review & editing. **C. Galán:** Supervision, Writing – review & editing.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2021.118637.

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