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Long-term trends and influence of climate and land-use changes on pollen profiles of a Mediterranean oak forest

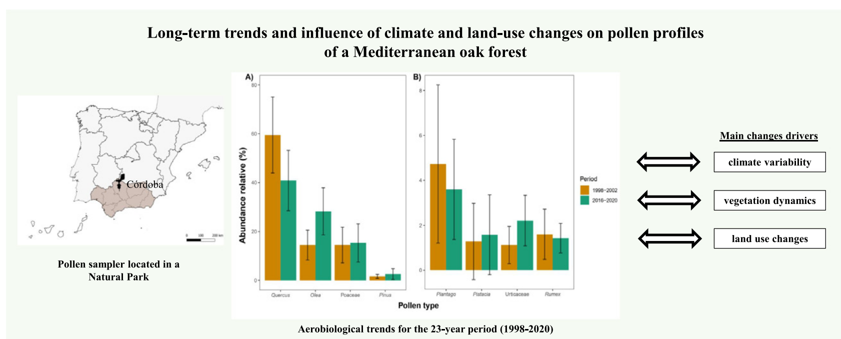
R. López-Orozco *, H. García-Mozo, J. Oteros, C. Galán

Department of Botany, Ecology and Plant Physiology, Agrifood Campus of International Excellence CeiA3, University of Cordoba, Rabbinates Campus, Celestino Mutis Building, E-14071 Córdoba, Spain
Andalusian Inter-University Institute for Earth System IISTA, University of Cordoba, Spain

HIGHLIGHTS

- The airborne pollen concentration has increased for most pollen types during spring over the last 23 years.
- *Quercus* and *Olea* pollen types have undergone significant relative abundance changes in opposite directions.
- Significant correlations between some meteorological and pollen parameters were found.
- Changes in pollen spectrum are related to changes in land use, with increase in agriculture.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change is disrupting phenology and interaction patterns of natural ecosystems, but also human activities that modify land-uses have a direct impact, especially on species distribution and loss of biodiversity. The objective of this study is to evaluate the impact of climate and land-use changes on phenology and airborne pollen spectrum in a Mediterranean natural area, dominated by *Quercus* Forest and 'dehesa', in the South of the Iberian Peninsula. 61 different pollen types were identified over a 23-year period (1998–2020), mainly from trees and shrubs, such as *Quercus*, *Olea*, *Pinus* or *Pistacia*, and from herbaceous plants, such as *Poaceae*, *Plantago*, *Urticaceae* or *Rumex*. A comparison of pollen data from the first years of the study (1998–2002) up recent years (2016–2020), showed a substantial decrease in the relative abundance of pollen from autochthonous species associated with natural areas, such as *Quercus* or *Plantago*. However, the relative abundance of the pollen from cultivated ones such as *Olea* and *Pinus*, which is used for reforestation has increased. Regarding flowering phenology trends, our analyses revealed variations between −1.5 and 1.5 days per year. Taxa showing an advance phenology were *Olea*, *Poaceae* and *Urticaceae*, whereas *Quercus*, *Pinus*, *Plantago*, *Pistacia* or *Cyperaceae* experienced delayed pollination.
Meteorological trends in the area generally resulted in an increase in both minimum and maximum temperatures, along with a decrease in precipitations. Changes in pollen concentration and phenology were correlated with changes in air temperatures and precipitation, although the positive or negative influence varied for each pollen type. The results suggest that climate change together with those motivated by land cover changes lead by human activities are having an impact on the phenology and pollen concentration, with the related consequences on pollination and therefore biodiversity more concerning in threatened areas as the Mediterranean Basin.

* Corresponding author at: Department of Botany, Ecology and Plant Physiology, Agrifood Campus of International Excellence CeiA3, University of Cordoba, Rabbinates Campus, Celestino Mutis Building, E-14071 Córdoba, Spain.
E-mail addresses: rlorozco@uco.es (R. López-Orozco), bv2gamoh@uco.es (H. García-Mozo), b42otmoj@uco.es (J. Oteros), bv1gasoc@uco.es (C. Galán).

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1. Introduction

Climatic change and anthropogenic factors are modeling the current landscape in the Mediterranean area. Climate change is, along with deforestation, the overexploitation of aquifers, and the loss of biodiversity, exacerbating the desertification and erosion processes and the scarcity of water resources. All these processes have contributed to the classification of the area as Biodiversity Hotspot, it means a biogeographic region with significant levels of biodiversity that is highly threatened by different causes, mainly human activities (Myers et al., 2000). Our study area is defined by two natural landscapes that define the Mediterranean area on the Iberian Peninsula, i.e., the Mediterranean oak forest and the 'dehesas', meadow ecosystems containing oak trees whose main purpose is to provide pasture and acorns for the breeding of sheep and Iberian pigs. One of the characteristics of these Mediterranean ecosystems is their high percentage of anemophilous species (García-Mozo et al., 2007, 2022). This feature allows biomonitoring by means of airborne pollen sampling. The analysis of long-term airborne pollen data provides the possibility of studying changes in land cover and biodiversity, and even of evaluating the effects of climate change on floral phenology.

The present study analyses the long-term concentration of airborne pollen in a natural area dominated by the Mediterranean oak forest, and 'dehesas', in which the most abundant tree is *Quercus ilex* subsp. *Ballota* (Desf.) Samp. (holm oak). The presence of *Pinus* is also common in reforestation areas, as is *Olea europaea* which is the main tree species cultivated. Moreover, there are a large number of herbaceous taxa in the 'dehesa' landscape, including grasses (*Poaceae*), *Chenopodium*, *Plantago*, *Rumex* and *Urtica* (López-Sánchez et al., 2016; Petanidou and Vokou, 1990).

Very few previous studies have analyzed airborne pollen in natural areas, because of monitoring stations are mostly located in highly populated urban areas for the purpose of allergy studies (Skjøth et al., 2013). Nevertheless, those studies that do analyze long-term pollen trends from aerobiological stations in the Mediterranean region are indicating that there are some changes in the phenology and distribution of anemophilous species. They are revealing that woody species flowering in winter or early spring, such as *Quercus*, are more influenced by higher temperatures in those periods, than are herbaceous species, such as *Artemisia* or grasses (Romero-Morte et al., 2020; Sofiev and Bergmann, 2012; Wang et al., 2019). The influence of the higher temperature in oaks leads to changes in the pollination timing and the intensity, mainly longer pollen seasons and greater atmospheric pollen availability (López-Orozco et al., 2021). Another important change is the decrease in annual pollen production along with a delay in pollination in herbaceous species, which is probably connected to the decrease in precipitations in the Mediterranean area as a result of climate change (Boullayali et al., 2021; Caloiero et al., 2018; Galán et al., 2016). Climate change is also impacting on the aerobiological processes of pollen dispersion and deposition, stronger precipitation events related to high humidity values provoke a more rapid deposition of pollen from the lower troposphere, thus leading to an important decrease in pollen concentrations under certain conditions (Kluska et al., 2020).

In the case of the Iberian Peninsula current aerobiological studies in different climatic areas are revealing the influence of climate change on plant phenology, especially in the Mediterranean area (Galán et al., 2016; Mercuri et al., 2013). This influence is leading to a wide variety of direct (e. g., significant rising trend of annual pollen concentrations, or delays in the main dates of the floral phenology in *Quercus* species) and indirect effects (problems in pollination, fruit set as well as in the survival of the species) caused by an increase in temperatures, especially maximum and mean, along with decrease in the total amount of precipitation (Dosio, 2016; López-Orozco et al., 2021; Monjo and Martin-Vide, 2016; Valdes-Abellan et al., 2017). The effects of climate change may, therefore, have critical consequences for the dynamics and equilibrium of natural ecosystems, agriculture, health, and the economy (Abd-Elmabod et al., 2020; Jhariya et al., 2019; Ziska et al., 2019).

The present study, which analyze 23 years (1998–2020) of airborne pollen data in a natural area of the aforementioned region, provides the possibility of establishing the real influence of climate, together with the human management of agroforestry systems, on the biodiversity, phenology, and species distribution, especially those of an anemophilous nature, which are abundant and so ecologically important in natural Mediterranean ecosystems. The interest and novelty of the present research also lies in the location of the aerobiological sampler in a natural landscape (20 km from the nearest inhabited area) which has a high environmental value and is denominated under the European Union Habitats Directive as the Biosphere Reserve of 'Dehesas de Sierra Morena' by UNESCO Man and Biosphere program (MAB) in 2002.

The main objective of the present work is to evaluate the impact of climate change and human management on airborne pollen spectrum in this natural area, and therefore the influence on plant biodiversity during recent years. In order to achieve this main objective, the following secondary ones were pursued so as to attain an insightful understanding of problem: (1) an analysis of changes in airborne pollen concentrations, as well as in floral phenology; (2) the characterization of the long-term changes in meteorological conditions and their relationship with observed changes in the floral phenology on anemophilous species and the intensity of airborne pollen, and (3) the detection of changes in land cover uses and how they are related to the observed changes in plant biodiversity.

2. Materials and methods

2.1. Characterization and location of study area

The present study was carried out on the 'El Cabril' estate (38°4′N, 5°24′W) in the limits of the Hornachuelos Natural Park, which is located in southern Spain (Andalusia Region). This Natural Park is part of the Sierra Morena Mountain chain, in the northwest of the province of Cordoba. The average elevation ranges from 450 to 600 m above sea level. The climate is subhumid Mediterranean with an average annual rainfall of 700 mm and an average temperature of 17 °C, with the average of minimum and maximum temperatures being 10 and 23.5 °C, respectively (García-Mozo et al., 2007).

Hornachuelos Natural Park is protected by law by several legal concept: Biosphere Reserve (UNESCO- MaB programme, 2002); Special Protection Area for Birds included in the Inventory of Protected Natural Areas of Andalusia; part of the List of Places of Community Importance, and member of the European Charter for Sustainable Tourism, and Special Conservation Zone (CSMAEA, 2023).

This protected natural area has an extension of >60,000 ha in which the dominant ecosystems are the Mediterranean oak forest and the 'dehesas'. 'Dehesas' are semi-natural meadow formations dominated by evergreen *Quercus* trees cultivated for the breeding of sheep and pigs, which have a high socioeconomic importance in Central and South Spain. The area has a very small population (only 23,450 inhabitants in 2022), which is distributed in 5 small villages in its area of influence (IECA, 2022). The vegetation is characterized by the predominance of *Quercus* L., particularly *Q. ilex* subsp. *ballota* (Desf.) Samp., which flowers in early spring (March–April), followed by *Q. suber* L., which flowers in late spring or even early summer (May–June). The Natural Park also contains areas of riverbank forest, which is associated with rivers and water reservoirs (https://www.juntadeandalucia.es/medioambiente). It additionally has spaces that have been reforested with *Pinus pinea* L. trees and crop areas in which olive trees (*Olea europaea* L.) dominate. The herbaceous species are composed principally of grass genera such as *Avena* sp., *Briza* sp., *Bromus* sp., *Poa* sp. Other prevalent genera are *Plantago* sp., *Echium* sp., *Rumex*., and some fabacean genera such as *Trifolium* sp. are also abundant. In the case of the shrub formations, *Arbutus unedo* L., *Olea europaea* var. *sylvestris* L., *Phillyrea* L., *Pistacia lentiscus* L., *Quercus coccifera* L., *Cistus* sp., and *Lavandula stoechas* L. are the most representative (García-Mozo et al., 2007).

2.2. Airborne pollen, meteorological parameters, and land-use

Aerobiological sampling was performed over a 23 years period (1998–2020) using a Hirst-type volumetric spore trap (Hirst, 1952), located in the area of the 'El Cabril' estate. The sampler was placed on a hill 450 m above a valley dominated by Mediterranean forest vegetation, 20 km from the nearest village. Daily pollen data were managed and analyzed during spring period, from March 20th to June 21st, by 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) and European standard EN 16868 (CEN, 2019).

The relative abundance was analyzed in order to avoid the use of absolute values because these ones present difference among species depending on abundance and annual variations in each taxon due to meteorological influence but also genetic factors such as seed germination success in herbs or masting years' phenomenon in trees. In this sense, the relative abundance of the 8 most represented pollen types, which comprise >1 % of the total spectrum, were analyzed by comparing the first years of the study period (1998–2002) with more recent ones (2016–2020). The relative abundance indicates the percentage that each pollen type occupies in relation to the other taxa.

Furthermore, variations in different aerobiological parameters in spring were studied for 19 well-represented pollen types (> 0.1 % of relative abundance): Season Pollen Integral (SPIn), as the sum of pollen concentrations during the pollen season (pollen grains*day/m^3); the Peak value, as the value of the maximum pollen concentration registered in a day (pollen grains*day/m^3); and the Peak Day, as the date of the year on which the Peak value is recorded. Data analysis was focused on the spring because >95 % of the pollen detected annually in the study area is concentrated in that period (García-Mozo et al., 2007).

Meteorological data were obtained by the European Climate Assessment and Dataset (ECA&D) project on a daily basis during the period studied (1998–2020), which led to attainment of gridded data at a resolution of 0.1° latitude and 0.1 degrees longitude (Cornes et al., 2018). These data are available on the ECA&D website at https://www.ecad.eu/. The main meteorological parameters, such as minimum and maximum temperature expressed in degrees Celsius (°C) (Tmin and Tmax, respectively) and precipitation expressed in mm (Prec), were studied.

Changes in land-use surrounding the pollen sampler between the first years of the study and the most recent ones were also evaluated, considering different distances. Land-use data were obtained from the European CORINE (Coordination of Information on the Environment) Land Cover project (Heymann et al., 1994; Büttner et al., 2004). These data enabled an analysis of changes in land-use recorded between 2000 and 2018 (the median of the periods compared for pollen: 1998–2002 and 2016–2020).

2.3. Statistical analysis

Both airborne pollen and meteorological data were analyzed and managed using the R software version 4.2.1, which was also used for all statistics analyses (R Core Team, 2022). Aerobiological parameters such as SPIn, Peak value and Peak Day were calculated using the functions contained in the specific package AeRobiology (Rojo et al., 2019). Results from the first and the last 5-year periods were considered and compared in order to detect some possible changes in the relative abundance of the main pollen types (> 1 %).

Pollen data were first analyzed using the Kolmogorov-Smirnov normality test which showed non-normally distributed results. In order to detect significant differences between the two periods analyzed in relation to relative abundance, Mann–Whitney–Wilcoxon test was used. Since the results had non-parametric behavior, the Mann-Kendall test with Sen's slope estimation was selected as the statistical method with which to calculate trends (McLeod, 2011). Trends were estimated for aerobiological and meteorological parameters throughout the study period. In the case of aerobiological variables, the types of pollen that had >0.1 % of relative abundance (19 pollen types) were studied. Those results that had a p-value < 0.05 were considered to be significant values.

Spearman's correlation coefficients (p-value < 0.05) were used to establish the statistical monotonic relationships between aerobiological data and meteorological parameters during the 23-year study period.

3. Results

In the present study, 61 different pollen-types were identified during the entire period monitored. Details of the list are shown in the supplementary material in Table S1.

The main pollen types that had >1 % of the relative abundance of the total pollen types found in the period between 1998 and 2020 were, in order from highest to lowest, the following: *Quercus* (46.7 %), *Olea* (25.6 %), *Poaceae* (14.4 %), *Pinus* (3.3 %), *Plantago* (2.8 %), *Pistacia* (1.5 %), *Urticaceae* (1.4 %) and *Rumex* (1.3 %). The analysis of the changes in the relative abundance of these taxa in relation to other pollen types was performed by comparing the periods 1998–2002 and 2016–2020. Fig. 1 shows the main changes during these two periods with significant values for *Olea* and *Urticaceae* (p-value = 0.02 and 0.03, respectively). *Quercus* pollen type stands out, since it has undergone a relative abundance loss of 18.6 % in the last few years; however, *Olea* pollen has increased to 13.9 %. *Pinus* pollen has also increased, since its percentage has almost doubled (from 1.6 to 2.6 %) in the last few years. Similar results have been observed for some herbaceous species, such as *Urticaceae* (from 1.1 to 2.2 %).

Fig. 2 shows the trends (units/year) during the period 1998–2020 of different aerobiological parameters (Season Pollen Integral, SPIn; Peak Day and Peak value) for the 19 most abundant pollen types (> 0.1 % relative abundance) when using the Mann–Kendall test and Sen's estimation method at a confidence interval of 95 %. Details of the trends of pollen features are shown in the supplementary material in Table S2.

In the case of the analysis of SPIn trends, the results revealed that although most pollen types registered positive values, only 9 had statistically significant trends: *Urticaceae* (30 pollen grains*day/m^3 per year), *Asteraceae* and *Echium* (10 pollen grains*day/m^3 per year, respectively), *Amaranthaceae/Chenopodiaceae* (5 pollen grains*day/m^3 per year), *Brassicaceae* (2 pollen grains*day/m^3 per year), *Moraceae* (4 pollen grains*day/m^3 per year), *Cupressaceae* (2 pollen grains*day/m^3 per year), *Cyperaceae* (4 pollen grains*day/m^3 per year) and *Castanea* (4 pollen grains*day/m^3 per year). It is shown that all pollen types, except *Pistacia* (−47 pollen grains*day/m^3 per year), showed positive trends which 9 of them presented statistically significant values, 6 refer to herbaceous and 3 to arboreal taxa. It is remarkable he great increase of pollen, although without significant values, of some taxa such as *Quercus*, *Olea*, *Poaceae* and *Pinus* (533, 383, 103, 68 pollen grains*day/m^3 per year, respectively).

In the case of the Peak value, the analysis indicated that the main pollen taxa that most contribute to airborne pollen concentrations also attained the greatest increase, although most of the statistical results were not significant. *Quercus* (58 pollen grains*day/m^3 per year), *Olea* (32 pollen grains*day/m^3 per year), *Poaceae* (14 pollen grains*day/m^3 per year), *Pinus* (15 pollen grains*day/m^3 per year), *Plantago* (1.5 pollen grains*day/m^3 per year), and *Urticaceae* (2 pollen grains*day/m^3 per year), with the latter being the only significant one. Most of the herbaceous taxa showed significant results and only *Castanea* among the arboreal ones. However, in the case of *Pistacia*, the airborne pollen concentration on the Peak Day underwent a decrease (−8.5 pollen grains*day/m^3 per year).

With regard to flowering phenology, the analysis of the Peak Day trends revealed variations for all the taxa, ranging between −1.5 and 1.5 days per year. A positive trend signifies a delay in the date of the Peak Day, while a negative value indicates an advance. The greatest advance was undergone by *Urticaceae* (−1.3 days per year), whereas the dates recorded for *Cyperaceae* were delayed (1.4 days per year), both with statistically significant results. Other taxa that underwent an advance in flowering were *Olea* (−0.08 days per year) and *Poaceae* (−0.2 days per year), although without significant results. Other taxa experienced a delay: *Quercus* (0.6 days per year), *Pinus* (0.9 days per year), *Plantago* (0.06 days per year) and *Pistacia* (0.2 days per year).

Meteorological parameter trends were estimated by applying the Mann-Kendall test and Sen's slope estimation per season for the 1998–2020 period, as shown in Fig. 3. Significant trends were detected as regards the minimum temperature (+0.05 °C per year), and the maximum temperature in summer (+0.09 °C per year), and even for the maximum temperature in

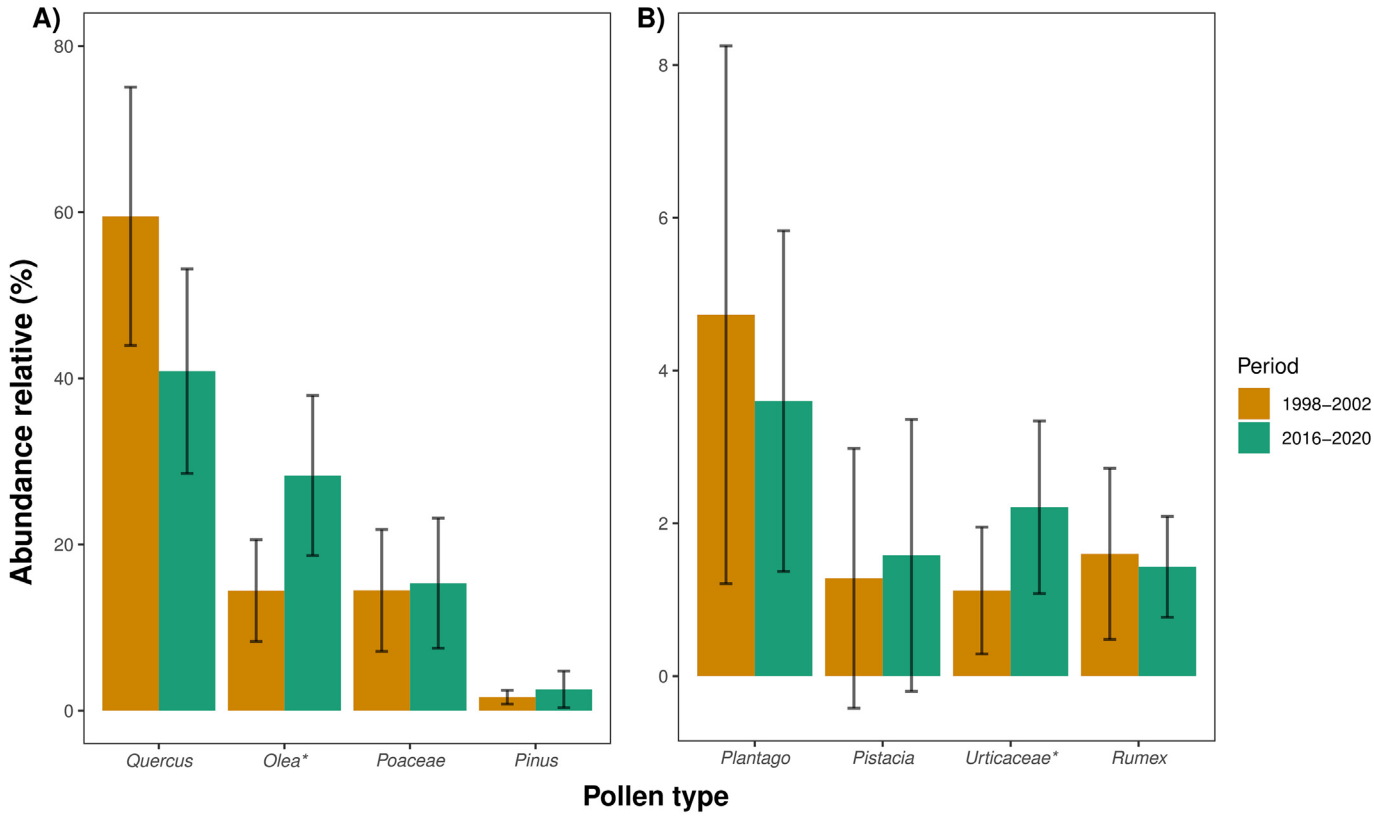

Fig. 1. Relative abundance changes in main pollen types detected during spring (March 21st – June 21st) in the area when comparing data from two periods: 1998–2002 (ochre color) and 2016–2020 (turquoise color). The most prevalent pollen taxa are shown in (A), while pollen taxa with a prevalence of between 10 % and 1 % are shown in (B). *Significant differences between the two periods studied using the Mann–Whitney–Wilcoxon test.

autumn (+0.13 °C per year). In general, the results indicated a tendency to warmer and drier conditions in the area.

Fig. 4 shows the Spearman correlations between the aerobiological and meteorological parameters in the winter and spring for the 8 main pollen types in the spectrum (>1 % of the relative abundance). With regard to SPIn, winter precipitation had a positive but not significant relation with all the taxa (except for *Pistacia*), whereas spring rainfall positively influenced on herbaceous pollen concentrations, with a significant correlation for *Rumex* (0.60) and *Plantago* (0.65), but negative and not significant relation with arboreal taxa such as *Quercus (−0.32)*, *Olea* (−0.17) and *Pistacia (−0.05)*. The maximum temperature in spring correlated negatively with arboreal pollen concentrations and positively with herbaceous ones and had negative and significant correlations with *Rumex* and *Plantago* (−0.57 and −0.46, respectively). The minimum winter temperature attained a positive correlation with all the taxa (except for *Pistacia*), being significant for *Poaceae* (0.54) and *Rumex* (0.61). The minimum spring temperature and the *Olea* pollen type also had a significant and positive correlation (0.55). Similar correlation results were observed in the case of the Peak value and meteorological parameters.

With regard to the relationship between the date of the Peak Day and the meteorological variables, negative and significant correlation values were detected between *Pistacia* and the maximum temperature in winter (−0.56), while the opposite was found for *Rumex* (0.44). Positive correlation values were recorded in the case of precipitation during the spring and the *Rumex* (0.52) and *Poaceae* (0.55) pollen types. Although not statistically significant, the influence of the winter temperature was negative for the main arboreal taxa, such as *Quercus* and *Olea*, whereas the influence of the spring temperature delayed the *Quercus* phenology and advance that of *Olea* one.

Fig. 5 displays the land-uses around the 'El Cabril' estate in 2000 and 2018. The first represents the land-uses in the year 2000, while the second in for the year 2018, showing the percentage of change in land-use. Note that the hectares of forest increased, as did the areas of agriculture, while the scrub and/or herbaceous associated vegetation decreased, even as regards the urban cover related to the nearby towns and villages. The bar chart represents the changes undergone suffered in the region at different ring distances (5, 10, 20 and 30 km) from the 'El Cabril' estate. It is possible to observe a decreased in the nearest agroforest ('dehesa') areas. In the case of 'scrub and grassland' areas, the decrease was general for all the distances indicated, with the same pattern as that of urban land-use. However, forest areas grew, especially in a diameter of 10 km. In more distant areas, the surface devoted to crops increased, as did open places.

4. Discussion

The results presented in this study provide insights into the long-term trends and annual variability of aerobiological and meteorological parameters in a Mediterranean natural area dominated by oak forest and 'dehesa' on the Iberian Peninsula. Our findings show a complex picture of changing pollen profiles reporting a high diversity of pollen types identified with several ones experiencing a significant increase in terms of relative abundance and airborne pollen concentrations over the 23-year spring study period. The trends observed in the aerobiological parameters are likely driven by a combination of biotic and abiotic factors, including land-use changes, climatic variations, and vegetation dynamics being the *Quercus* taxa which has suffered the most decrease and *Olea* the most increase one. The results obtained herein showed a high atmospheric representation of the natural vegetation of the environment, with almost half of the airborne pollen originating from the most represented tree formations, such as the *Quercus* species.

Changes in the airborne pollen spectrum of a protected natural area with a high environmental value have been studied in deep in the present study. This was done by analyzing the trends of the main aerobiological

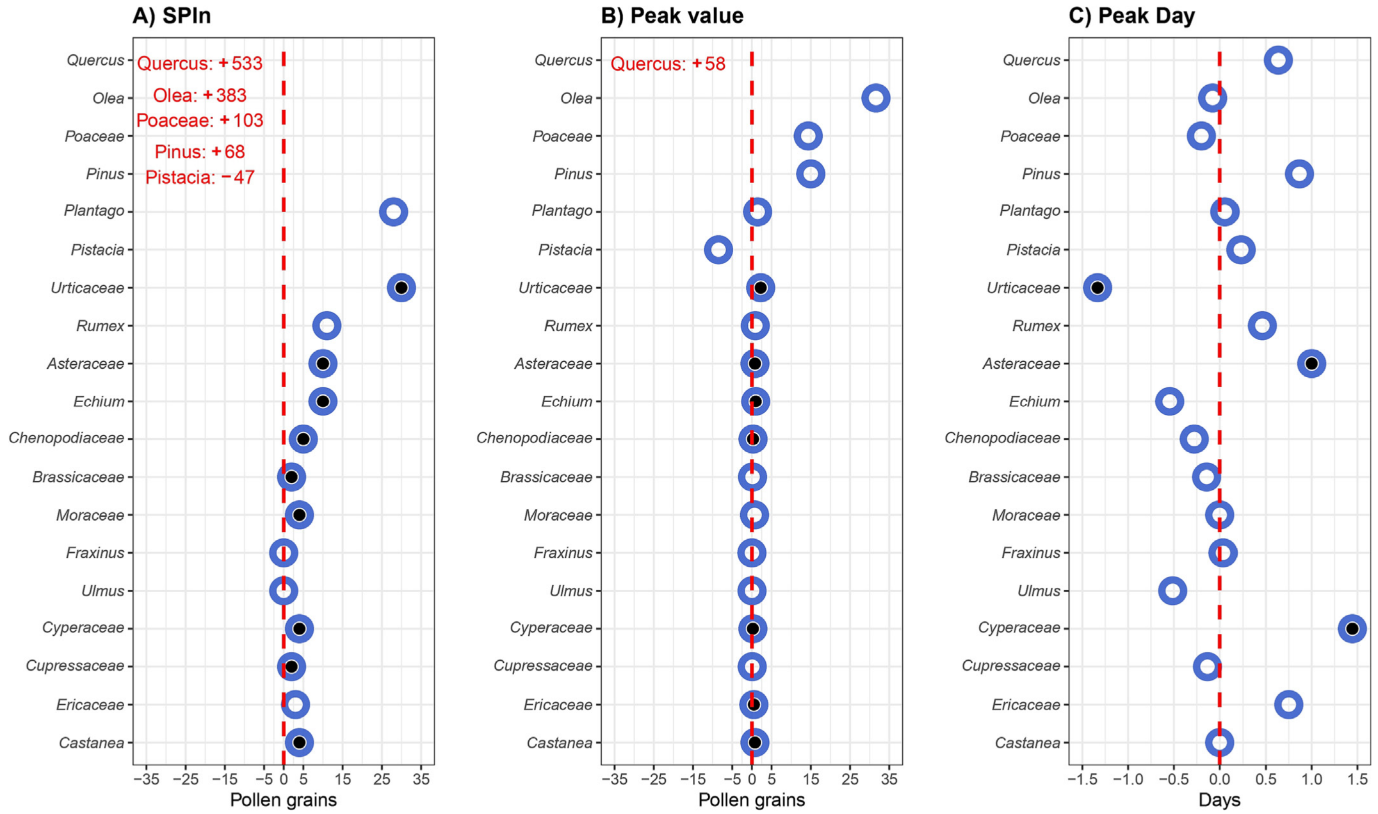

Fig. 2. Trends (units/year) of the main aerobiological parameters were estimated for the 23-year period (1998 2020) on the 'El Cabril' estate located in Cordoba province (Spain). The pollen types that had >0.1 % of relative abundance were analyzed. Parameters: A) Season Pollen Integral (SPIn, pollen grains*day/m^3); B) The value of Peak Day (Peak value, pollen grains*day /m^3); C) Peak Day of the SPIn (Peak Day, days). Black points represent significant trends (p-value <0.05). Out-of-range values are shown in red.

parameters together with their relationship with the main climate features. The influence of the changes in land-use throughout the period studied was also considered to explain the changes detected. This is the first time that a study of these characteristics covering such a wide range of data (23 years) has been carried out in a natural area, since most of the related works have been carried out in urban areas or have covered a shorter period of time (García-Mozo et al., 2007; Gehrig and Clot, 2021; Murray and Galán, 2016; Picornell et al., 2019; Rodríguez-de la Cruz et al., 2020).

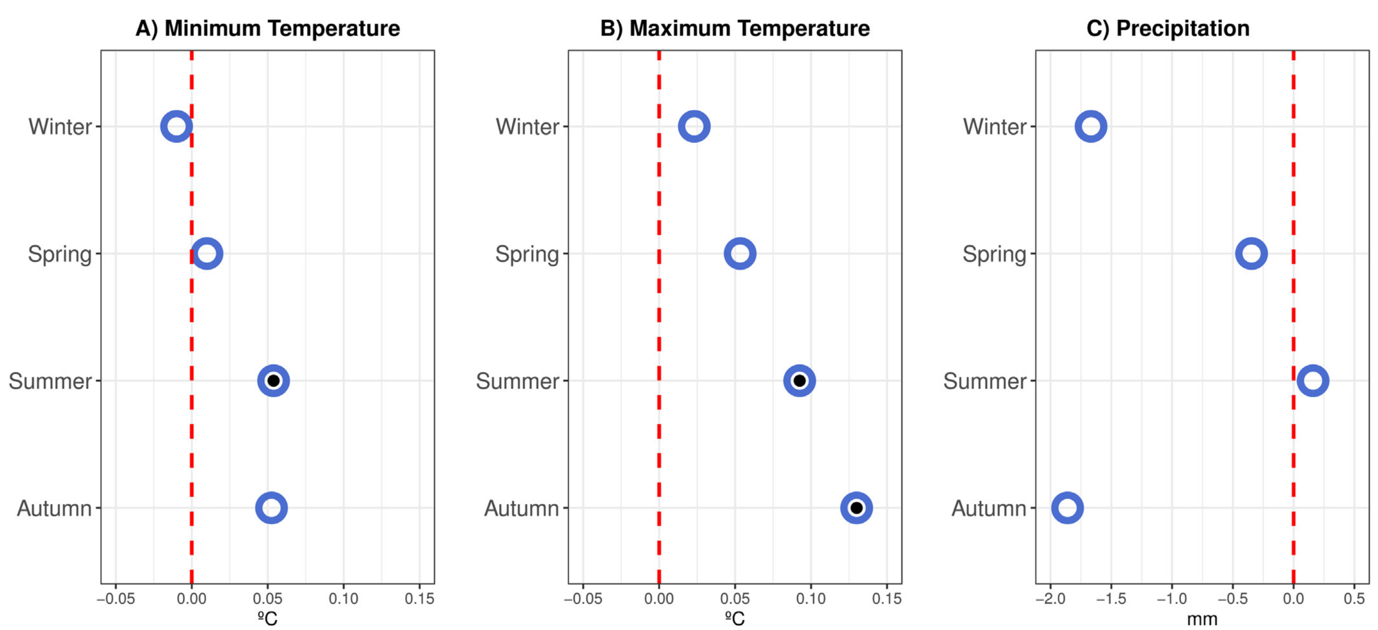

Fig. 3. Trends of meteorological parameters obtained using Mann-Kendall test and Sen's slope estimation (units/year) per season on the 'El Cabril' estate located in Cordoba province (Spain) during the period 1998–2020. Parameters: A) Minimum temperature (°C); B) Maximum Temperature (°C); C) Precipitation (mm). Black points represent significant trends (p-value <0.05).

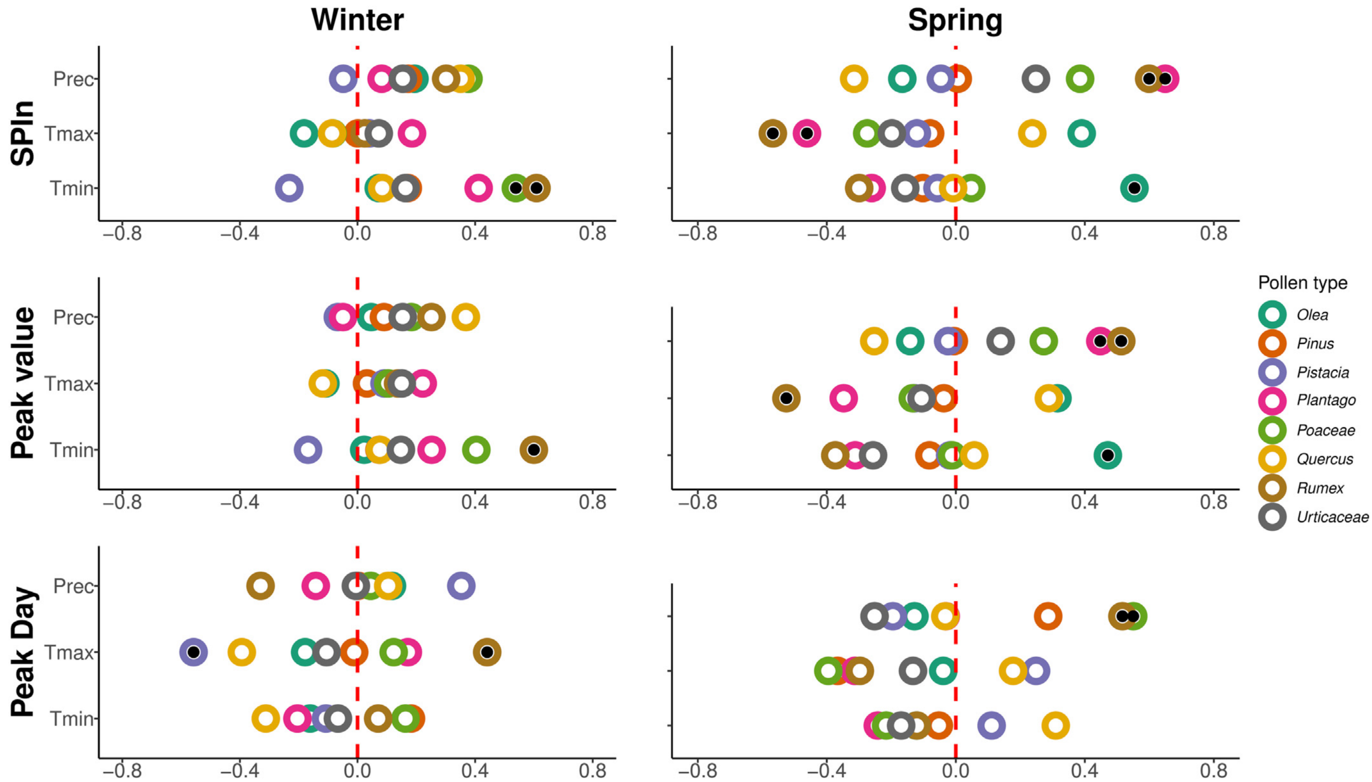

Fig. 4. Spearman correlations between meteorological (Prec = precipitation, Tmax = Maximum temperature and Tmin = Minimum Temperature) and aerobiological parameters (SPIn = Season Pollen Integral, Peak Day, and Peak value) for winter and spring during the period 1998–2020 in the 'El Cabril' estate located in Cordoba province (Spain). Black points represent significant trends (p-value <0.05).

The monitoring period was spring, season in which most species release pollen in Mediterranean area (Velasco-Jiménez et al., 2020). A great diversity of airborne pollen types was detected, with 61 pollen types. This number was higher than those detected in other natural or rural Mediterranean areas, where around 30 pollen types were identified (García-Mozo et al., 2007; Martínez-Bracero et al., 2019; Picornell et al., 2019), and even higher than those detected in urban aerobiological studies concerning the same climatic area (Martínez-Bracero et al., 2015; Pecero-Casimiro et al., 2020). Moreover, we detected fewer pollen types from the ornamental plants compared with studies in urban areas, and consequently lower percentages of allergenic pollen from common taxa in Mediterranean cities were found (Velasco-Jiménez et al., 2014, 2020). Furthermore, the species belonging to *Quercus* were the most abundant, contributing to almost 50 % of the pollen spectrum, thus reflecting the importance of natural vegetation in airborne biological particles in contrast to the pollen spectrum of urban areas where the percentage of pollen from natural autochthonous species and cultivated (agronomic and/or ornamental) is lower. Even in nearby urban areas of South Spain, where oaks are not usually planted for ornamental purposes, the contribution of *Quercus* to the pollen curve is around 10–15 % (Martínez-Bracero et al., 2015). Other reports in other natural areas of the Iberian Peninsula where evergreen oaks predominate in relation to deciduous species have shown a similar contribution (Picornell et al., 2019). These findings might be expected since it is the most important genus in Mediterranean forests and in anthropized 'dehesa' systems. In the case of the presence of *Olea*, this value was lower than that detected in Andalusian cities, being people less exposed to this type of pollen, with a high rate of allergenicity throughout the Andalusian area (Martínez-Bracero et al., 2015, 2019; Velasco-Jiménez et al., 2014). With regard to the levels of grasses detected, the results showed higher values than those found in urban and rural nearby areas (Martínez-Bracero et al., 2015, 2019; Picornell et al., 2019).

The results of the comparison of the relative abundance in two different periods indicated a decrease of some species related to natural areas of 'dehesa', such as *Quercus*, *Plantago* and *Rumex*, whereas the percentage of other species related to crop areas (*Olea*), or reforested actions (*Pinus*) have increased. The increase in *Urticaceae* pollen, which originates from ruderal species associated with the edges of crops, was also notable.

The values of the Season Pollen Integral (SPIn), along with the concentration and the date of the Peak Day were analyzed in wind pollinated plants in areas surrounding the sampling station as an indicator of flowering intensity and timing, respectively. The results revealed a generalized increase in SPIn and in the Peak pollen concentration for all taxa during the 23 years monitored. Other studies carried out in different Mediterranean locations have reported similar findings (Galán et al., 2016). An increase has been detected for certain pollen types: *Quercus*, in Cordoba, Cartagena, Ciudad Real, Barcelona, Leon, Vigo and Ourense (Spain) (Fernández-González et al., 2021; Galán et al., 2016; López-Orozco et al., 2021; Recio et al., 2018); *Olea* in Cordoba, Cartagena, and Barcelona (Spain) (Galán et al., 2016); *Poaceae*, in Andalusian, Extremadura, Cartagena and Leon in Spain (Galán et al., 2016; García-Mozo et al., 2010, 2016; Oduber et al., 2019; Recio et al., 2010) and also in the UK (Smith and Emberlin, 2005) and in Greece (Damialis et al., 2007); *Fraxinus* in Cordoba, Granada, Barcelona, Ourense and Leon (Spain) (Galán et al., 2016; Oduber et al., 2019), and *Cupressaceae* in Granada, Leon and Ourense (Spain) (Galán et al., 2016).

Nevertheless, the SPIn for *Poaceae* were not in line with the trends found in other Mediterranean areas where negative values were reported such as Italy from April to September in 2015, during 1990–2004 yearly, and from1994 to 2011, respectively (Ghitarrini et al., 2017; Mercuri et al., 2016; Ugolotti et al., 2015), or in Poland (Stach et al., 2008), Portugal during 15 years from 2002 to 2017 (Camacho et al., 2020), even Badajoz (Spain) (Galán et al., 2016). Those for *Pinus* decreased in Vigo, Ourense and Toledo (Fernández-González et al., 2021); those for *Urticaceae* decreased in Malaga, Cordoba and Vigo (Spain) (García-Mozo et al., 2016; Recio et al., 2009). The values for *Cupressaceae* decreased in Malaga (Spain) (Galán et al., 2016) and those for *Amaranthaceae*, *Rumex*, *Plantago*

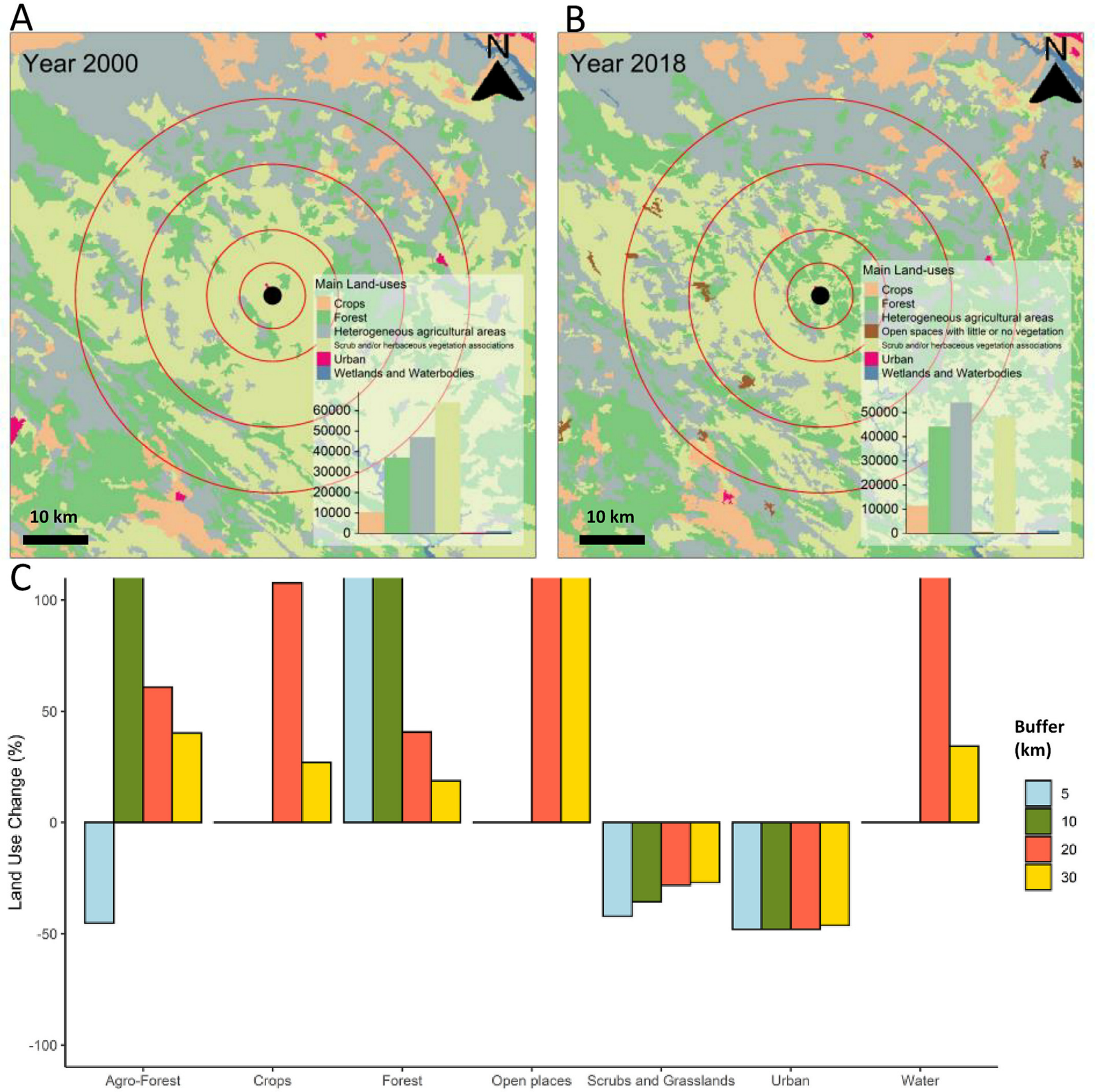

Fig. 5. Land-use zones around the 'El Cabril' estate located in Cordoba province (Spain) for two years: 2000 (5A, left) and 2018 (5B, right) according to the CORINE land cover. Several rings are depicted at different distances around the pollen traps (5, 10, 20 and 30 km). The summary of total surface (ha) of each land-use displayed in panels A and B correspond to the square containing completely the 20 km buffer (i.e., 160,000 ha). Panel C display the percent (%) of land-use change between years (2000 and 2018) withing the surface cotted on each represented buffer: 7854 ha (5 km buffer); 31,416 ha (10 km buffer); 125,664 ha (20 km buffer) and 282,744 ha (30 km buffer).

decreased in Cordoba (Spain) (García-Mozo et al., 2016). In other Mediterranean regions, such as Morocco (Tetouan) a generally decrease has been detected in *Cupressaceae*, *Urticaceae*, *Pinus* and *Quercus*, which was highly significant in the case of *Cupressaceae* and *Pinus* (Boullayali et al., 2021). One exception to the increase was found in the case of the *Pistacia* pollen type, whose decrease could be owing to the decrease in shrub cover in the area in recent years as the land cover changes showed, since this is the most common layer in which these species are usually found.

The sum of the relative percentages of *Quercus*, *Olea* and *Poaceae* represented >85 % of relative abundance in our study with *Olea* being the most pollen taxa influenced by the human management. In this case, there is a positive and significant correlation with the increase in the minimum spring temperature, which may be causing an intensification of its flowering as a survival response (López-Orozco et al., 2021; Rodríguez-de la Cruz et al., 2020). Additionally, it was observed that olive cultivation has increased, signifying that the increase in pollen from this source could be owing to both climate change and changes in land-use (Guzmán et al., 2022; Oteros et al., 2015, 2017). According to García-Tejero et al., 2018, 5,000,000 ha are allocated to agriculture in the Mediterranean basin alone, with Spain being the world's leading olive producer. It is, therefore, a flagship species in its agroecosystem (Florenzano et al., 2017; Negral et al., 2021).

Our findings suggest that the observed trends in aerobiological parameters are likely driven by a combination of biotic and abiotic factors, including land-use changes, climatic variations, and vegetation dynamics. In particular, the increase in airborne pollen concentrations and the relative abundance of some pollen types could be related to the effects of climate change and rising concentrations of CO_2. Higher temperatures and longer growing seasons may contribute to the expansion and intensification of pollen seasons, while elevated atmospheric CO_2 levels could stimulate plant growth and increase pollen production (Schmidt, 2016; Zhang et al., 2014). These changes have important implications for ecosystem functioning, biodiversity, and human health, as they may affect the timing and intensity of plant-pollinator interactions, plant distribution and survival, and the prevalence of allergic diseases. Many studies have highlighted global warming, which is principally the result of the increases in CH_4, CO_2 and N_2O in the atmosphere (Kumaş and Akyüz, 2023; Peacock et al., 2017). This may change the number of invasive species (Drake et al., 2017), the reproductive physiology and phenology of plants (Hidalgo-Galvez et al., 2018; Jacques et al., 2015; Ziello et al., 2012), pollen production (Zhang et al., 2014), the advance, the delay or both (Blecharczyk et al., 2016) of the flowering time (Fernández-Rodríguez et al., 2018), as certain phenological parameters show. The modeling approach employed indicates that climate change is a key driver of atmospheric pollen concentrations, projecting dramatic changes in the future depend on location and climate change scenario (Rojo et al., 2021). Recent weather trends are predicted to continue at least into the next century, and the 'Mediterraneanization' of the northern Iberian Peninsula and 'aridification' of southern regions have been identified as significant trends for the future (Fernández-González et al., 2005). As occurs in the general bibliography, we have also observed a generalized advance in the spring pollen season, and we also link this to increases in temperature (Ziello et al., 2012). The same results have been found in studies on deciduous trees such as *Corylus avellana*, *Morus*, *Fraxinus* and *Salix* located near our study area, as well as in some grasses species (Cebrino et al., 2016; Hidalgo-Galvez et al., 2018). In the case of *Quercus* (mostly evergreen species) a delay in the Peak Day has also been reported (López-Orozco et al., 2021; Ruiz-Valenzuela and Aguilera, 2018). In this study, an advance for Peak Day in *Urticaceae* and a delay *Cyperaceae* were showed with statistically significant results. In contrast, in Ruiz-Valenzuela and Aguilera (2018) a delay was found for *Urticaceae*. In general terms, the pollen season trend in last decades of species flowering during early spring are usually in advance; however, for those flowering during end spring, especially herbaceous species, flowering does not occur until sufficient water availability in the soil, with a possible delay (Galán and Thibaudon, 2020).

However, we have also observed the key role played by land-use changes. The land-use changes observed in our study area during the 23-year period are consistent in part with the general trends of land cover changes in Andalusia, which are characterized by a progressive expansion of agriculture, along with a decline in scrublands and grasslands (Martínez-Vega et al., 2021). Our land-use data indicates the expansion of agriculture areas, overall olive croplands, which agrees with pollen data trends. It is also reflected in the decrease of relative abundance of *Quercus* in the area despite of the increase of raw pollen data through the study years. It could be explained due to the reduction of the surface devoted to the main agroforest system of the area, the 'dehesa' in the nearest location to the sampler, in contrast to the increase of agricultural areas. On the other hand, *Quercus* forest increase in farther areas, contributing to the pollen spectrum, but not significatively to the relative percentage. Apart for the influence on the pollen spectrum, it is important to remark that the reduction of 'dehesa' may have important implications for ecosystem services, such as biodiversity conservation and carbon sequestration (Yang and Cao, 2022).

It is likely that the land-use changes observed have contributed to the changes in the airborne pollen spectra detected in our study. For example, the increase in forest cover may explain the increase in the abundance of *Pinus* pollen, which is a typical forest species. Similarly, the increase in olive groves may explain the increase in the abundance of *Olea* pollen, which is associated with olive flowering. The decline in 'dehesa' in the nearest area of the aerobiological sampler may have contributed to the decline in *Quercus* pollen percentage in relation to the rest of pollen types, specially to crop ones. In the case of the decrease of urban cover, it is due to most of them are farmhouses or rural houses that have been left in disuse or abandoned in recent years. Overall, our results highlight the need to consider land-use changes as a potential driver of changes in airborne pollen concentrations.

In summary, this study sheds light on the long-term trends and annual variability of aerobiological and meteorological parameters in a Mediterranean oak forest on the Iberian Peninsula, providing valuable insights into the implications of changing pollen profiles.

5. Conclusions

As conclusions it is possible to point out that airborne pollen is an important biological indicator of flowering intensity, phenology, and species distribution. Our results have a special interest given the few numbers of aerobiological surveys performed in natural areas. Our results reveal 61 different pollen types detected during spring in the area, being the most prevalent pollen types were *Quercus*, *Olea*, *Poaceae*, *Pinus*, *Plantago*, *Pistacia*, *Urticaceae*, and *Rumex*. Through the study period significant variations in airborne pollen concentrations were observed for both, woody and herbaceous plants showing a statistically significant increase of SPIn in 9 out of 19 taxa and *Pistacia* as the only taxon with negative values. Nevertheless, the most abundant pollen type, *Quercus*, has undergone a relative loss in abundance of 18.6 % in recent years associated to the reduction of 'dehesa' areas, despite of the increase of raw pollen levels probably coming from farther *Quercus* forest areas. On the other hand, species related to agriculture of reforestation works, such as *Olea* and *Pinus*, has increased the pollen presence in an area of the Iberian Peninsula with recent climate trends contributing to variability in phenology. In relation to changes on phenology, taxa showing an advance phenology were *Olea*, *Poaceae* and *Urticaceae*, whereas *Quercus*, *Pinus*, *Plantago*, *Pistacia* or *Cyperaceae* experienced a delay. In the case of the relationship between pollen concentration and phenology with air temperatures and precipitation, the positive or negative influence varied for each pollen type. Our results indicate that the main drivers of the observed trends as regards airborne pollen concentrations are land-use changes and climate variability. Given the potential impact of climate change on phenology and biodiversity, we advocate an increased monitoring of aerobiological parameters and phenology on the Iberian Peninsula in order to provide information to management and conservation strategies.

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CRediT authorship contribution statement

RLO, HGM, JO and CG contributed equally to the conceptualisation of this study. RLO and HGM collected the data. RLO and JO conducted the statistical analyses, and the data were interpreted by all the authors. RLO, HGM, JO and CG wrote the manuscript. All the authors have read and agreed to the version of the manuscript submitted for publication.

Data availability

The data that has been used is confidential.

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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