



Airborne pollen trends in the Iberian Peninsula

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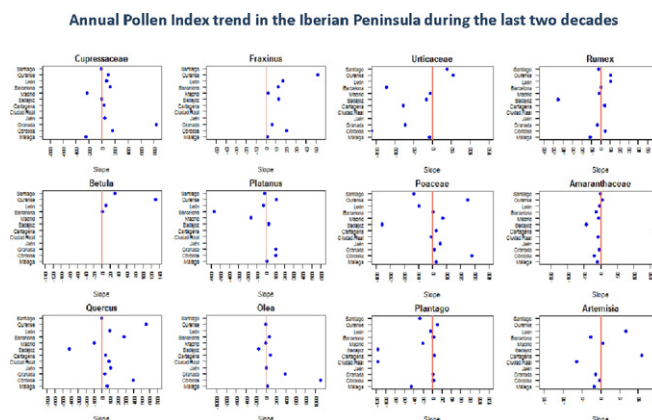
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HIGHLIGHTS

- We studied the airborne pollen of 12 anemophilous taxa in the Iberian Peninsula.
- We show variations in flowering intensity over the last two decades.
- Results revealed differences in the distribution and flowering intensity.
- A negative correlation was observed between airborne pollen and winter NAO index
- Changes in rainfall pattern play a key role as driver of climate change effects.

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ABSTRACT

Airborne pollen monitoring is an effective tool for studying the reproductive phenology of anemophilous plants, an important bioindicator of plant behavior. Recent decades have revealed a trend towards rising airborne pollen concentrations in Europe, attributing these trends to an increase in anthropogenic CO₂ emissions and temperature. However, the lack of water availability in southern Europe may prompt a trend towards lower flowering intensity, especially in herbaceous plants. Here we show variations in flowering intensity by analyzing the Annual

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Pollen Index (API) of 12 anemophilous taxa across 12 locations in the Iberian Peninsula, over the last two decades, and detecting the influence of the North Atlantic Oscillation (NAO). Results revealed differences in the distribution and flowering intensity of anemophilous species. A negative correlation was observed between airborne pollen concentrations and winter averages of the NAO index. This study confirms that changes in rainfall in the Mediterranean region, attributed to climate change, have an important impact on the phenology of plants.

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1. Introduction

Changes in climate can have different effects on ecosystems and species (Walther, 2010). Variations in species distribution have been observed over recent decades in response not only to global warming but also to habitat fragmentation and changes in land use (Heap et al., 2014). The last assessment report by the Intergovernmental Panel on Climate Change (IPCC, 2014) notes that each of the last three decades has consecutively been the warmest on record and that the first decade of the 21st century was the warmest on instrumental record in terms of the Earth's overall mean surface temperature. The report concludes that global warming over the last few decades is prompting phenological changes in plants and animals. Species may respond to climate change through a varying degree of genotypic and phenotypic plasticity (Hedhly et al., 2009). However, variations in temperature and the high degree of plant plasticity suggest that genetic variations between populations may be insignificant in relation to changes in reproductive phenology (Chaine and Belmonte, 2004).

A number of authors report a generalized advance in flowering (Cook et al., 2012) as well as greater flowering intensity (Ziello et al., 2012). Research has highlighted the major contribution of rainfall and photoperiod to plant phenology, and various papers have paid special attention to changes in precipitation and water availability as a major driver of climate change in the Mediterranean area (Peñuelas et al., 2004).

In southern Europe, a generalized advance has been reported in flowering, especially in woody species blooming in early spring (García-Mozo et al., 2010a, 2010b). However, it becomes more difficult to define a model in autumn, probably due to a greater annual regional oscillations (Gordo and Sanz, 2005).

Today, airborne pollen monitoring is regarded as an effective tool for studying the reproductive phenology of anemophilous plant species, especially as a bioindicator of their behavior in areas where there are variations in pollen concentrations. Research over the last few years has revealed a trend towards rising airborne pollen concentrations (Ziello et al., 2012; Fernandez-Llamazares et al., 2014), especially for tree species flowering in winter and early spring. Some authors have analyzed variations in the Annual Pollen Index (API) with a view to charting trends in flowering intensity, attributing these trends to an increase in anthropogenic CO₂ emissions (Rogers et al., 2006). Abrupt changes in species distribution have also been ascribed to human activity (Cariñanos and Casares-Porcel, 2011; Oteros et al., 2013b; Velasco-Jiménez et al., 2013). Ziello et al. (2012) report increased flowering intensity over the last few decades for a range of species across Europe, observing more pronounced trends in urban than in rural or semi-rural areas, and also stronger trends in Northern Europe. In Southern Europe, by contrast, lack of water availability may prompt a trend towards lower flowering intensity, especially in herbaceous plants (Alcázar et al., 2009; Recio et al., 2009). Rainfall is governed in part by the influence of the North Atlantic Oscillation (NAO) (Gallego et al., 2005), and research points to a link between the timing and/or intensity of flowering and different phases of the NAO in Europe, and especially in Northern Europe (Smith et al., 2009; Stach et al., 2008).

The main goal of this paper was to investigate variations in flowering intensity by analyzing the Annual Pollen Index (API) of 12 anemophilous taxa across 12 locations in the Iberian Peninsula and charting trends over the last two decades. A secondary aim was to detect the possible influence of the NAO index on flowering intensity.

2. Material and methods

2.1. Study areas and pollen data

This study focused on the Iberian Peninsula. Airborne pollen concentrations were obtained from the Spanish Aerobiology Network (REA) www.uco.es/rea database. Pollen data from 12 monitoring stations, which have data for the 20 year period (1994 to 2013), have been considered (Fig. 1). Airborne pollen data were collected using a Hirst-type volumetric spore-trap, based on the impaction process (Hirst, 1952). This device allows continuous monitoring of the atmosphere and enables daily concentrations (daily average of pollen grains per cubic meter of air) or even hourly data. Data were obtained by REA members following a standardized procedure outlined in the *Management and Quality Manual* (Galán et al., 2007), which complies to the minimum requirements described by the European Aerobiology Society's (EAS) Working Group on Quality Control (Galán et al., 2014). REA members are involved in performing external quality control exercises, both at national (Oteros et al., 2013a) and European level (Galán et al., 2014).

This paper examined flowering intensity in anemophilous plants, taking the parameter Annual Pollen Index (API) as the sum of daily pollen concentration during the year. Due to the fact that pollen grains from several taxa are stenopalynous and share certain features under light microscope, airborne pollen grains were classified into pollen

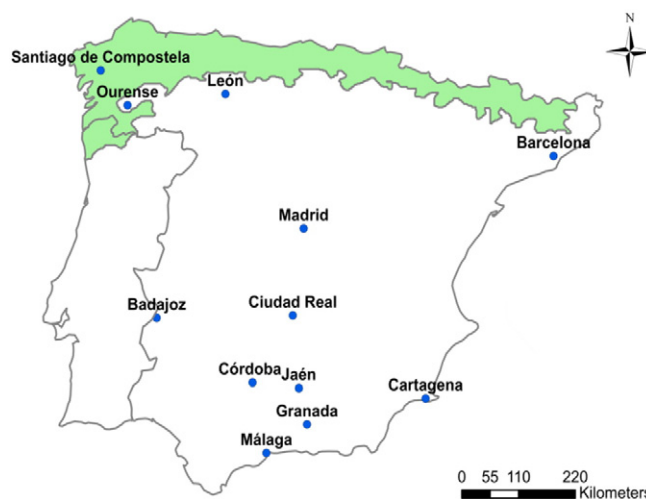


Fig. 1. Location of airborne pollen monitoring sites in the Iberian Peninsula. Green for Eurosiberian region and white for Mediterranean region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

types based on morphological characteristics at different taxonomic levels: species, genus or family. The study focused on 12 taxa, the most frequent pollen types in the Iberian Peninsula. Tree taxa studied were Cupressaceae, *Fraxinus* L., *Betula* L., *Platanus* L., *Quercus* L. and *Olea europaea* L.; herbaceous taxa were Urticaceae, *Plantago* L., *Rumex* L., Poaceae, Amaranthaceae; and *Artemisia* L. was selected as an under-shrub species. It should be noted that recent research classifies the former Chenopodiaceae as a new subfamily of Amaranthaceae (APG, 2009); since Chenopodiaceae and Amaranthaceae pollens are stenopalynous, this pollen type was labeled Amaranthaceae. Pollen types are cited and represented here in order of flowering time, starting in winter.

2.2. Statistical analysis

Analysis covered a total of 2880 datasets for 12 pollen types over two decades at 12 monitoring stations. Descriptive analysis was performed first. Mean and standard variations (SD) of the API in each taxon at each location were calculated for the whole study period.

Secondly, temporal trends were analyzed by linear regression and significance values were recorded. Different parameters were calculated: slope of the simple linear regression over time, standard error of the regression slope (SE), and the probability level (p) for the linear trends; p -value was calculated by contrast analysis using the F-test. Results with a p -value of <0.05 were considered statistically significant.

Thirdly, a statistical test was applied to chart the correlation between the API and the North Atlantic Oscillation (NAO). Correlation coefficient (r) and probability level (p) were calculated. The NAO is calculated as the difference in atmospheric pressure between Gibraltar and south-western Iceland (Reykjavik), as recommended by P.D. Jones at the University of East Anglia (D'Odorico et al., 2002). Pearson correlation tests were applied to data in order to examine correlations between the NAO and the API for each pollen type. Two periods of averaged NAO values were tested: from December to February, and from December to March. Only those pollen types for which 20-year databases were available—with only sporadic missing values—at each monitoring station were represented. Trends were considered significant at $p < 0.05$.

3. Results

3.1. Annual Pollen Index

The Annual Pollen Index (API), the annual sum of daily airborne pollen concentration, can provide information on the distribution and flowering intensity of wind-pollinated plants (Fig. 1; Tables 1A, 1B). A higher API was detected for trees than for herbaceous plants, and especially for Cupressaceae (average API of 18,132 pollen grains in Granada); *Platanus* (15,599 pollen grains in Barcelona), *Quercus* (14,568 pollen grains in Badajoz) and *O. europaea* (48,011 pollen grains in Jaén) (Table 1A). For herbaceous species, the highest API was recorded for Urticaceae (3931 pollen grains in Granada), Poaceae (9094 pollen grains in Badajoz) and Amaranthaceae (2955 pollen grains in Cartagena) (Table 1B). Although higher APIs were observed in trees, the greatest year-on-year variations were found for herbaceous species.

In general, clear differences were observed in the geographical distribution of APIs as a function of areas of species distribution in the vicinity of pollen traps. Land use was largely responsible for current species distribution: for example *Quercus* and *Fraxinus* were found to predominate in forestry-linked areas, Cupressaceae, *Fraxinus* and *Platanus* in urban green spaces, and *O. europaea* in areas given over to commercial crops. The same land use may give rise to the predominance of different species depending on the biogeographical region within the Iberian Peninsula. Observed API distribution patterns for each region revealed that, for tree species (Table 1A), *Betula* and deciduous *Quercus* species were representative of the temperate Eurosiberian Region; while Cupressaceae, sclerophyllous *Quercus* species and *O. europaea*

Table 1A

Results of time trends. Linear trends in tree airborne pollen, Annual Pollen Index (API).

	Locality	Mean	SD	Slope	SE	p
Cupressaceae	Málaga	5559	3618.774	−250.572	131.523	0.072 +
	Córdoba	6316	4558.925	166.380	177.348	0.360
	Jaén	2428	1148.113	49.489	45.390	0.291
	Granada	18132	8169.235	835.487	265.597	0.006**
	Cartagena	2627	1075.484	25.132	42.696	0.564
	Badajoz	2914	1483.711	−4.025	59.105	0.946
	Madrid	9885	6629.250	−231.605	280.567	0.421
	Barcelona	6587	2479.575	128.600	94.017	0.188
	León	985	707.885	75.547	24.395	0.006**
	Ourense	1031	816.502	100.790	22.223	0.000***
Fraxinus	Santiago	777.5	313.072	−11.749	12.162	0.347
	Málaga	79	34.500	1.132	1.348	0.412
	Córdoba	234	180.777	20.503	5.34	0.001**
	Granada	93	47.785	6.099	1.319	0.000***
	Badajoz	649	439.541	10.570	18.402	0.553
	Madrid	633	432.563	−1.796	17.840	0.903
	Barcelona	281	114.323	7.795	4.478	0.002**
	León	750	525.618	22.975	19.636	0.434
	Ourense	434	429.681	51.512	12.356	0.001***
	Barcelona	190	146.703	1.749	5.830	0.767
Betula	León	318	145.346	9.793	5.449	0.090 +
	Ourense	2236	1266.170	130.393	40.998	0.095**
	Santiago	5862	4506.516	32.590	185.986	0.863
Platanus	Málaga	400	134.854	11.954	4.575	0.017*
	Córdoba	7493	5049.920	104.056	199.693	0.609
	Granada	2677	1479.349	102.846	55.114	0.079 +
	Badajoz	1021	809.208	25.794	31.661	0.426
	Madrid	12330	7869.318	−164.854	311.513	0.603
	Barcelona	15599	6792.556	−564.682	259.993	0.046*
	León	696	761.387	−26.773	29.671	0.378
	Ourense	3196	2053.025	111.859	77.429	0.166
	Santiago	699	640.324	−17.859	25.161	0.486
Quercus	Málaga	4877	2123.791	66.297	83.161	0.435
	Córdoba	10211	5760.167	391.071	210.165	0.079 +
	Jaén	3795	2313.710	111.186	88.377	0.224
	Granada	3678	1783.640	38.039	72.354	0.606
	Cartagena	1181	585.850	44.936	20.801	0.044*
	Badajoz	14568	7340.298	−431.439	274.195	0.133
	Ciudad Real	9611	3666.233	86.843	188.696	0.652
	Madrid	5836	3153.144	−97.459	138.198	0.041
	Barcelona	5599	2873.070	276.967	99.575	0.013*
	León	1846	1076.233	99.701	35.865	0.012*
Olea	Ourense	4893	4022.317	556.648	92.014	0.000***
	Santiago	886	668.432	−1.185	26.626	0.964
	Málaga	11279	4723.471	32.571	197.317	0.871
	Córdoba	21856	8790.430	1107.830	238.804	0.000***
	Jaén	48011	20922.346	948.252	843.552	0.277
	Granada	21511	8669.626	382.946	342.150	0.278
	Cartagena	1974	879.690	87.670	28.007	0.006**
	Badajoz	5168	2638.384	−155.91	98.483	0.13
	Madrid	1662	1269.376	−6.462	62.494	0.919
	Barcelona	1340	655.292	66.402	20.896	0.005**
	Ourense	237	134–922	−2.094	5.494	0.708

+ 0.1.

*** 0.001.

** 0.01.

* 0.05.

predominated in the Mediterranean basin. However, geographical differences in the *Quercus* API were unclear, partly because different species share similar pollen morphology and they are usually included in the same pollen type. Higher concentrations were detected in Córdoba, a city located close to the Sierra Morena, whose vast tracts of woodland are clearly dominated by *Quercus* species, and especially by *Quercus ilex* subsp. *ballota* (Desf.) Samp. *Fraxinus* was found to be widespread in riparian forests, especially in the north, and also as an ornamental in urban spaces nationwide; pollen concentrations were appreciably lower in the south (Table 1A). *Platanus* was most abundant in the streets, gardens and urban green spaces of Madrid and Barcelona, but also common in Ourense, Córdoba and Granada; lower values were

Table 1B

Results of time trends Linear trends in herbaceous and undershrub airborne pollen, Annual Pollen Index (API).

	Locality	Mean	SD	Slope	SE	p
Urticaceae	Málaga	1261	374.989	−8.773	14.096	0.561
	Córdoba	2468	1982.006	−162.765	69.019	0.029*
	Granada	3931	1557.898	−72.490	61.234	0.252
	Cartagena	2167	1042.571	−78.280	37.214	0.049*
	Badajoz	1230	576.598	−11.837	22.802	0.61
	Madrid	535	255.154	−5.837	10.726	0.593
	Barcelona	2689	2688.736	−123.332	42.064	0.009**
	León	553	311.952	31.792	12.276	0.021*
	Ourense	1521	822.778	55.586	30.048	0.081 +
	Santiago	739	587.370	−37.970	21.622	0.086 +
Plantago	Málaga	1408	651.368	−45.483	23.633	0.070 +
	Córdoba	900	531.193	15.171	20.859	0.476
	Granada	309	162.651	0.582	6.691	0.931
	Cartagena	281	163.798	4.386	6.435	0.484
	Badajoz	2346	1210.594	−116.980	39.686	0.009**
	Madrid	931	640.462	−20.655	25.048	0.420
	Barcelona	400	128.723	0.686	5.379	0.900
	León	699	324.159	−4.260	13.721	0.005
	Ourense	621	294.798	10.106	11.501	0.391
	Santiago	675	317.283	−27.817	10.808	0.019*
Rumex	Málaga	498	220.738	−11.382	12.859	0.190
	Córdoba	357	166.647	4.583	6.551	0.493
	Granada	172	87.904	−3.357	3.501	0.351
	Cartagena	82	43.293	4.211	1.428	0.01**
	Badajoz	988	480.794	−50.294	15.046	0.004**
	Madrid	423	250.354	−1.372	10.232	0.894
	Barcelona	80	24.472	0.005	0.975	0.996
	León	770	356.661	10.703	14.544	0.472
	Ourense	386	171.527	10.845	6.502	0.114
	Santiago	106	49.028	−2.496	1.863	0.197
Poaceae	Málaga	2852	1219.544	25.472	48.215	0.603
	Córdoba	5855	3679.316	279.023	131.006	0.047
	Jaén	2549	1091.826	56.183	49.866	0.279
	Granada	1953	978.216	13.356	39.871	0.742
	Cartagena	793	392.132	26.016	14.514	0.078 +
	Badajoz	9094	5066.846	−358.729	183.307	0.066 +
	Madrid	2781	1653.378	73.941	63.477	0.261
	Barcelona	1161	289.173	5.603	11.445	0.630
	León	3524	1235.452	−94.591	43.910	0.047*
	Ourense	3932	1970.152	250.702	52.857	0.0001**
Amaranthaceae	Santiago	2739	1494.404	−132.835	50.641	0.017*
	Málaga	1456	362.688	−9.388	14.279	0.159
	Córdoba	742	335.490	−20.039	12.504	0.126
	Granada	612	193.467	−7.840	7.869	0.333
	Cartagena	2955	1688.901	167.940	54.412	0.006**
	Badajoz	725	339.010	−45.600	8.018	0.001***
	Ciudad Real	384	220.157	−8.979	10.148	0.391
	Madrid	267	202.425	−7.162	10.441	0.446
	Barcelona	538	129.309	−6.608	4.911	0.195
	León	125	43.152	−2.861	1.594	0.090 +
Artemisia	Ourense	99	46.752	3.621	1.656	0.042*
	Santiago	33	15.638	−0.289	0.619	0.645
	Málaga	159.000	78.693	−1.663	3.111	0.599
	Córdoba	66.000	38.696	−0.334	1.542	0.829
	Granada	381.000	213.197	−1.914	9.200	0.837
	Cartagena	231.000	140.946	11.031	4.977	0.039*
	Madrid	69.000	43.592	0.598	1.810	0.746
	Barcelona	149.000	61.219	−2.762	2.351	0.255
	León	176.000	78.445	6.676	2.792	0.029*

+0.1.

*** 0.001.

** 0.01.

* 0.05.

recorded in the northwest and the Costa del Sol, though differences were largely attributable to the design of urban green spaces.

Greater differences in distribution were found for herbaceous plants and undershrubs (Table 1B), reflecting a clear adaptation to water availability. Amaranthaceae and *Artemisia* was representative of the Mediterranean area, especially in the southeast, and in gypsum territories, i.e. in the Ebro Basin. Some species have adapted to drought conditions

in the semi-arid climate of the south-eastern Iberian Peninsula, with a high API in Cartagena, especially for Amaranthaceae. Some Urticaceae species display highly-specific ecological behavior. Even when pollen from Urticaceae species was not identified separately, in this case it is important to mention the different ecological behavior at this level. *Parietaria judaica* L., for example, is most widespread in wall-cracks, ruined buildings in old cities and ruderal environments. Whereas *Urtica membranacea* Poir. in Lam. is representative of the peripheral South Mediterranean basin. Species of *Rumex*, *Plantago* and Poaceae were more abundant in Atlantic and continental areas, such as Badajoz, with an extent area of grasslands and pastures (Table 1B).

3.2. Temporal trends

An increase in the annual API over time was observed for most species; the trend was more significant in north-western areas and wherever certain species were abundant either as ornamentals—e.g. Cupressaceae (API from 6427 in 1995 to 33856 in 2009 in Granada) and *Fraxinus* (API from 33 in 1994 to 1683 in 2012 in Ourense)—or crops—e.g. olive crops at various locations in the south-eastern Mediterranean area (API from 9462 in 1994 to 35333 in 2013 in Córdoba) (Table 1A). No clear trend was discerned for *Platanus*, probably reflecting its varying abundance as an ornamental, or for *Quercus*, probably because of the various species—both sclerophyllous and deciduous species—contributing to airborne pollen concentrations with the same pollen type. Most herbaceous plants displayed a negative API trend, except in north-western areas, with positive correlations although with low significance (Table 1B). The trend for grasses, even though they are herbaceous plants, showed a positive trend in most places (API from 463 in 1994 to 7052 in 2013 in Ourense), except in the Atlantic Mediterranean region, e.g. Badajoz. A significant positive trend was observed for Amaranthaceae species that have adapted to a semi-arid climate, e.g. Cartagena (API from 622 in 2000 to 7136 in 2008), although significant negative trends were recorded for other Amaranthaceae species growing in the Atlantic area of the Mediterranean region, e.g. Badajoz. *Artemisia*—more abundant in south-eastern locations—displayed a non-significant positive trend (Table 1B).

3.3. Correlations between API and NAO

A negative correlation was observed between most pollen types and locations and the winter NAO from December to February of the year before and the same year (Tables 2A,2B), significant in 46% of the cases of the year before and 21% of the same year. A prior comparative study using the NAO index from December to February and also from December to March, found that better results were obtained using only the first three months in all cases (results not shown). Trees flowering in winter or early spring (Cupressaceae, *Fraxinus*, *Betula*, *Platanus* and *Quercus*) showed a stronger correlation with the winter NAO index for the previous year, whereas *O. europaea*—which flowers in late spring—displayed a stronger correlation with the winter NAO index for the year of flowering. Among herbaceous species, Urticaceae comprises species flowering in different seasons, mainly in winter or spring, and exhibited a stronger correlation with the winter NAO index for the previous year. However, plants flowering in spring or summer-autumn (*Plantago* L., *Rumex* L., Poaceae, Amaranthaceae and *Artemisia*) displayed a stronger correlation with the winter NAO index for the year of flowering. More significant correlations were observed in the south of the Iberian Peninsula and in Mediterranean coastal areas (Tables 2A and 2B).

4. Discussion

This study focused on the most frequent pollen types—from both woody and herbaceous plants—in the Iberian Peninsula. The Annual Pollen Index (API) was analyzed as an indicator of flowering intensity

Table 2A

Pearson correlation analysis between API and the winter NAO index (December–February) from the year before.

	Cupressaceae	Fraxinus	Betula	Platanus	Quercus	Urticaceae
Málaga	−0.574*	−0.594**		−0.275	−0.211	0.492***
Córdoba	−0.547***	−0.607**		−0.524*	−0.179*	0.008
Jaén	−0.604**				−0.338	
Granada	−0.377	−0.502*		−0.117	−0.131	0.204
Cartagena	−0.548*				−0.180	0.008
Badajoz	−0.263	−0.541*		−0.013	−0.278	0.180
Madrid	−0.574*	−0.265		−0.125	−0.211	0.492*
Barcelona	−0.582**	−0.224	−0.222	−0.015	−0.649**	−0.090
León	−0.584**	0.008	0.065	−0.076	−0.618**	−0.156
Ourense	−0.049	−0.328	−0.153	−0.021	−0.278	0.034
Santiago	0.089		0.015	−0.512*	−0.472*	−0.090

*** Significant ($p \leq 0.001$).** Significant ($p \leq 0.01$).* Significant ($p \leq 0.05$).

in anemophilous plants in areas surrounding the sampling station. Results revealed differences in the distribution of anemophilous tree species (*Betula*, *Fraxinus* and *Quercus*) across the Iberian Peninsula, and highlighted the major contribution to the total airborne pollen both of extensive olive crops in the south and of abundant ornamentals in green urban spaces (*Cupressaceae*, *Fraxinus* and *Platanus*). The findings suggested that, in general, the geographical distribution of herbaceous or undershrub species included in a specific pollen type was largely dictated by rainfall patterns. Some species (e.g. *Amaranthaceae* and *Artemisia*) displayed clear adaptation to low water availability, and were most abundant in semi-arid south-eastern locations, while others (e.g. *Rumex*, *Plantago* and *Poaceae*) were more frequent in the Atlantic continental sector of the Mediterranean region, with an extended area of grasslands and pastures, and other (*Urticaceae*) are frequent in urban environments (walls and ruderalized spots).

Skjøth et al. (2008) have suggested that while forest inventories, crop databases, land cover and remote sensing data are considered as *bottom-up* inventories for mapping ground-based vegetation, temporal and spatial API datasets can be considered as a *top down* inventory in environmental science, providing information on plant distribution and pollen source locations on a different scale. Sofiev and Bergmann (2012) compared a *top down* approach from the European Aeroallergen Network (EAN) to *bottom-up* mapping where available. One clear constraint in the present study was that only those Spanish Aerobiology Network (REA) monitoring stations with data going back over 20 years were used; this limitation with the presence of many gaps in the map clearly hinders a *top down* mapping approach for the Iberian Peninsula. Future research could usefully focus on a shorter but fuller dataset, still within the framework of the REA.

The magnitude of flowering-intensity trends varies depending on the species, the geographical area, the flowering season, and climatic trends; in all cases, however, trends are better appreciated over longer

periods (Clot, 2003; Gordo and Sanz, 2005). The present study examined data over the same 20-year period at all locations, and generally speaking, APIs have increased over recent years, although the increase is more evident for trees than for herbs, which display greater year-on-year variation, probably reflecting a greater dependence on water availability (rainy vs. dry years).

An earlier study in Europe revealed a generally-positive API trend over recent decades at most monitoring sites, with no clear trend for Spain; the trend may be attributable in some cases to rising temperatures or water availability, but is also likely to be influenced by increased CO₂ emissions (Ziello et al., 2012). The Iberian Peninsula comprises two clearly differentiated biogeographical regions (Fig. 1): the North and in the Atlantic part of the Peninsula belongs to the Eurosiberian Region, a narrow temperate area with a uniform climate pattern; the rest of the Peninsula forms part of the Mediterranean Region, comprising various climatic sub-regions. Research on plant phenology has confirmed that changes in rainfall patterns and water availability in the Mediterranean region play a key role as drivers of climate change, especially in arid environments (Peñuelas et al., 2004).

There is evidence to suggest that woody and herbaceous species respond differently to water stress and changing temperatures (Cariñanos et al., 2004). Flowering in trees is more affected by conditions during the months prior to flowering, while herbaceous species display an immediate response to current weather conditions, sometimes waiting for a sufficient water supply before flowering. Although water availability is a major constraint in much of the Iberian Peninsula, a positive API trend was observed for trees, especially where they are abundant. Similar trends have been reported for a number of forest species in a range of environments, e.g. in arid areas (south-eastern Spain) (Cariñanos et al., 2004); in the Atlantic temperate climate (north-western Spain) (Rodríguez-Rajo et al., 2011); in centre Europe, Basel (Switzerland) (Frei and Gassner, 2008).

Table 2B

Pearson correlation analysis between tree API and the winter NAO index (December–February) from the same year.

	Olea	Plantago	Rumex	Poaceae	Amaranthaceae	Artemisia
Málaga	0.018	−0.135	−0.312	−0.593**	−0.262	−0.008*
Córdoba	−0.389**	−0.253	−0.609***	−0.162*	−0.101	−0.400*
Jaén	−0.258			−0.161		
Granada	0.019	−0.415	−0.382	−0.406	−0.044	−0.685**
Cartagena	−0.389	−0.253	−0.607**	0.162	−0.101	−0.400
Badajoz	0.026	0.059	−0.197	−0.056	0.178	
Madrid	0.017	−0.137	−0.313	−0.437	−0.263	−0.008
Barcelona	−0.254	−0.261	−0.067	−0.340	−0.010	−0.285
León		−0.114	−0.517*	−0.315	0.115	−0.170
Ourense	0.031	0.104	0.031	−0.184	0.005	
Santiago		0.140	−0.143	0.226	−0.131	

*** Significant ($p \leq 0.001$).** Significant ($p \leq 0.01$).* Significant ($p \leq 0.05$).

The trends recorded for urban ornamental trees are often apparently clear, e.g. for *Platanus* (Alcazar et al., 2011) and for olive crops (Orlandi et al., 2010), however, these trends are unlikely to be solely due to climate, or to any specific component of climate change, and they are dictated more by local changes due to human activity. For example, though plane trees have become more widespread in gardens and urban green spaces over the last twenty years, the adoption in some cities of gardening practices such as pruning before flowering has reduced flowering intensity, leading to lower airborne pollen concentrations than in other cities, e.g. León (Fernandez-Gonzalez et al., 2010). Elsewhere, new environmental health policies have prompted a more limited use of allergenic ornamentals. In the case of olive, the biennial rhythm sometimes exhibited in earlier decades (Díaz de la Guardia et al., 2003; Galán et al., 2001) is not longer clearly evident (Oteros et al., 2014). It has been supported by this study and probably occurs due to the different flowering behavior of trees (loading/unloading cycles) in the same geographical area, or to the introduction of improved drip-irrigation systems into big extensions.

Some herbaceous and undershrub species are more tolerant than others of water stress, and the present results revealed a significant positive trend in semi-arid areas of the south-eastern Iberian Peninsula for *Amaranthaceae* and *Artemisia*. However, other species displayed a negative trend that has also been reported in different climatic environments, e.g. in southern Spain (Alcázar et al., 2009), in North-East Spain (Fernandez-Llamazares et al., 2014) and in western Poland (Bogawski et al., 2014). Negative trends have also been found for other pollen types, including *Urticaceae* (e.g. in northern and southern Spain (Recio et al., 2009)); *Plantago* (e.g. in north-western Spain (Gonzalez Parrado et al., 2009) and in south-western Spain (Tormo-Molina et al., 2010)); *Amaranthaceae* (e.g. in southern Spain (Cariñanos et al., 2014) and in south-western Spain (Tormo-Molina et al., 2010)); and *Artemisia* (e.g. in southern Spain (Cariñanos et al., 2013) and in Poland (Stach et al., 2007)). Reported findings for *Poaceae*, by contrast, differ considerably: some authors have recorded negative trends in western Spain (e.g. in north-western Spain (Rodríguez-Rajo et al., 2010) and in south-western Spain (Tormo-Molina et al., 2010)), while others have noted positive trends for grass pollen in southern Spain (García-Mozo et al., 2010a) and no change in North-East Spain (Fernandez-Llamazares et al., 2014). The present study observed non-significant positive trends in more Mediterranean locations. Differences in herb behavior probably reflect differing endogenous processes of adaptation to climate change among the species belonging to the various pollen types. Interestingly, however, similar positive trends have been reported for *Quercus* and grass APIs, especially in the south (except Badajoz and Ciudad Real); this may be linked to the recovery of Mediterranean forests in these areas, with an attendant impact on grasses as part of the herbaceous layer of these forests, and the abandonment of crop fields.

A number of authors have highlighted the correlation, in Europe, between temperatures and rainfall and the North Atlantic Oscillation (NAO), particularly in winter (Hurrell, 1995), prompting research into the potential influence of the winter NAO on the timing of flowering. D'Odorico et al. (2002) reported that the NAO index from December to March, i.e. the months preceding flowering, correlated with the timing of the pollen season, noting that winter temperature patterns were strongly affected by NAO phases. Other studies have focused on correlations between the NAO and flowering intensity. Stach et al. (2008) observed that the length of the *Betula* pollen season both in Poznan (Poland) and in Worcester and London (UK) was correlated with different phases of the NAO, correlations being positive for Poznan and negative for Worcester and London during the year before pollination but positive at UK monitoring sites during the same year. Smith et al. (2009) studied the spatial influence of the winter NAO (December–March) in Europe on the timing and intensity of grass pollen seasons. Results showed a significant negative correlation between winter NAO and the pollen-season start-date, except in Córdoba

(southern Spain) where the correlation was weaker. It should be noted, however, that Córdoba was the only site displaying a significant negative correlation for flowering intensity. There is evidence to suggest that the NAO plays a major role in the climate of the Iberian Peninsula, and attention has particularly been drawn to the negative correlation of winter NAO with the frequency and intensity of winter rainfall (Gallego et al., 2005). The negative correlation between winter NAO and flowering intensity must therefore be largely attributable to water availability. In this context, some authors report that while a negative NAO has a greater impact on the western Iberian Peninsula, a positive NAO appears to influence the whole country, with similar dry conditions in all areas (Muñoz-Díaz and Rodrigo, 2004).

The present study obtained better results when using the winter NAO over December–February of the previous year for plants flowering in winter or early spring. It was true that all tree species except the olive, which flowers in late spring, displayed a better response to the winter NAO during the previous year. Since most herbs bloom in spring or autumn, better results were obtained with the winter NAO for the same year; the exception was *Urticaceae*, with some winter-flowering species. Correlations obtained for tree species were more significant than for other plants, especially in the Mediterranean region. These findings confirm the crucial role of water supply during the months prior to flowering, especially in the southern and south-eastern Iberian Peninsula.

5. Conclusions

Airborne pollen is regarded as a key biological indicator of flowering intensity, phenology and species distribution. The results obtained here point to considerable variations in airborne pollen concentrations for both woody and herbaceous plants in different areas of the Iberian Peninsula, and recent climate trends are prompting greater variations in phenology. The scientific community predicts that current weather trends will continue at least into the next century. According to the *Evaluation of Climate Change Impacts in Spain*, the “Mediterraneanization” of the northern Iberian Peninsula and the “aridification” of southern areas appear to be the most significant trends for the next century (Fernández-González et al., 2005). This may have dramatic consequences for global biology, with an alarming impact on ecosystems, on the global economy and on global power supplies. For this reason we agree with Fernández-González et al. (2005), recommending greater support for phenological research, including aerobiological sampling, in order to monitor impacts on plant biodiversity and phenology in the Iberian Peninsula.

Author contribution

C.G. data analysis, experimental design, data collection, redaction, management and supervision; P.A., J.O., H.G.M., and E.D.V. experimental design, supervision, data collection, redaction and management; M.A., J.B., D.F.G., R.T., R.P.B. and M.M.T. data collection, supervision, redaction and testing; C.D.G., M.G.B., S.M., J.R.R. and L.R.V. data collection, redaction and supervision.

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