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ORIGINAL ARTICLE

The impact of temperature on increased airborne pollen and earlier onset of the pollen season in Trentino, Northern Italy

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Abstract

The impact of climate change on ecosystems can be assessed through pollen dispersion data, which acts as a proxy for the plant flowering stage. The aim of this study is to verify if changes occurred in the season and concentration of airborne pollen in Trentino (Northern Italy), and to evaluate if temperature (T), precipitation (P), and/or land use influenced such changes in the period 1989–2018. Airborne pollen, sampled by a Hirst-type trap, was analyzed by light microscopy, and pollen concentrations were obtained. Twenty-four taxa, covering 95% of the local pollen spectrum, were considered for this study. A significant upward trend in annual pollen integral (APIn) is the main outcome over the study period. The increase in APIn is more evident when analyzing the data in three decadic blocks, both for all the considered taxa (+ 58%) and for Arboreal Pollen (AP; + 155%). Considering both the annual data and the decadic blocks, APIn shows a significant positive trend for Cupressaceae/Taxaceae, *Ulmus*, *Populus*, *Salix*, *Ostrya*, *Quercus*, *Olea* (AP), and *Plantago*, Cannabaceae, *Ambrosia* (non-arboreal pollen, NAP); a significantly earlier start of the Main Pollen Season (MPS) is proved for *Rumex* and Poaceae. APIn for 24 taxa shows a significant positive correlation with annual T min (< 0.005) and T mean (< 0.001), both of which showing a significant increase, and a negative correlation (< 0.025) with the number of frost days. From a human health perspective, higher temperatures, driven by climate changes, lead to higher concentrations of allergenic airborne pollen, turning into a higher risk for allergy sufferers.

Keywords Pollen · Air temperature · Climate change · Human health · Temporal trend

Introduction

Ongoing climate change (IPCC Report 2022) has wide-ranging effects on ecosystems, human health, and economic sectors, with numerous repercussions for global well-being (EAA Report 2017).

Phenology, the science of natural recurring events, is one of the indicators for observing the impacts of climate change on ecosystems and biological processes (Parmesan 2006). The shift in phenology as a high-temporal resolution signal of this impact (Menzel et al. 2006) is examined in different geographical contexts, taking both animal and plant organisms into consideration (Parmesan 2006; Walther et al. 2002).

In the plant world, different phenological phases such as bud burst, leaf unfolding, flowering, and senescence are investigated through direct observations, but an increasing number of studies consider pollen dispersal data as a proxy for flowering in anemophilous plants (Bock et al. 2014; Hidalgo-Galvez et al. 2018; Morin et al. 2009). Even

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though plant flowering and pollen dispersal are not exactly overlapping phases, and airborne pollen dispersion is also influenced by transport phenomena (Damialis et al. 2020), airborne pollen data can be useful for its multiple advantages such as standardized data collection and analysis (e.g., UNI EN 16868:2019 at European level), global level sampling (https://www.zaum-online.de/pollen/pollen-monitoring-map-of-the-world.html, accessed on 19 December 2023), and the possibility to rely on long time series. The detection of trends, in fact, is extremely dependent on extended data series, in order to overcome the signal of the natural interannual variability in pollen production, particularly robust in the case of arboreal plants (Pesendorfer et al. 2016).

To highlight trends and evaluate changes in airborne pollen data, a set of pollen season descriptors has been elaborated and recommendations for a coherent terminology were published (Bastl et al. 2018). An increase in the total pollen sampled by aerobiological monitoring was reported over the northern hemisphere (Ziska et al. 2019), reflecting the effects of an increase in the annual pollen index (APIn) for arboreal pollen (AP) (Anderegg et al. 2021; Bruffaerts et al. 2018; Gehrig and Clot 2021; Glick et al. 2021; Ziello et al. 2012), often detailed in single species trends, such as *Corylus* (Bruffaerts et al. 2018; Hoebeke et al. 2018; Jochner-Oette et al. 2019), *Betula* and *Quercus* (Adams-Groom et al. 2022), and Cupressaceae/Taxaceae (Gehrig and Clot 2021).

Similarly, time trends of other pollen season descriptors were reported by several authors; an earlier MPS start, in particular, was highlighted for many taxa, such as *Corylus*, *Quercus*, Poaceae, and Urticaceae (Cristofolini et al. 2020; Glick et al. 2021; Hoebeke et al. 2018; Rojo et al. 2021), *Betula* (Frei and Gassner 2008; Lind et al. 2016; Rojo et al. 2021), Cupressaceae/Taxaceae (Gehrig and Clot 2021), and *Olea* (Garcia-Mozo et al. 2014). Results, though, can be very variable depending on the site (Ziello et al. 2012) and taxon (Damialis et al. 2007; Galan et al. 2016) considered and do not lead to general conclusions.

The possible drivers of change for pollen season descriptors, and thus for changes in plant phenology and biodiversity, can be several, but the most relevant include global change, mainly described through meteorological variables and land use. Pollen season is more often analyzed in relation to climate change, with temperature as the most investigated variable. Overall, air temperature evidences a marked effect on seasonality (Frei and Gassner 2008; Gehrig 2006; Hoebeke et al. 2018; Makra et al. 2014), determining an earlier and longer pollen season (Aguilera and Ruiz-Valenzuela 2014; Gehrig and Clot 2021; Majeed et al. 2018; Schramm et al. 2021; Zhang et al. 2015; Zhang and Steiner 2022), and higher pollen concentrations (Bogawski et al. 2014; Damialis et al. 2007; Wan et al. 2002; Ziska et al. 2019).

Precipitation is also often considered among meteorological parameters influencing pollen season descriptors (Schramm et al. 2021). Precipitation contributes to water availability, ensuring plant viability, development, and reproduction, with the concurrent pollen release, especially in Mediterranean areas, where water shortage may occur (Penuelas et al. 2004). On the short term, though, precipitation may reduce the airborne pollen concentration by removing it from the atmosphere.

In addition to meteorological variables, land use can play a role in plant species composition and spatial distribution, which in turn is reflected in the airborne pollen spectrum (Maya-Manzano et al. 2017; Rojo et al. 2015).

The study of pollen and its spatio-temporal changes, other than its ecological significance for interpreting plant phenology and biodiversity, is of paramount importance due to the allergenicity of many airborne pollen taxa. Current estimates place the incidence of pollen allergy to approximately 25–40% of the population, globally (D'Amato et al. 2007; Husna et al. 2022; Gani et al. 2018), following an increasing trend (Barnes 2018; D'Amato et al. 2015). Such increase is partly related to a higher exposure to airborne allergenic pollen, which is in turn connected to climate change. Milder weather, air pollution, and elevated CO_2 levels, in fact, influence pollen production and allergenicity, as well as the spread of neophytes producing allergenic pollen (Beck et al. 2013; D'Amato et al. 2020; Luschkova et al. 2022; Rauer et al. 2021).

The present study, based on a 30-year aerobiological dataset collected in San Michele all'Adige, Northern Italy, aims to (i) verify if significant changes occurred in the timing and quantity of airborne pollen from 1989 to 2018 and (ii) evaluate the relationship between pollen season descriptors and air temperature, precipitation, and land use.

Materials and methods

Study area

The aerobiological monitoring site is located at San Michele all'Adige, Trentino, North Italy. The region is orographically complex, within the Alpine biogeographical region, characterized by a predominantly oceanic climate (Eccel et al. 2016) and a high diversity of plant associations. The sampling site is at the bottom of the Adige Valley (46.19, 11.13; 206 m a.s.l.), in a rural area mainly covered by vineyards and apple orchards, where also herbaceous species as Poaceae, *Parietaria*, *Artemisia*, and *Plantago* are present. Broadleaved and mixed forests (*Ostrya carpinifolia* Scop., *Fraxinus ornus* L., *Quercus pubescens* Willd., *Corylus avellana* L., *Alnus* sp., and *Salix* sp.) dominate the lateral slopes, while beech (*Fagus sylvatica* L.) and conifers (*Pinus sylvestris* L., *Pinus nigra* Arnold., and *Picea abies* (L.) H.Karst.) expand as the altitude increases.

Data collection

Data on airborne pollen concentration were collected over 30 years, from 1989 to 2018, by a Hirst-type volumetric sampler (VPPS 2000, Lanzoni, Bologna, Italy), installed at the top of a 10-m tilt-down pole. Identification and counting of pollen were performed by light microscopy (Leitz Diaplan, Wild Leitz GmbH, Wetzlar, Germany), and the daily concentration of airborne pollen (P*m^{-3}) was calculated for each taxon. The sampling and analysis of airborne pollen were conducted in accordance with the UNI EN 16868:2019 European standard procedure.

Air temperature (°C) and precipitation (mm) were recorded within 1.5 km of the aerobiological sampling site, in the Adige valley floor at the same elevation as the aerobiological sampler. The weather station consists of a TMF500 datalogger (NESA s.r.l, Treviso, Italy), connected to several sensors including a Vaisala HMP155 thermo-hygrometer and a SIAP+MICROS rain gauge with a 400 cmq opening. The datalogger reads the sensors every 10 s and stores the meteorological data every 15 min.

Land cover was analyzed within a 1-km, 5-km, and 30-km radius area centered on the aerobiological sampler, considering the Corine Land Cover (CLC) level 1 classes (1. Artificial surfaces, 2. Agricultural areas, and 3. Forests and semi-natural areas; https://land.copernicus.eu/pan-european/corine-land-cover, accessed on 12 December 2023) for the years 1990, 2000, 2006, 2012, and 2018.

Data analysis

The San Michele all'Adige pollen spectrum consists of more than 60 taxa. For this study, the main 24 pollen taxa, covering 95% of the total pollen, were considered. Pollen taxa were assigned to the taxonomical level of plant species, genus, or family based on morphological features, referring to the updated nomenclature (https://www.worldfloraonline.org/, accessed on 12 December 2023).

The following pollen season descriptors were calculated for each taxon: (i) annual pollen integral (APIn; pollen*m^{-3}); (ii) main pollen season (MPS) start and end, as the day of the year when 2.5% and 97.5% of the APIn was reached, respectively (i.e., MPS start, MPS end); (iii) MPS length, as the difference between MPS end and MPS start, plus 1; (iv) MPS peak value, as the maximum concentration registered during the MPS; (v) MPS peak, as the day when the MPS peak value occurs. Pollen descriptors were calculated for each calendar year.

In order to verify data completeness, the mean MPS over the 30-year study period was calculated for each taxon; the mean MPS start corresponds to the average of the annual MPS start dates minus a standard deviation (SD), and the mean MPS end corresponds to the average of the annual MPS end dates plus a SD. The analyses were performed only on years with at least 80% of data available within the mean MPS. The annual APIn for arboreal (AP) and non-arboreal (NAP) taxa and the number of high-concentration days (i.e., the number of days in a year when pollen concentration of at least one taxon exceeds a threshold of 100 P*m^{-3} for AP (AP > 100), and 50 P*m-3 for NAP (NAP > 50)) were also calculated (Pfaar et al. 2017).

Air temperature data (Tmean, Tmin, Tmax) were averaged on a yearly and monthly basis. Daily precipitation values (P) were accumulated on annual (P tot) basis. The number of days with precipitation (P days) was calculated for each year. The number of frost days was calculated for each year as the number of days when the minimum temperature was < 0 °C.

The presence of a monotonic upward or downward temporal trend in pollen season descriptors and meteorological variables was verified by means of the non-parametric Mann-Kendall test; the slope of the linear trend was calculated using Sen's estimate (MAKESENS 1.0 version freeware, Finnish Meteorological Institute).

Correlations between pollen season descriptors and meteorological variables were analyzed using the non-parametric Spearman's rank correlation (TIBCO Statistica® 14.1.0). Temperature and precipitation data considered for the analysis covered the period from the month including the MPS descriptor (i.e., MPS start, peak, end) backwards to October of the previous year.

In addition, pollen season descriptors and meteorological variables were averaged within each of three decadic blocks (i.e., 1989–1998, 1999–2008, and 2009–2018), to minimize the effect of interannual fluctuations in pollen production and to highlight relevant changes during the study period. Parametric one-way ANOVA (for meteorological variables) and non-parametric Kruskal-Wallis ANOVA (for pollen season descriptors) were performed to identify significant differences between the three 10-year data blocks, followed by the post-hoc LSD Fisher (parametric) and Mann-Whitney *U* (non-parametric) test to highlight the significantly different pairs.

Results

Figure 1 shows the pollen spectrum of San Michele all'Adige, based on the 30-year dataset. In terms of plant growth form, 16 out of 24 pollen taxa considered belong to arboreal plants (i.e., AP), and 8 out of 24 taxa belong to non-arboreal plants (i.e., NAP). Urticaceae and *Ostrya* are responsible for nearly half of the total airborne pollen (47.6%), followed by Poaceae (11.2%) and Cupressaceae/Taxaceae (6.1%).

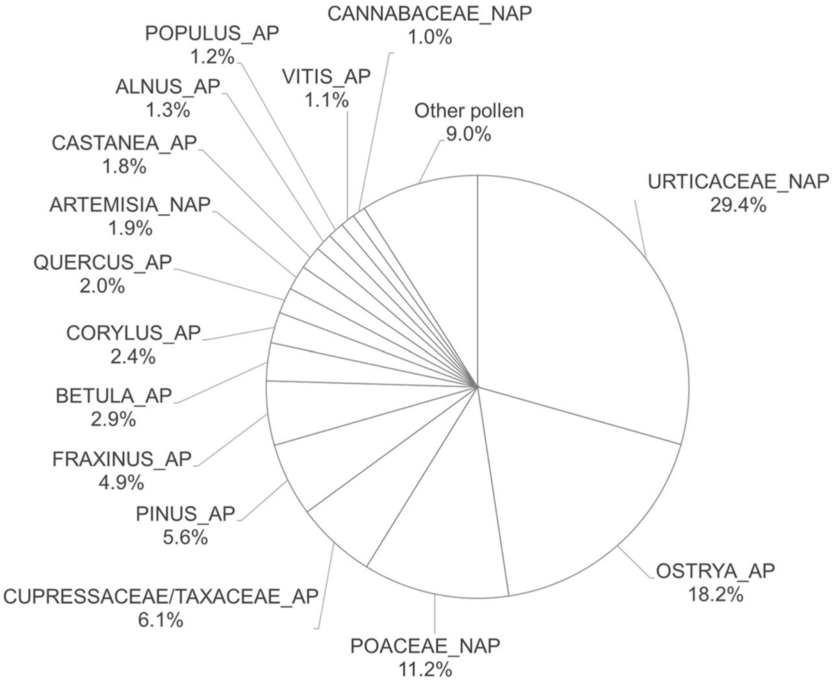

Fig. 1 Pollen spectrum of San Michele all'Adige, calculated for the 1989–2018 period. Arboreal taxa are indicated with _AP; non-arboreal with _NAP. Other pollen (9%) groups minor taxa, including the AP taxa *Ulmus*, *Salix*, *Fagus*, *Picea*, and *Olea*, and the NAP taxa *Rumex*, *Plantago*, Chenopodiaceae, and *Ambrosia*

Trend analysis

The most evident signal deriving from the analyses of the local time series of pollen data concerns the monotonic significant trend for the increase in total pollen, expressed by the APIn index, even more pronounced for arboreal pollen (Fig. 2). AP displays also a significant ($p = 0.08$) upward trend in the number of high-concentration days (AP > 100), with an increase of about 9 days per 10 years.

When detailing the analysis at taxon level, more than half of the taxa shows a significantly increasing trend for APIn (13 on 24); a very high significance ($p < 0.001$) is reported for Cupressaceae/Taxaceae, *Populus*, *Salix*, *Quercus*, *Plantago*, and Cannabaceae; a high significance ($p < 0.01$) is evidenced for *Ulmus*, *Ostrya*, *Olea*, and *Ambrosia*; *Alnus*, *Picea*, and *Rumex* display a significant trend ($p < 0.05$) (Table 1).

Coherently, also MPS peak values show a significant upward trend for most of the taxa (11 on 24), except for Poaceae, which peak values decrease during the study period. The significant upward trend for MPS peak value is generally associated with an APIn upward trend, except for Amaranthaceae, which MPS peak value has an increasing trend despite APIn remains stable during the study period.

A significantly earlier MPS start is observed for 6 out of 24 taxa (two AP, *Fagus* and *Pinus*; four NAP, *Rumex*, Poaceae, Urticaceae, *Plantago*), with an advance of 5.4 (min 3.3–max 8.0) days every ten years, on average.

As for MPS peak, end, and length, no coherent change is observable across the different taxa.

As for meteorological variables, precipitation does not show a trend along the time series. Analyzing temperatures and number of frost days, on the contrary, significant trends are highlighted, as reported in Table 2.. There is a significant upward trend in the annual Tmin and Tmean. Monthly Tmin for November of the previous year (Tmin 11py), February (Tmin 2), April (Tmin 4), and June (Tmin 6) significantly increase. Monthly Tmean for November of the previous year (Tmean 11py), and April (Tmean 4) also increase significantly. Conversely, the annual Tmax and the monthly Tmax for January (Tmax 1) and February (Tmax 2) have a significant negative trend. A significant decrease is observed in the annual number of frost days.

Pollen season descriptors and meteorological variables

Total pollen amount (APIn for 24 taxa) shows a significant positive correlation with annual Tmin (< 0.005) and Tmean (< 0.001), and negative (< 0.025) with the number of frost days. The significant positive correlation with annual Tmin and Tmean is evidenced also for APIn of AP ($p < 0.01$ and $p < 0.005$, respectively) and NAP ($p < 0.01$ and $p < 0.0025$, respectively); APIn of NAP shows a significant positive correlation with the number of days with precipitation ($p < 0.025$) and negative correlation with the number of frost days ($p < 0.025$). The number of high-concentration days, both for arboreal (AP > 100) and non-arboreal (NAP > 50) taxa, positively correlates with annual mean temperature ($p < 0.02$); a significant positive correlation is also evidenced

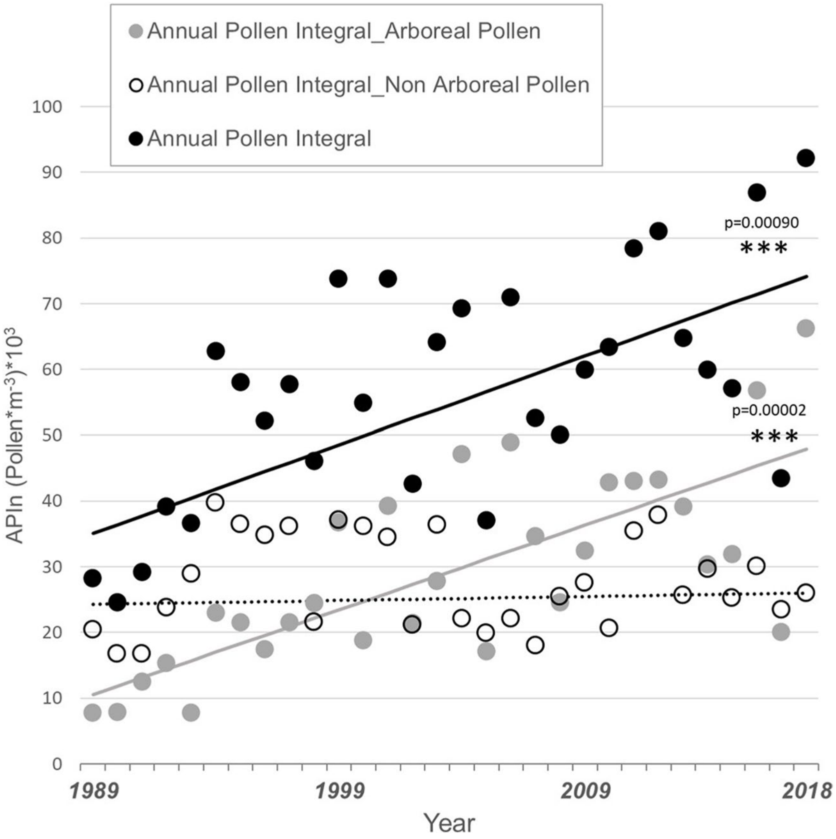

Fig. 2 Time trend (Sen's slope) of the annual pollen integral (APIn) for the total pollen of the 24 taxa considered in the study (black line for the trend and black dots for annual values) and separated for arboreal pollen (gray line and dots), and non-arboreal pollen (dashed line, white dots). *P* values are indicated next to the line for the significant trends

between NAP > 50 and the number of days with precipitation (P days; Table 3).

The significant ($p < 0.05$) correlations between pollen season descriptors (MPS start, peak, and end) and monthly air temperatures are reported in Online Resource 1 ((a) Tmin; (b) Tmean; (c) Tmax). MPS start shows the highest number of correlations—mostly negative—with the pre-seasonal air temperature, more frequent for AP taxa flowering from February to April.

MPS peak of AP taxa shows a negative significant correlation with air temperature, mostly Tmean and Tmax, occurring up to ca. 2–3 months prior to the event. NAP taxa show a less evident effect of temperature on MPS peak timing.

MPS end evidences very few negative correlations with temperatures, mainly for AP taxa ending the pollen season in April with March Tmean (Tmean 3) and Tmax (Tmax 3).

Land cover

Table 4 details the first level of classification of CLC in 1990, 2000, 2006, 2012, and 2018 within three buffer zones centered on the aerobiological sampler, and with a radius of 1 km, 5 km, and 30 km.

Within the 1-km buffer, a reduction in the agricultural area between 2006 and 2018 is evident, with the concurrent increase in artificial surfaces between 2000 and 2018, and in forest and seminatural areas between 2012 and 2018. The overall changes from 1990 to 2018 range from 10.6 to 12% of the area related to each level I CLC category, and only from − 0.6 to 0.3% when considering the change in relation to the buffer area.

Within the 5-km buffer zone, there is an overall increase of 51 ha in artificial surfaces, corresponding to 8.3% of the category area, but only to 0.01% of the buffer area; agricultural and forest seminatural areas decrease slightly between 1990 and 2018 (− 1.3% and 0.3% of each category area). The maximum percentual change when referring to the buffer area is 0.1%.

Within the 30-km buffer, a remarkable expansion of artificial surfaces is noted (14.6%), mainly referrable to the period 1990–2006; on the contrary, agricultural areas slightly decrease (− 5.3%). Forest and seminatural areas remain quite stable during the period 1990–2018. When referring to the buffer area, changes are between − 0.01% and 0.01%.

Table 1 Time trends over the 30 years (1989–2018) of the pollen season descriptors of the 24 taxa considered in the study, 16 of which belonging to arboreal pollen and 8 to non-arboreal pollen. *n* is the number of years of data per taxon. The pollen season descriptors are (i) main pollen season (MPS) start and end, as the day of the year when 2.5% and 97.5% of the annual pollen integral was reached; (ii) MPS length, as the difference between MPS end and MPS start, plus 1; (iii) MPS peak value, as the maximum concentration registered during the MPS; (iv) MPS peak, as the day when the MPS peak value occurs; (v) annual pollen integral (APIn; pollen*m^{-3}). Significant trends (*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$) are evidenced; red cells are for increasing trends, while blue ones indicate decreasing trends

		Main Pollen Season					Annual Pollen Integral
Taxon	n	start	peak	end	lenght	peak value	
Arboreal Pollen							
Corylus	29						
Alnus	29				🟦 *		🟥 *
Cupressaceae/Taxaceae	29			🟥 *	🟥 **	🟥 ***	🟥 ***
Ulmus	29					🟥 *	🟥 **
Populus	29		🟥 *	🟦 **		🟥 **	🟥 ***
Salix	29					🟥 ***	🟥 ***
Betula	29			🟥 *	🟦 *		
Fraxinus	23						
Ostrya	29			🟦 *	🟦 **	🟥 *	🟥 **
Quercus	29			🟥 **		🟥 **	🟥 ***
Fagus	29	🟦 *					
Picea	23			🟦 *		🟥 *	🟥 *
Pinus	23	🟦 *					
Olea	19						🟥 **
Vitis	19						
Castanea	28		🟦 *		🟦 *		
Non Arboreal Pollen							
Rumex	30	🟦 ***	🟦 ***			🟥 **	🟥 *
Poaceae	30	🟦 ***	🟦 **		🟥 ***	🟦 *	
Urticaceae	29	🟦 *					
Plantago	30	🟦 *			🟥 **	🟥 ***	🟥 ***
Amaranthaceae	28					🟥 *	
Cannabaceae	30					🟥 ***	🟥 ***
Artemisia	25		🟥 ***				
Ambrosia	26						🟥 **

Decadic block data analysis

The meteorological and pollen season descriptor data (mean ± sd) for the three decadic blocks are reported in Table 5, only when a significant variation between the blocks is verified. As for meteorological variables (Table 5), temperature exhibits significant changes across the decades. A significant increase of 1.0 °C in annual minimum temperature occurs from the first to the third decadic block, mainly driven by the considerable increase in April minimum temperature (+ 2.0 °C). No significant change occurs in the annual mean temperature across the decadic blocks, while it increases significantly particularly in April (+ 1.7 °C) and June (+ 0.9 °C). In contrast, the annual maximum temperature decreases significantly, in January (− 1.1 °C) and February (− 2.4 °C).

Regarding pollen amount (Table 6), the most evident signal corresponds to the highly significant increase in APIn (+ 58%), which is even more marked when considering only AP (+ 155%). Concurrently, AP shows a significant increase (+ 20 days) in the number of days with high pollen concentrations (i.e., AP > 100).

When considering the AP individual taxa, both APIn and MPS peak value significantly increase across the decadic blocks for Cupressaceae/Taxaceae, *Ulmus*, *Populus*, *Quercus*, *Salix*, and *Olea*; *Ostrya* APIn has a remarkable and significant increase (+ 189% from the first to the third decade), while MPS peak value significantly increases for *Picea*. MPS peak values exhibit a significant downward trend only for *Vitis*.

As for NAP taxa, APIn and MPS peak values significantly increase for *Plantago*, Amaranthaceae, Cannabaceae, and *Artemisia*; APIn increase is limited to the first and second decadic blocks for *Ambrosia*.

When analyzing MPS timing (Table 7), Poaceae express a significantly earlier MPS start (− 11 days) and peak (− 6 days) and a significantly later MPS end (+ 20 days) across the three decadic blocks, resulting in a longer pollen season.

Table 2. Time trends of meteorological parameters. Number of years (*n*), Mann-Kendall (MK) trend test results, *p*-value, and the slope (*Q*) are detailed for significant trends. Red cells are for increasing trends, while blue ones indicate decreasing trends

Meteorological variable	n	MK	p	Q
Tmin 11py	29	1.970	0.049	0.102
Tmin 2	30	2.462	0.014	0.091
Tmin 4	30	2.855	0.004	0.089
Tmin 6	30	1.998	0.046	0.060
Tmin year	30	2.926	0.003	0.049
Tmean 11py	29	1.970	0.049	0.060
Tmean 4	30	3.604	0.001	0.083
Tmean year	30	2.462	0.014	0.029
Tmax 1	30	-1.963	0.050	-0.050
Tmax 2	30	-2.355	0.018	-0.113
Tmax year	30	-1.963	0.050	-0.031
Frost days	30	-2.253	0.025	-0.786

Rumex shows a significantly earlier MPS start and peak, and a significantly later MPS peak is pointed out for *Artemisia* only. A shorter MPS length is demonstrated for the *Betula* and *Castanea* AP taxa, connected to an earlier MPS end. Cupressaceae/Taxaceae, on the contrary, undergo a lengthening of the MPS.

Urticaceae, the most represented taxon in the local pollen spectrum, shows no significant change in any pollen season descriptors.

Discussion and conclusion

Overall, the key findings of this 30-year aerobiological study in Trentino (Northern Italy), carried out on 24 pollen taxa, are (i) an impressive increase in annual pollen amount and

Table 3 *p* values for correlations between pollen descriptors and meteorological variables. Non-significant correlations are indicated by n.s.; positive correlations are colored in red, negative ones in blue. APIn is the annual pollen integral for all 24 taxa (APIn tot), arboreal pollen (AP), and non-arboreal pollen (NAP). The number of high-concentration days is indicated by AP > 100, where 100 is the concentration threshold (in $P*m^{-3}$) considered for arboreal pollen, and by NAP > 50 for non-arboreal pollen, where the threshold is 50 $P*m^{-3}$

Pollen descriptor	Tmin year	Tmean year	Tmax year	P tot	P days	Frost days
APIn tot	<0.005	<0.001	n.s.	n.s.	n.s.	<0.025
APIn AP	<0.01	<0.005	n.s.	n.s.	n.s.	n.s.
APIn NAP	<0.01	<0.0025	n.s.	n.s.	<0.025	<0.025
AP>100	n.s.	<0.01	n.s.	n.s.	n.s.	n.s.
NAP>50	n.s.	<0.02	n.s.	n.s.	<0.05	n.s.

Table 4 Characterization of land use changes during the study period. The table shows the hectares (ha) of area classified by Corine Land Cover (CLC) Level I in artificial surfaces (code 1), agricultural areas (code 2), and forests and seminatural areas (code 3), within a buffer of 1-km, 5-km, and 30-km radius from the aerobiological sampler. Differences are indicated between 2018 and 1990, in ha and in percentage of the level I classification, and of the buffer area. The total area of the buffer is reported in brackets

Buffer radius (buffer ha)	Area per Corinne Land Cover category (ha) *Reference year*					Area variation		
Level 1 CLC	*1990*	*2000*	*2006*	*2012*	*2018*	Difference 2018–1990		
1 km (314 ha)						ha	% within category	% within buffer
1_Artificial surfaces	68	68	71	76	76	8	11.87	0.03
2_Agricultural areas	166	166	164	158	148	-18	-10.75	-0.06
3_Forests and seminatural areas	79	79	79	79	89	10	12.57	0.03
5 km (7850 ha)								
1_Artificial surfaces	608	639	647	653	659	51	8.39	0.01
2_Agricultural areas	3503	3494	3488	3487	3467	-36	-1.03	0.00
3_Forests and seminatural areas	3710	3688	3687	3681	3697	-14	-0.37	0.00
30 km (282,600 ha)								
1_Artificial surfaces	10,471	11,580	11,975	12,047	12,004	1533	14.64	0.01
2_Agricultural areas	56,755	55,581	54,209	54,148	53,777	-2,979	-5.25	-0.01
3_Forests and seminatural areas	212,219	212,285	213,246	213,234	213,487	1267	0.60	0.00

Table 5 Significant trends, as detailed by ANOVA *p* values, over the three decades for mean (± standard deviation, sd) values of meteorological parameters

	1989–1998			1999–2008			2009–2018			One-way ANOVA *p* value	Post hoc LSD Fisher test
	Mean	sd		Mean	sd		Mean	sd			
Tmin 4	5.7	1.46	*a*	6.6	1.25	*ab*	7.7	0.99	*b*	0.005	1 vs 3
Tmin year	6.2	0.92	*a*	6.8	0.78	*ab*	7.2	0.74	*b*	0.044	1 vs 3
Tmean 4	12.0	0.89	*a*	12.9	1.37	*ab*	13.7	0.92	*b*	0.006	1 vs 3
Tmean 6	20.0	1.25	*a*	21.5	1.11	*b*	20.9	0.70	*b*	0.009	1 vs 2, 1 vs 3
Tmax 1	7.9	7.86	*ab*	8.1	1.45	*a*	6.8	0.97	*b*	0.048	2 vs 3
Tmax 2	11.9	2.40	*a*	11.2	1.89	*ab*	9.5	1.30	*b*	0.026	1 vs 3
Tmax 6	27.2	1.31	*a*	28.7	1.78	*b*	27.4	0.67	*a*	0.043	1 vs 2, 2 vs 3
Tmax year	19.4	0.67	*ab*	19.6	0.97	*a*	18.8	0.57	*b*	0.049	2 vs 3

Post hoc test results are indicated by the letters a, b, and c

Table 6 Significant trends, as detailed by ANOVA *p* values, for the number of days with high pollen concentrations (i.e., AP > 100), APIn, and MPS peak value

	1989–1998			1999–2008			2009–2018			Kruskal-Wallis ANOVA *p* value	Mann-Whitney *U* test
	mean	sd		mean	sd		mean	sd			
AP > 100	30.2	16.8	a	52.0	10.1	b	50.3	11.0	b	0.007	1 vs 2, 1 vs 3
Annual pollen integral (APIn)											
Total pollen	43431.9	13847.1	a	58882.2	13340.4	b	68687.2	15253.8	b	0.005	1 vs 2, 1 vs 3
AP	15899.2	6639.9	a	31613.1	11423.5	b	40558.1	13375.9	b	0.001	1 vs 2, 1 vs 3
Cupressaceae	2173.3	920.6	a	4024.7	883.9	b	5252.3	1622.6	b	0.0002	1 vs 2, 1 vs 3
Ulmus	209.25	154.9	a	226.1	96.2	a	378.8	151.1	b	0.0194	1 vs 3, 2 vs 3
Populus	449.4	236.5	a	862.4	315.4	b	1020.3	409.4	b	0.0033	1 vs 2, 1 vs 3
Salix	195.4	109.6	a	304.4	73.4	a	444.4	105.0	b	0.0008	1 vs 3, 2 vs 3
Ostrya	5512.4	3395.5	a	12715.4	9065.5	ab	15910.1	10736.8	b	0.0256	1 vs 3
Quercus	856.0	484.1	a	1093.9	311.7	a	1676.5	557.9	b	0.0013	1 vs 3, 2 vs 3
Olea	105.0	3.3	a	94.8	64.1	a	339.3	146.9	b	0.0014	1 vs 3, 2 vs 3
Plantago	*276.5*	*231.5*	a	*655.4*	*183.7*	b	*786.4*	*154.0*	b	0.0002	*1 vs 2, 1 vs 3*
Amaranthaceae	372.7	143.9	a	624.4	216.1	b	558.2	314.6	ab	0.0164	1 vs 2
Cannabaceae	413.4	200.9	a	580.8	125.4	ab	846.2	350.3	b	0.0082	1 vs 3
Artemisia	1166.5	326.5	ab	862.3	276.9	a	1511.3	564.5	b	0.0210	2 vs 3
Ambrosia	18.4	13.7	a	53.3	27.2	b	65.9	38.9	b	0.0046	1 vs 2, 1 vs 3
MPS peak value											
Cupressaceae	219.0	88.2	a	435.0	158.0	b	444.1	121.2	b	0.001	1 vs 2, 1 vs 3
Ulmus	27.8	22.5	a	25.8	9.7	a	55.7	31.4	b	0.033	1 vs 3, 2 vs 3
Populus	69.0	38.3	a	110.0	52.0	ab	138.4	78.3	b	0.049	1 vs 3
Salix	20.4	12.2	a	38.4	15.9	b	43.4	11.4	b	0.004	1 vs 2, 1 vs 3
Quercus	83.4	57.7	a	93.4	26.4	a	143.0	57.2	b	0.016	2 vs 3, 1 vs 3
Picea	15.2	16.0	a	38.2	31.8	ab	67.4	46.2	b	0.045	1vs3
Olea	18.5	3.8	a	17.5	13.9	a	42.4	21.2	b	0.033	1 vs 3, 2 vs 3
Vitis	103.4	63.1	ab	156.4	67.4	a	72.5	26.4	b	0.021	2 vs 3
Plantago	13.3	9.7	a	22.0	4.3	b	26.6	6.8	b	0.003	1 vs 2, 1 vs 3
Amaranthaceae	17.7	7.2	a	46.6	29.1	b	37.6	27.8	b	0.005	1 vs 2, 1 vs 3
Cannabaceae	44.7	21.1	a	64.6	18.5	b	84.5	33.5	b	0.008	1 vs 2, 1 vs 3
Artemisia	124.4	45.5	ab	80.4	41.7	a	170.7	84.8	b	0.017	2 vs 3

Post hoc test results are indicated by the letters a, b, and c

(ii) an earlier pollen season start, both related to rising air temperatures.

The significant increase in annual pollen amount, consistent with previous studies at different spatial scales (Anderegg et al. 2021; Cristofori et al. 2010; Gehrig and Clot 2021; Rojo et al. 2021; Ziello et al. 2012; Ziska 2020), is even more evident when considering data aggregated in decadic blocks, thus minimizing the effects of interannual fluctuations in pollen production. The increase in annual pollen amount can be due to several—even concurring—factors, such as to changes in vegetation composition (García-Mozo et al. 2016), to a larger production of pollen by the individual plants (Katz et al. 2020), or to changes in atmospheric factors that may influence pollen release and airborne transport (Picornell et al. 2023). In this study, no relevant changes in land use are verified within the buffer areas centered on the aerobiological sampler, leading to the exclusion of this as a possible cause of the increase in pollen amount. Rather, the significant increase in annual minimum and mean air temperatures registered in the study area, as well as the decrease in frost days, which positively correlate with the annual pollen amount, supports the evidence about the important role of meteorological variables on pollen production (Zhang and Steiner 2022). Precipitation does not show any change and there is no significant correlation with pollen season descriptors, likely because of the absence of hydric stress in the study area, in contrast to Mediterranean sites (Penuelas et al. 2004). The number of rainy days is the only precipitation-related variable that significantly correlates with the annual pollen integral of non-arboreal taxa. Pollen production can also depend on plant nutritional state (Jochner et al. 2013) and on carbon dioxide (CO_2) levels in the atmosphere (Ziska 2020). It has been proven, mostly under controlled conditions, that elevated CO_2 levels induce pollen production (Albertine et al. 2014; Rogers et al. 2006). Moreover, some authors (Zhang and Steiner 2022; Ziello et al. 2012) report that climate-driven changes alone have a smaller impact on pollen production when compared to the additional effect of CO_2, even if temperature is a stronger driver in real conditions (Anderegg et al. 2021). In this study, the effect of CO_2 on pollen amount was not directly investigated, but since CO_2 and air temperature are two interconnected factors, it may have contributed to its radiative forcing (Koutsoyiannis and Kundzewicz 2020).

Basically, several climate and non-climate drivers affect pollen production, to varying degrees depending on the pollen taxa considered. In this study, *Ostrya* (hop hornbeam) and Cupressaceae/Taxaceae are the most represented arboreal taxa, accounting for 24% of the pollen spectrum. Hop hornbeam, which pollen amount tripled from the first to the third decadic block, is a native plant species that characterizes the mixed deciduous woodlands in the surroundings

Table 7 Significant trends, as detailed by ANOVA *p* values, for MPS start, peak, end, and length

	1989–1998			1999–2008			2009–2018			K-W ANOVA *p* value	Mann-Whitney *U* test
	mean	sd		mean	sd		mean	sd			
MPS start											
Olea	140.3	2.5	a	152.0	8.6	b	143.8	7.8	ab	0.031	1 vs 2
Poaceae	117.5	5.5	a	113.5	7.4	a	106.1	8.8	b	0.003	2 vs 3, 1 vs 3
Rumex	113.1	12.2	a	106.0	6.7	a	97.5	8.0	b	0.004	2 vs 3, 1 vs 3
Ambrosia	223.3	8.8	a	231.0	3.5	b	223.7	5.6	a	0.013	1 vs 2, 2 vs 3
MPS peak											
Rumex	152.3	30.6	a	121.7	12.5	b	108.5	15.5	c	0.0003	1 vs 2, 1 vs 3, 2 vs 3
Poaceae	126.7	4.0	a	128.1	13.3	ab	120.6	4.7	b	0.0401	1 vs 3
Artemisia	227.2	2.5	a	227.4	2.8	a	254.0	19.2	b	0.0081	1 vs 3, 2 vs 3
MPS end											
Betula	123.0	8.7	a	130.6	7.5	b	118.9	7.5	a	0.0131	1 vs 2, 2 vs 3
Fraxinus	144.8	14.1	ab	151.5	11.8	a	137.7	6.8	b	0.0394	2 vs 3
Castanea	207.6	5.6	a	198.6	6.3	b	199.0	5.9	b	0.0029	1 vs 2, 1 vs 3
Poaceae	222.4	12.4	a	232.7	17.5	ab	242.0	19.0	b	0.049	1 vs 3
MPS length											
Alnus	142.6	11.5	a	129.6	9.8	b	132.1	13.5	ab	0.044	1 vs 2
Cupressaceae	84.3	12.6	a	92.2	19.7	ab	109.0	17.6	b	0.034	1 vs 3
Betula	44.1	13.4	ab	47.6	7.3	a	34.4	6.5	b	0.013	2 vs 3
Castanea	45.5	5.2	a	38.2	4.9	b	40.2	4.8	b	0.014	1 vs 2, 1 vs 3
Poaceae	105.9	12.7	a	120.2	21.0	ab	136.9	19.9	b	0.007	1 vs 3

Post hoc test results are indicated by the letters a, b, and c of the sampling area. The distribution of this species in the study area can be deemed to have remained constant during the last decades, due to the low management on this species, and to the scarce use of this plant in public and private greenery. Thus, the observed increase in pollen amount could be attributable to a larger production by the native plants, likely driven by climate change; we cannot exclude a concurrent age effect of the tree stands, which entails an expansion of the crown and consequently of the number of flowers. Hop hornbeam pollen is seldom taken into due consideration in aerobiological studies (Puljak et al. 2016), despite its high allergenicity (Voltolini et al. 2011) and the high potential levels of pollen exposure due to the large distribution area of this species (https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:295664-1, accessed on 13 December 2023).

Unlike hop hornbeam, the Cupressaceae/Taxaceae taxon is widely considered in the literature; the increase in pollen amount observed in this study is in line with previous results obtained in Switzerland (Gehrig and Clot 2021), Germany (Rojo et al. 2021), Iberian Peninsula (Galan et al. 2016), and Greece (Damialis et al. 2007). The marked increase (+ 142%) of this pollen in our study area can be explained with the more and more frequent use of these plants in urban parks and gardens for ornamental purposes, which is reflected in the aerobiological spectrum (Ciani et al. 2021). Such an increase in pollen amount, coupled by a concurrent lengthening of the pollen season, aggravates the exposure to this allergenic pollen, responsible for winter pollinosis, which is rising especially in Mediterranean countries (Charpin et al. 2019). Moreover, due to global warming, the distribution of these species is likely to expand in the Alps (Zorer et al. 2014).

Although *Olea* is not one of the most representative taxa in the study area, it can be discussed as an example of the potential impact of agronomic practices. *Olea* pollen significantly increased in the last decade, 2009–2018, with threefold values compared to the previous 20 years, confirming the trend already observed by other authors (Galera et al. 2018; Garcia-Mozo et al. 2014). For *Olea*, as well as for *Vitis*, the agronomic practices (e.g., fertilization, pest control, irrigation) may have had an impact on the reproductive phase and thus on the pollen amount.

Among the non-arboreal taxa (NAP), *Ambrosia* pollen markedly increased from the first to the second decade; then, it remained almost unchanged. Among the factors influencing changes in pollen amount, it is important to consider the spatial dispersion dynamics of this invasive plant species. The appearance of ragweed pollen in the local aerobiological samples was first observed in 1992 and further confirmed by the finding of this plant in the surrounding area (Gottardini and Cristofolini 1996). As expected, the distribution of this invasive species rapidly spread in the region (Prosser et al. 2019), with a consequent increase in airborne pollen amount during the expansion phase, likely reaching a stabilization afterwards, as reflected by the steady pollen amount. A concurrent impact on *Ambrosia* pollen might have been played by the containment measures adopted to reduce the plant spread at larger scale during the third decade (Bonini and Ceriotti 2020). The dynamics of invasive species help to also justify the shift in MPS peak for *Artemisia* pollen, driven by the spread of the late flowering invasive species *A. annua* and *A. verlotiorum* across the region (Cristofori et al. 2020).

A general tendency toward an earlier pollen season start, particularly pronounced for herbaceous taxa, is the second key finding of this study. Six pollen taxa are starting the MPS at a significant earlier date, with an average advance of 5.4 (min 3.3–max 8.0) days per 10 years, much higher than reported by other authors (e.g., ca. 2 days/10 years (Gehrig and Clot 2021); 3 days/10 years (Zhang et al. 2015)). Several studies pointed out an earlier pollen season start trend that interests the norther hemisphere (Bruffaerts et al. 2018; Cristofolini et al. 2020; Lind et al. 2016; Zhang et al. 2015; Ziska et al. 2019). This phenomenon is often related to the increase of air temperature and, in a broader sense, to climate change. Pre-seasonal temperature impacts on flowering and pollen release, and the extent of responses may vary depending on the plant species (Menzel et al. 2020). In our study, the correlations are negative between MPS start and temperature of the pre-flowering period, meaning that an increase of temperature close to the event leads to an earlier pollen season start. This is especially evident for taxa which MPS starts from February to April, as Poaceae and Urticaceae, confirming that pre-flowering temperature is an important driver of pollen release for spring and early summer flowering plants (Gehrig and Clot 2021). The minimum temperature rising after the vernalization period may accelerate the heat accumulation phase, inducing the start of the pollen season (Dahl et al. 2013). It should also be considered that Poaceae taxon includes a large variety of species; thus, shifts in pollen seasonality could also be due to changes in species composition, with species flowering in slightly different periods (Ghitarrini et al. 2017).

The present study, whose results are largely consistent with other surveys, has some peculiarities: (i) the high number of pollen taxa analyzed, reflecting the complexity of the local pollen spectrum, and (ii) the rural context, less frequently considered in aerobiological studies. Since the study area is scarcely influenced by typically urban phenomena such as the heat island (Chapman et al. 2017), the observed changes in MPS timing may likely be the result of a background environmental situation, without additional urban forcing factors on phenological phases (Ziello et al. 2012).

In conclusion, from a human health perspective, the increasing amount of pollen, linked to the air temperature rise, as verified in the study area over a 30-year period, can negatively affect the well-being of people suffering from pollen allergies. This finding assumes even greater importance in the perspective of climate change, where global temperatures are expected to warm significantly. In addition to the well-recognized value of airborne pollen data for allergy prophylaxis, this study underlines how long-term aerobiological monitoring may represent a valid tool to detect the consequences of the ongoing environmental changes.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10113-024-02223-6.

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Data Availability Original data are available under request.

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