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Effects of climate change on pollen season features of herbaceous species in the Milan area, Northern Italy

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Different herbaceous plant species release allergenic pollen that can have adverse effects on human health. Climate change, which alters plant physiology and phenology, can affect airborne pollen levels, increasing the risk for allergy sufferers. This study examines trends in airborne pollen concentrations and seasonal characteristics, aiming to identify potential shifts in the onset, end, and duration of the main pollen seasons of herbaceous plant species over the last few decades, with particular attention to exploring the association between phenological changes and climate parameters. Moreover, forecasting scenarios of pollen season features trends concerning the meteorological variables we presented. To this purpose, data from the aerobiological station of the Milan area (Legnano, Lombardy, Italy), located in one of the most invaded parts by *Ambrosia artemisiifolia* in Italy and Europe, and characterized by a time series of nearly 30 years, from 1995 to 2022, were analysed. The results showed a clear correlation between main pollen season features and meteorological variables for Poaceae, Urticaceae, *Artemisia* and *Ambrosia*. Generally, increasing temperature and solar radiation were linked to an anticipated onset of the pollen season, while precipitation and relative humidity to an earlier end date. Moreover, in the study areas, a strong increase in annual average temperature has been observed since 1975, projected to continue over the next 60 years. This increase was predicted to lead to an earlier start and longer duration of the pollen season for weed species, potentially advancing by up to 2 weeks over 60 years. These findings indicate an elevated risk of exposure for individuals with allergies in the short term and underscore the urgent need to implement long-term monitoring frameworks for both ecological and public health purposes.

Keywords Climate change, Pollen season, Temporal trends

Allergic respiratory diseases are increasing worldwide in both school-age children and adults[1–4]. In particular, asthma and allergic rhinitis globally affect about 339 million people (www.who.int, accessed 04/12/24) and more than 400 million people (www.worldallergy.org, accessed 04/12/24), respectively, posing relevant individual and societal burdens. Patients suffer from a decreased quality of life due to physical and mental health impacts[4], while direct medical costs and productivity loss have recently been recognized as a serious economic issue in several countries (e.g., the estimate of the direct cost of allergic rhinitis in the USA exceeds $4.5 billion per year[4]).

Regarding risk factors, pollen is among the main inhalant allergens that cause respiratory diseases[4,5]. In particular, herbaceous plant pollen, especially those belonging to the Poaceae family (traditionally termed as "grass" species), is considered among the main causes of pollinosis worldwide[6–8]. As a consequence, investigating temporal trends in pollen concentration is crucial to better understand their impact on human health[9]. In the United States, Erbas et al.[10] observed an increase in the number of asthma emergency department (ED) visits of children and adolescents associated with every 10-unit increase (grains/m^3) in daily grass pollen concentrations. Moreover, Neumann et al.[11] projected an increase of US allergic asthma ED visits of 8-14% in 2090, attributable to the lengthening of pollen season due to climate change, with grass pollen as the primary contributor.

Global warming and extended periods of rainfall or drought linked to climate change are known to have altered plant physiology and phenology, modifying development, reproduction, flower, and seed production[12].

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Over the last few decades, significant shifts in flowering and, consequently, pollen release have been observed in several herbaceous species. These changes include earlier or delayed start and end dates of the pollen season, as well as modifications in the season's duration and seasonal pollen concentrations[13,14]. For example, temperature is one of the most important meteorological factors driving the physiological development of grasses, thereby influencing the timing of phenological phases and atmospheric pollen concentrations[6,7,15]. In southern Iberian Peninsula, a longer pollen season duration and an increased number of high pollen days over the year have been reported for Poaceae, tracking the regional warming trend[16,17].Similarly, an earlier onset was recorded in Italy, correlated with higher mean temperatures during the pre-flowering period[18–20]. Even if precipitation usually decreases airborne pollen concentration by washing it out of the air[6,20], rain increased the mean number of days with open flowers per inflorescence in a wild grass species, *Dactylis glomerata*, in Spain[21]. In contrast, a study conducted in Poland from 2001 to 2022, showed that high temperatures in June and July, combined with intense sunshine, were negative correlated with *Artemisia* pollen peak values and total pollen counts during August[22].

The impact of climate change on plant phenology may vary among geographical areas[23]. In Italy, Tagliaferro et al.[24] observed different trends in the Seasonal Pollen Integral (SPIn) for several taxa in various climatic zones for the Veneto Region. For example, the subcontinental western area showed a greater increase in Poaceae (1349 pollen grains per cubic meter of air (p/m^3)) SPIn, while the subcontinental eastern area showed the most pronounced decreases in Urticaceae (-625 p/m^3) and *Artemisia* (-47 p/m^3) SPIn compared to the whole Region. Moreover, projected climatic changes, particularly rising temperatures, are expected to cause asymmetric advances in the flowering onset of different taxa. These shifts can create new overlaps between the flowering phases of species co-occurring in the local vegetation, resulting in altered maximum total daily pollen emission and increased pollen allergen exposure for the human population[25]. Within this context, studies investigating local-scale temporal trends of pollen season parameters in relation to meteorological factors are of paramount importance from a clinical and public health perspective.

To the best of our knowledge, few studies have addressed long-term pollen trends in Italy, and none have focused specifically on the Lombardy Region. Our research stands out from previous works[8,19,20,24]due to its 30-year time series (1995–2022). Such a duration is considered ideal for detecting long-term shifts attributable to climate change[26–29]. Furthermore, this study extends beyond historical trend analysis by developing forecasting scenarios for pollen season characteristics based on key meteorological drivers, such as temperature and solar radiation.. In particular, the purpose was to examine the pollen load and seasonal patterns of herbaceous plant species that pose health concerns in the Milan area (Lombardy, Italy). The study aims to evaluate potential changes in the timing and duration of the main pollen season by examining their relationship with key meteorological variables as indicators of climate change.

Materials and methods

Study area

The study was conducted in the municipality of Legnano, in the Po Plain (Northern Italy), approximately 28 km northwest of Milan. The city of Legnano hosts one of the oldest aerobiological monitoring station, still functioning, of the Lombardy Region (45° 34’ 50” N, 8° 53’ 18” E), activated in 1995. The station is embedded in a rural landscape, in one of the most invaded areas by *Ambrosia artemisiifolia* in Italy and Europe[30]. The climate of the Po plain is continental, with cold and moist winters, frequent dense fogs, and warm and muggy summers. Mean annual temperature is around 12°C (min. 1°C in January, max. 22.5°C in July), while mean annual precipitation is around 800 mm concentrated in spring and autumn. Arable and anthropic areas characterize land use, while natural vegetation mainly corresponds to forest communities and riparian or wetland vegetation.

Pollen data and local climate trends

Daily airborne pollen concentrations in Legnano (North-West Milan area, Italy) were collected from 1995 to 2022 by the Agency for Health Protection of the Metropolitan Area of Milan (ATS CMM) using a Hirst volumetric trap. Pollen grains were counted under a microscope at 400x by specialized technicians, following European Norm EN 16868:2019 and the Minimum Recommendations of the European Aerobiology Society Working Group on Quality Control[31]. Daily pollen concentrations are expressed as particles per cubic meter of air (p/m^3). The study focused on herbaceous taxa with high allergenic potential in Europe: *Ambrosia*, *Artemisia*, Cannabaceae, Chenopodiaceae/Amarantaceae, Poaceae, and Urticaceae. For each taxon, the main pollen season descriptors were calculated as follows: start and end dates (days when cumulative daily pollen reaches 2.5% and 97.5% of the annual total[32]), season duration (number of days between start and end), peak day and value (day with the highest daily pollen concentration and its value), days with concentrations > 1 p/m^3, Annual Pollen Integral (APIn, sum of daily pollen concentrations over the year[33]), and Seasonal Pollen Integral (SPIn, sum of daily pollen concentration over the main pollen season). Given the extremely high correlation observed between the Annual Pollen Integral (APIn) and the Seasonal Pollen Integral (SPIn) across all taxa (Pearson correlation $\hat{\rho} = 0.9999734$), we elected to use only the SPIn in subsequent analyses. This metric was deemed sufficient to capture the essential characteristics of the pollen season dynamics for the purpose of this study, thereby avoiding redundancy in the statistical models.

Defining the start and end of the pollen season is challenging. The phenological season is influenced by local landscape heterogeneity (e.g., shadows from slopes, trees, buildings), which introduces uncertainty and can “blur” the aerobiological season recorded by pollen traps[34]. Long-range transport can also produce peaks before or after the local season. Moreover, the clinical relevance of a pollen season depends on both timing and intensity, specifically when pollen concentrations exceed established biological thresholds known to trigger allergic symptoms[9]; low overall concentrations may prevent the emergence of a medical season, even when aerobiological and phenological seasons occur. To account for these complexities, we used the 2.5%-97.5% percentile criterion to define season timing, following the approach of previous studies[32]. Absolute concentration thresholds are less reliable due to high inter-annual variability[35]. While the percentile method could, in principle, be influenced by long-range transport trends, the Milan region is primarily protected by the Alps (north) and the sea (south-west and east). Therefore, this criterion provides a robust and appropriate measure for defining the pollen season in this study. In parallel, our analysis of local meteorological data revealed a clear warming trend in the Milan area over the past decades, consistent with observations across Italy and Europe. Mean annual temperatures have increased and are projected to continue rising over the next 60 years. Solar radiation is expected to increase with temperature, consistent with their usual association. Observed and projected precipitation trends indicate a general increase, particularly in spring and winter, in line with continental-scale patterns. These climate trends provide the basis for interpreting observed shifts in airborne pollen seasonality, such as earlier onset dates and extended pollen seasons. While direct phenological observations of plants were not conducted, changes in the timing of airborne pollen concentrations serve as a reliable proxy for understanding the response of plant reproductive cycles to climate variability, expecially in anemophilous plants[20,36,37].

Meteorological data

Daily meteorological data were extracted from the ERA5 reanalysis[38], within the Copernicus Climate Change Service (C3S). The data were aggregated by considering the daily mean value of each time series. The following weather parameters were selected: daily average of standard air temperature ($^\circ$C) at 2m above the surface, i.e., the "nose-level" temperature, and relative humidity (%) at 2m above the surface; wind speed (m/s); convective precipitation, i.e., water level accumulated during the last one hour (mm); surface short-wave solar radiation downwards, which comprises both direct and diffuse solar radiation accumulated during the last hour (J/m^2).

Statistical analysis

To analyse the association between pollen-season descriptors (start date, end date, duration, peak day, peak value, APIn, SPIn, and number of days with concentration > 1) and the meteorological variables described in "Meteorological data", we used two complementary correlation coefficients. Pearson's ρ was applied to quantify linear relationships, as it is particularly effective when variables exhibit approximate normality and linear dependence. In contrast, Spearman's rank correlation coefficient (ρ_S) was used to detect monotonic associations that may not follow a linear pattern, without requiring assumptions regarding the distribution or linearity of the data. This dual approach allows us to distinguish linear from purely monotonic associations and to understand better how different types of relationships manifest in the data.

For each taxon, we calculated the pollen season (start and end) according to the definition provided in "Pollen data and local climate trends". For the correlation analysis, we used the daily average of each meteorological variable calculated over the specific pollen season period. This approach was chosen to capture the average environmental intensity during the season, ensuring that the indicators remain independent of the varying duration of the pollen seasons across years and taxa.

To explore possible future scenarios of climate change impacts on pollen variables, we analysed the temporal trends of each meteorological variable using the full historical dataset provided by Copernicus (1975–2022). Given that pollen observations cover approximately 30 years, only 30 annual values are available for each pollen metric. This limited sample size imposes strict constraints on model complexity: more flexible approaches–such as regression splines or non-linear models–would likely overfit the available data, providing a better in-sample fit but yielding unstable and unreliable long-term projections. For this reason, a simple linear regression model was adopted to estimate long-term tendencies in meteorological variables and pollen descriptors. This choice reflects a deliberate bias–variance trade-off: linear models have lower variance, are more robust when data are scarce, and yield interpretable estimates of directional trends rather than precise forecasts.

Results

Tables 1, 2, 3, and 4 present the correlation test results between selected meteorological variables and various pollen season metrics: the starting day, the ending day, the duration, and the number of days within a season with a concentration value greater than 1, respectively. Each table reports Pearson's correlation coefficient ($\hat{\rho}$) and Spearman's rank correlation coefficient ($\hat{\rho}_S$), along with their significance levels. Note that, almost everywhere, the two implemented correlation tests are consistent in their assessment of statistical evidence. We also computed the correlation between $\hat{\rho}$ and $\hat{\rho}_S$ for each pollen season metric, obtaining very high values: starting day 0.963, ending day 0.946, duration 0.978, and number of days above threshold 0.981. This shows that both measures convey essentially the same information and provide consistent evidence of the linear associations between meteorological variables and pollen season characteristics.

For the starting day of the pollen season (Table 1), only temperature shows statistically significant correlations, and exclusively for Poaceae and Urticaceae. In both cases the associations are moderately strong and negative, indicating that higher temperatures are linked to an earlier start of the season for these taxa. Among the meteorological factors analyzed, no other variable exhibited a significant effect on the pollen season onset across species. Within the scope of the included variables, these results indicate that temperature is the primary driver of the interannual variability in the start date for Poaceae and Urticaceae.

For the end of the pollen season (Table 2), significant correlations emerge only for *Artemisia*, which shows a coherent response across several meteorological variables. Higher temperatures and solar radiation are associated with a later season end, whereas increases in relative humidity and precipitation correspond to an earlier end. No other taxa display statistically significant associations with the meteorological features considered, indicating that the season-end timing is generally less sensitive to interannual meteorological variability, except for *Artemisia*.

Regarding the duration of the pollen season (Table 3), significant correlations emerge for a limited subset of taxa and meteorological variables. *Ambrosia* and Urticaceae show a positive association with temperature, suggesting longer seasons in warmer years. *Ambrosia* and *Artemisia* also respond significantly to wind speed

Meteo feature	Pollen specie	$\hat{\rho}$	p-val (ρ)	$\hat{\rho}_S$	p-val (ρ_S)
temperature	*Ambrosia*	– 0.325	0.092	– 0.346	0.071
	Artemisia	0.069	0.729	0.092	0.643
	Cannabaceae	– 0.086	0.665	– 0.067	0.733
	Chenopodiaceae/Amarantaceae	– 0.041	0.834	– 0.050	0.802
	Poaceae	– 0.595	**0.001**	– 0.599	**0.001**
	Urticaceae	– 0.583	**0.001**	– 0.564	**0.002**
wind speed	*Ambrosia*	0.194	0.323	0.213	0.276
	Artemisia	0.059	0.766	0.081	0.680
	Cannabaceae	– 0.248	0.204	– 0.273	0.161
	Chenopodiaceae/Amarantaceae	– 0.057	0.773	– 0.054	0.786
	Poaceae	0.296	0.127	0.280	0.149
	Urticaceae	0.076	0.700	– 0.041	0.836
relative humidity	*Ambrosia*	– 0.056	0.766	– 0.086	0.663
	Artemisia	0.078	0.693	– 0.044	0.823
	Cannabaceae	0.187	0.340	0.292	0.132
	Chenopodiaceae/Amarantaceae	0.070	0.724	0.147	0.457
	Poaceae	– 0.286	0.140	– 0.283	0.144
	Urticaceae	– 0.103	0.600	– 0.032	0.871
precipitation	*Ambrosia*	– 0.215	0.272	– 0.310	0.109
	Artemisia	– 0.119	0.546	– 0.146	0.460
	Cannabaceae	0.162	0.412	0.227	0.246
	Chenopodiaceae/Amarantaceae	0.044	0.824	0.022	0.910
	Poaceae	– 0.164	0.405	– 0.127	0.518
	Urticaceae	– 0.277	0.154	– 0.159	0.419
solar radiation	*Ambrosia*	– 0.049	0.736	– 0.043	0.826
	Artemisia	0.109	0.581	0.158	0.423
	Cannabaceae	– 0.161	0.414	– 0.278	0.151
	Chenopodiaceae/Amarantaceae	– 0.074	0.710	– 0.099	0.617
	Poaceae	0.089	0.651	0.123	0.533
	Urticaceae	– 0.083	0.675	– 0.139	0.481

Table 1. Correlation test results between selected meteorological variables and the pollen season starting day. The table reports Pearson's correlation coefficient ($\hat{\rho}$) and Spearman's rank correlation coefficient ($\hat{\rho}_S$) along with their significance levels. P-values ≤ 0.05 are shown in bold.

(positive) and to relative humidity and precipitation (negative), indicating that drier and windier conditions tend to prolong their seasons. Solar radiation shows a weaker but still significant effect, with positive correlations for *Ambrosia* and *Artemisia*. No significant relationships are detected for Cannabaceae, Chenopodiaceae/Amaranthaceae, or Poaceae regarding season duration. This lack of significance, contrasted with the results found for other taxa, highlights that the response of pollen season timing to meteorological drivers is not uniform across all species.

For the number of days with pollen concentrations above 1 (Table 4), significant correlations are found only for a small subset of taxa. Urticaceae exhibits a positive association with temperature and solar radiation, indicating that warmer and sunnier conditions are associated with a higher number of days with measurable pollen levels. *Ambrosia* exhibits negative correlations with relative humidity and precipitation, suggesting that drier conditions favour more pollen days. *Artemisia* shows a positive association with wind speed. No significant relationships are observed for Cannabaceae, Chenopodiaceae/Amaranthaceae or Poaceae.

For completeness, Supporting Information reports the correlation test results for the variables that were not statistically significant (p-value > 0.05).

A linear trend was then estimated for each meteorological variable to explore hypothetical scenarios for pollen levels for the different species at 20, 40, and 60 years into the future. We acknowledge that the linear trends estimated for the meteorological variables cannot capture all the variability present in the data, as also reflected in Table 5. Nevertheless, the strong agreement between Pearson's $\hat{\rho}$ and Spearman's $\hat{\rho}_S$ (correlations ranging from 0.95 to 0.98 across the four pollen season metrics: start, end, duration, and number of days with concentration above 1) indicates that both linear and monotonic trends point in the same direction. This supports the use of a linear approximation as a first-order representation of the underlying relationships. Our intention is not to predict exact future weather values, but to provide insight into the direction and relative magnitude of historical trends, which form a consistent basis for assessing potential changes in pollen seasonality under different meteorological scenarios. The uncertainty in these trend-based scenarios is explicitly acknowledged and taken into account in the interpretation of results.

Meteo feature	Pollen species	$\hat{\rho}$	p-val (ρ)	$\hat{\rho}_S$	p-val (ρ_S)
temperature	*Ambrosia*	– 0.074	0.709	– 0.122	0.537
	Artemisia	0.378	**0.048**	0.305	0.114
	Cannabaceae	0.101	0.610	0.100	0.611
	Chenopodiaceae/Amarantaceae	0.191	0.329	0.179	0.361
	Poaceae	0.058	0.770	– 0.033	0.868
	Urticaceae	0.353	0.065	0.233	0.233
wind speed	*Ambrosia*	– 0.087	0.660	– 0.011	0.956
	Artemisia	0.279	0.150	0.214	0.274
	Cannabaceae	0.274	0.158	0.318	0.099
	Chenopodiaceae/Amarantaceae	– 0.116	0.557	– 0.138	0.482
	Poaceae	0.108	0.585	– 0.030	0.881
	Urticaceae	0.013	0.948	0.047	0.812
relative humidity	*Ambrosia*	0.054	0.784	0.076	0.701
	Artemisia	– 0.414	**0.028**	– 0.393	**0.039**
	Cannabaceae	– 0.317	0.100	– 0.335	0.082
	Chenopodiaceae/Amarantaceae	0.008	0.966	– 0.059	0.764
	Poaceae	– 0.007	0.970	0.175	0.372
	Urticaceae	– 0.150	0.446	– 0.146	0.458
precipitation	*Ambrosia*	– 0.050	0.800	– 0.068	0.732
	Artemisia	– 0.413	**0.029**	– 0.375	**0.049**
	Cannabaceae	– 0.170	0.388	– 0.247	0.206
	Chenopodiaceae/Amarantaceae	– 0.118	0.549	– 0.087	0.660
	Poaceae	0.258	0.186	0.253	0.194
	Urticaceae	– 0.119	0.548	– 0.164	0.404
solar radiation	*Ambrosia*	– 0.036	0.854	0.030	0.880
	Artemisia	0.452	**0.016**	0.452	**0.016**
	Cannabaceae	0.035	0.858	0.033	0.866
	Chenopodiaceae/Amarantaceae	0.113	0.566	0.295	0.127
	Poaceae	– 0.105	0.596	– 0.153	0.438
	Urticaceae	0.298	0.123	0.303	0.118

Table 2. Correlation test results between selected meteorological variables and the pollen season-ending day. The table reports Pearson's correlation coefficient ($\hat{\rho}$) and Spearman's rank correlation coefficient ($\hat{\rho}_S$) along with their significance levels. P-values ≤ 0.05 are shown in bold.

The results of the estimated linear models are presented in Table 5. The estimated models show a clearly increasing trend (p-value < 0.01) for the average standard temperature at 2m above the surface and for the average surface short-wave solar downwards radiation accumulated during the last one hour (J/m^2) (see Fig. 1). A weakly increasing trend is also observed for annual mean convective precipitation, i.e., water level accumulated during the last one hour (mm), although with substantial interannual variability (p-value < 0.1). Conversely, relative humidity shows a slightly decreasing trend (p-value < 0.1), whileno statistically significant linear trend is detected for wind speed (see Fig. 2). This indicates that long-term meteorological change in the study area is driven primarily by temperature.

For meteorological variables with a significant or marginally significant linear trend (specifically temperature, solar radiation, and with $p - value < 0.07$, humidity and precipitation), the extrapolated values were used as inputs to estimate potential pollen levels. Two sensitivity scenarios were considered: a 'Trend-Persistence' scenario, based on the projected value at 20, 40, and 60 years from the last observation, and a 'Pessimistic' scenario, representing the most adverse climate conditions. These scenarios are intended as sensitivity analyses rather than deterministic forecasts, providing a framework to assess the potential response of pollen seasons under the assumption of continued linear climatic shifts. Specifically, for temperature, the upper bound of the 95% confidence interval of the estimated mean was used to estimate pollen levels, whereas for relative humidity, the lower bound was applied to simulate a worst-case scenario.

Poaceae and Urticaceae showed a statistically significant negative correlation between the starting day of the pollen season and the temperature (see Table 1); in other words, for these species, a mean increase in temperature has an anticipatory effect on the onset of the pollen season.

As shown in Fig. 3, the start and end dates of the Urticaceae pollen season exhibit clear linear relationships with temperature: panel (a) shows a negative linear association between temperature and the start of the season, indicating earlier onset in warmer years, while panel (b) shows a positive linear relationship between temperature and the end of the season, suggesting delayed termination. In contrast, the relationship between temperature and the overall duration of the pollen season, shown in panel (c), does not appear to be linear.

Meteo feature	Pollen species	$\hat{\rho}$	p-val (ρ)	$\hat{\rho}_S$	p-val (ρ_S)
temperature	*Ambrosia*	0.379	**0.047**	0.418	**0.027**
	Artemisia	– 0.052	0.792	– 0.008	0.969
	Cannabaceae	– 0.270	0.165	– 0.179	0.363
	Chenopodiaceae/Amarantaceae	– 0.066	0.739	– 0.075	0.705
	Poaceae	0.075	0.706	0.107	0.589
	Urticaceae	0.517	**0.005**	0.547	**0.003**
wind speed	*Ambrosia*	– 0.155	0.430	– 0.067	0.735
	Artemisia	0.489	**0.008**	0.528	**0.004**
	Cannabaceae	0.227	0.245	0.289	0.136
	Chenopodiaceae/Amarantaceae	0.114	0.565	0.116	0.557
	Poaceae	0.002	0.992	– 0.006	0.977
	Urticaceae	– 0.048	0.807	0.062	0.754
relative humidity	*Ambrosia*	– 0.396	**0.037**	– 0.440	**0.019**
	Artemisia	– 0.420	**0.026**	– 0.415	**0.028**
	Cannabaceae	– 0.194	0.322	– 0.290	0.135
	Chenopodiaceae/Amarantaceae	0.008	0.969	0.025	0.900
	Poaceae	0.134	0.498	0.118	0.550
	Urticaceae	– 0.051	0.797	– 0.063	0.751
precipitation	*Ambrosia*	– 0.490	**0.008**	– 0.530	**0.004**
	Artemisia	– 0.343	0.074	– 0.382	**0.045**
	Cannabaceae	– 0.194	0.323	– 0.343	0.074
	Chenopodiaceae/Amarantaceae	– 0.071	0.720	– 0.046	0.816
	Poaceae	0.218	0.265	0.186	0.344
	Urticaceae	– 0.104	0.600	– 0.120	0.543
solar radiation	*Ambrosia*	0.311	0.107	0.387	**0.042**
	Artemisia	0.235	0.228	0.399	**0.035**
	Cannabaceae	– 0.154	0.435	– 0.074	0.709
	Chenopodiaceae/Amarantaceae	– 0.185	0.345	– 0.173	0.378
	Poaceae	– 0.068	0.733	– 0.036	0.857
	Urticaceae	0.374	**0.050**	0.328	0.089

Table 3. Correlation test results between selected meteorological variables and the pollen season duration. The table reports Pearson's correlation coefficient ($\hat{\rho}$) and Spearman's rank correlation coefficient ($\hat{\rho}_S$) along with their significance levels. P-values ≤ 0.05 are shown in bold.

The duration increases with temperature up to a certain point, but then seems to decline at higher temperature values. A similar pattern is observed for Poaceae, as shown in Fig. 4, which follows the same panel structure. For this species, the relationship between temperature and the start of the pollen season remains clearly negative and linear, whereas the association with the end of the season appears non-linear. Regarding the season's duration, it exhibits a similar inverted U-shaped pattern, as illustrated for Urticaceae. Graphical representations of the temperature–pollen relationships are shown only for Poaceae and Urticaceae, which exhibited the strongest and most consistent associations. For the remaining taxa, correlations were weak or non-significant, and additional plots were omitted to avoid redundancy with the correlation tables.

Table 6 presents projections for the pollen season starting day (predictions with 95% confidence intervals) based on the linear extrapolation of temperature trends for Urticaceae and Poaceae. For each year, the first row corresponds to the 'Trend-Persistence' scenario, while the second row represents the 'Pessimistic' scenario under adverse climate conditions. Over a projected 60-year increase of approximately 3°C in annual mean temperature based on current linear trends, the Urticaceae pollen season could potentially start on average 13 days earlier than in 2022, with a maximum advance of 16 days under the pessimistic scenario. For Poaceae, the corresponding projected shifts are 12 and 14.6 days, respectively.

Table 7 shows projections for the Urticaceae pollen season duration and the number of days with concentrations exceeding 1 p/m^3 (scenario-based estimates and 95% confidence bounds) as a function of the standard 2 m "nose-level" temperature and the mean surface short-wave solar downward radiation accumulated over the last hour (J/m^2). For each year, the first row corresponds to the 'Trend-Persistence', while the second row represents a 'Pessimistic' scenario under adverse climatic conditions. An increase of 3 °C in the annual average temperature from 2022 to 2060 is is associated with a potential extension of the pollen season by 19 days on average and up to 23 days in the worst-case scenario. Solar radiation is also projected to contribute to the season's prolongation, although its impact appears less pronounced compared to temperature variations within the linear framework of this analysis.

Meteo feature	Pollen species	$\hat{\rho}$	p-val (ρ)	$\hat{\rho}_S$	p-val (ρ_S)
temperature	*Ambrosia*	0.277	0.153	0.306	0.114
	Artemisia	− 0.027	0.894	− 0.081	0.684
	Cannabaceae	− 0.196	0.318	− 0.199	0.310
	Chenopodiaceae/Amarantaceae	− 0.153	0.438	− 0.144	0.464
	Poaceae	0.049	0.803	0.063	0.751
	Urticaceae	0.572	**0.001**	0.605	**0.001**
wind speed	*Ambrosia*	0.019	0.922	0.104	0.597
	Artemisia	0.386	**0.043**	0.374	**0.050**
	Cannabaceae	0.372	0.051	0.346	0.071
	Chenopodiaceae/Amarantaceae	0.204	0.298	0.292	0.132
	Poaceae	0.117	0.554	0.130	0.511
	Urticaceae	− 0.005	0.980	0.124	0.530
relative humidity	*Ambrosia*	− 0.430	**0.022**	− 0.449	**0.017**
	Artemisia	− 0.269	0.166	− 0.268	0.168
	Cannabaceae	− 0.295	0.128	− 0.298	0.123
	Chenopodiaceae/Amarantaceae	− 0.173	0.380	− 0.302	0.118
	Poaceae	− 0.013	0.947	− 0.050	0.799
	Urticaceae	− 0.151	0.442	− 0.204	0.298
precipitation	*Ambrosia*	− 0.432	**0.022**	− 0.441	**0.019**
	Artemisia	− 0.194	0.322	− 0.274	0.158
	Cannabaceae	− 0.345	0.072	− 0.370	0.053
	Chenopodiaceae/Amarantaceae	0.016	0.936	− 0.098	0.619
	Poaceae	0.084	0.672	0.079	0.689
	Urticaceae	− 0.160	0.417	− 0.223	0.254
solar radiation	*Ambrosia*	0.223	0.254	0.243	0.213
	Artemisia	0.015	0.939	0.027	0.891
	Cannabaceae	− 0.028	0.887	0.002	0.993
	Chenopodiaceae/Amarantaceae	− 0.115	0.562	− 0.084	0.670
	Poaceae	0.094	0.634	0.118	0.551
	Urticaceae	0.411	**0.030**	0.407	**0.032**

Table 4. Correlation test results between selected meteorological variables and the number of days with a concentration value greater than 1 within a season. The table reports Pearson's correlation coefficient ($\hat{\rho}$) and Spearman's rank correlation coefficient ($\hat{\rho}_S$) along with their significance levels. P-values ≤ 0.05 are shown in bold.

Table 8 presents projections for the *Artemisia* pollen season duration and ending day, including 95% confidence bounds, as a function of relative humidity from the dew point (left) and surface short-wave solar radiation (right). Following the same scenario convention as above, a projected decrease in average annual humidity is associated with a 3-day delay in the end of the pollen season over 60 years in the 'Trend-Persistence' scenario and up to 5 days in the 'Pessimistic' scenario. This would result in an average estimated extension of the season of 5 days. Solar radiation shows a smaller but consistent modeled effect on season duration under these linear assumptions.

Table 9 presents projections for *Ambrosia* pollen season duration and the number of days with concentrations above 1 p/m^3, as a function of relative humidity from the dew point, 2m temperature, and convective precipitation (mm). According to the observed negative correlation between precipitation and season duration ($\hat{\rho} = -0.49$, p = 0.008), an increase in precipitation is projected to potentially reduce the mean season length from 47.5 days in 2022 to 45.5 days in 2060 under the 'Trend-Persistence' scenario.. Temperature increases are associated with a potential trend toward longer pollen seasons, while the modeled effect of precipitation under the 'Pessimistic' scenario remains minimal. For a more in-depth discussion on the necessity of considering these drivers for the ragweed pollen season, please refer to "Discussion".

Discussion

The results showed a clear correlation between main pollen season features and meteorological variables for several herbaceous taxa. In particular, significant associations were identified for *Ambrosia*, *Artemisia*, Poaceae, and Urticaceae. Overall, higher temperatures and increased solar radiation were associated with an earlier onset of the pollen season, whereas greater precipitation and relative humidity tended to be linked with earlier season end dates. In the study area, we observed a strong increase in the annual average temperature since 1975, with projections indicating a continued rise over the next 60 years. Under this warming trend, the models suggest an

Meteo variable		**Estimate**	**Std. error**	**t-value**	**p-value**
Temperature	(Intercept)	184.645	12.184	15.16	< 2e-16
	Year	0.051	0.0061	8.34	**2.3e-10**
	R^2	0.629			
Solar radiation	(Intercept)	− 738588.951	458664.461	− 1.610	0.115
	Year	654.231	229.213	2.854	**0.007**
	R^2	0.166			
Humidity	(Intercept)	199.279	68.025	2.929	0.006
	Year	− 0.063	0.034	− 1.868	0.069
	R^2	0.078			
Precipitation	(Intercept)	− 0.408	0.232	− 1.764	0.085
	Year	0.0002	0.0001	1.934	0.060
	R^2	0.084			
Wind	(Intercept)	0.603	1.488	0.405	0.688
	Year	0.001	0.001	0.7431	0.462
	R^2	0.013			

Table 5. Summary of the linear regression model for the mean annual value of each meteo variable as a function of the year, including estimated coefficients, standard errors, t-values, p-values, and goodness-of-fit measures. P-values ≤ 0.05 are shown in bold.

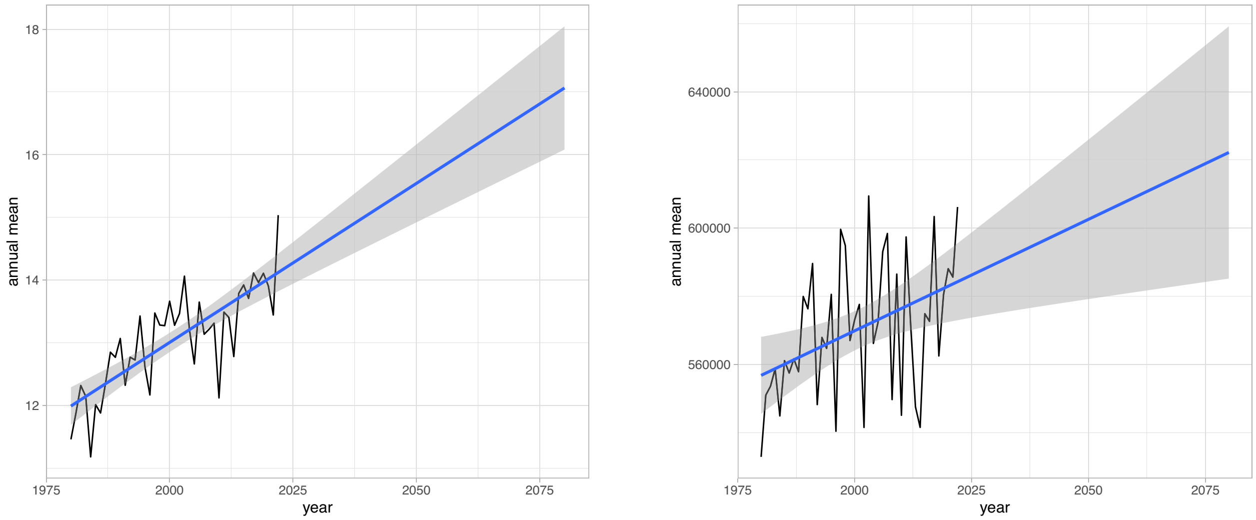


Figure 1. Plot of the annual mean value of 2m temperature (°C) (left) and the annual mean value of surface short-wave solar downward radiation accumulated over the last hour (J/m^2) (right), both shown as black solid lines. The regression line (blue solid line) is displayed with 95% confidence bounds (grey shaded area). Predicted values at 20, 40, and 60 years are also highlighted.

earlier start and an overall lengthening of the pollen season for weed species, with shifts of up to approximately two weeks over the 60-year horizon.

Relationship between meteorological variables and pollen season features

Our study provided clear evidence of climate warming in the Milan area, consistent with trends registered across Italy and Europe[13,20,24,39,40]. An observed significant increase in mean annual temperature was registered over the last decades. Similarly, precipitation amounts also increased during this period, mirroring regional findings, such as those noted for spring and winter seasons in the continental US[41]. Looking forward, significant warming is predicted: our projection of a $+3^{\circ}$C increase in the annual average temperature over the next 60 years aligns with estimates for other Mediterranean cities, such as the increase of up to 0.5°C/decade estimated for Barcelona between 2024–2100[40]. Furthermore, considering the observed local trends and the statistical association between these variables[42], both temperature and solar radiation are likely to follow similar upward patterns if current atmospheric conditions persist. Similarly, the effect of global warming on analyzed herbaceous pollen taxa is generally consistent with those of other studies conducted in Italy and across Europe. For Poaceae

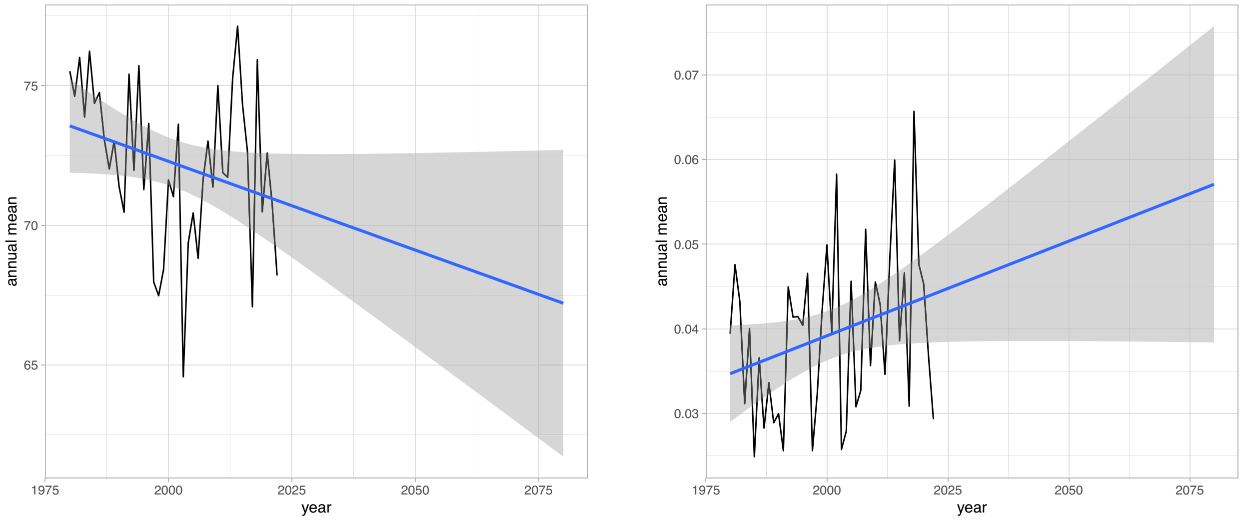
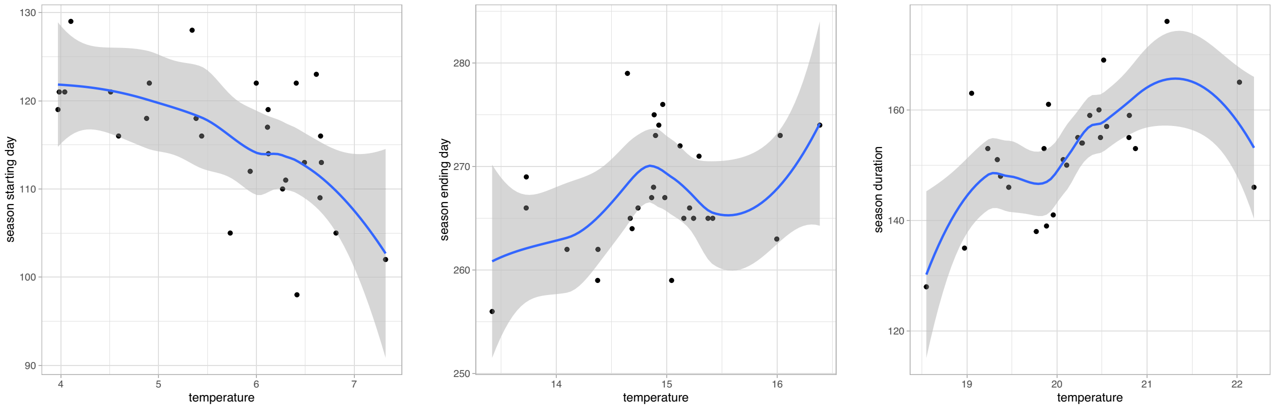


Figure 2. Plot of the annual mean value of relative humidity from the due point (%) (left) and the annual mean value of convective precipitation, water level accumulated during last one hour (mm) (right), both shown as black solid lines. The regression line (blue solid line) is displayed with 95% confidence bounds (grey shaded area). Predicted values at 20, 40, and 60 years are also highlighted.



(a) Pollen season starting day vs. temperature.

(b) Pollen season-ending day vs. temperature.

(c) Pollen season duration vs. temperature.

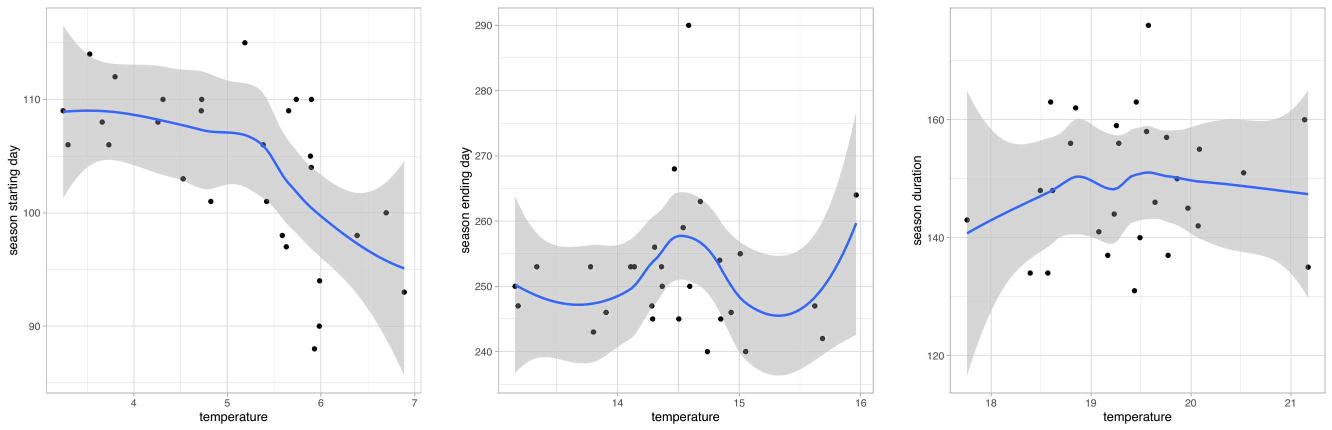
Figure 3. Relationship between mean seasonal temperature and characteristics of the Urticaceae pollen season. The three panels show: (**a**) start day of the pollen season, (**b**) end day of the pollen season, and (**c**) duration of the pollen season, each as a function of mean temperature (°C). Points represent observed values; the blue line shows a smoothed trend, with the shaded area representing the 95% confidence interval.

and Urticaceae, higher mean temperatures were associated with an earlier onset of the pollen season [14,19,43]. Several studies have documented an advanced start of the pollen season for herbaceous taxa, although only a few directly analyzed correlations with climatic parameters [13,24,26,39,44,45]. Plant phenological phases are strongly influenced by spring temperature, with flowering occurring earlier under warmer conditions [6,7,13,15,16].

Extended pollen seasons have also been reported for multiple taxa across different regions[46]. In the Milan area, elevated temperatures were associated with longer pollen seasons for Urticaceae and *Ambrosia*. Weeds tend to respond positively to warmer climates, which can enhance plant growth and pollen production, particularly in urban settings [46–48]. Interestingly, for Urticaceae, the relationship between temperature and pollen season duration appears non-linear: duration increases with temperature up to a threshold, but may decline under very high temperatures. This pattern likely reflects physiological responses to heat or drought stress.

Under very warm conditions, plants typically accelerate their phenological development, but they can also experience severe environmental stress (e.g., desiccation). This combination often leads to a shorter effective flowering period and a premature end to pollen release, consistent with findings reported in previous studies [27,49].

Accordingly, an increase in temperature and solar radiation delayed the *Artemisia* pollen season's end, while a higher amount of rainfall anticipated its end. Climatic context may drive the specific response of the Artemisia



(a) Pollen season starting day vs. temperature.

(b) Pollen season-ending day vs. temperature.

(c) Pollen season duration vs. temperature.

Figure 4. Relationship between mean seasonal temperature and characteristics of the Poaceae pollen season. The three panels show: (**a**) start day of the pollen season, (**b**) end day of the pollen season, and (**c**) duration of the pollen season, each as a function of mean temperature (°C). Points represent observed values; the blue line shows a smoothed trend, with the shaded area representing the 95% confidence interval.

Year	Temperature (°C)	Urticaceae	Poaceae
2022	14.1, [13.8, 14.4]	78.7, [57.8, 99.6]	67.6, [47.6, 87.6]
		77.4, [55.8, 99.0]	66.4, [45.8, 87.1]
2040	15.0, [14.5, 15.5]	74.8, [51.6, 97.9]	64.0, [42.0, 85.9]
		72.6, [48.2, 96.9]	62.0, [38.9, 85.0]
2060	16.0, [15.3, 16.8]	70.4, [44.8, 95.9]	59.9, [35.8, 84.1]
		66.8, [39.3, 94.4]	56.7, [30.8, 82.6]
2080	17.1, [16.1, 18.0]	65.5, [37.2, 93.8]	55.5, [28.9, 82.0]
		61.5, [31.0, 92.0]	51.8, [23.3, 80.4]

Table 6. Forecasts for the Urticaceae and Poaceae pollen season starting day (prediction and confidence bounds at 95% level) as a function of the standard temperature at 2m above the surface – the "nose-level" temperature.

genus to meteorological factors, depending on the species that compose the local flora. For example, in Poland, a downward trend in the amount of *Artemisia* pollen was observed, which was directly related to increases in summer temperatures and declining rainfall[22]. This adverse effect of global warming on the *Artemisia* pollen load has been linked to the environmental requirements of *Artemisia vulgaris*, one of the most widespread species in Poland, as it requires moist soil for successful growth. Conversely, other *Artemisia* species common in Southern Europe mainly thrive in dry, well-sunlit areas[22] and are thus expected to exhibit a different response to climate change.

There are shreds of evidence that, in northern Italy, the *Artemisia* pollen calendar comprises different species, with a first peak in August mostly due to *A. vulgaris*, and a second peak in late September, whose main contributors are the invasive species *A. annua* and *A. verlotiorum*[50]. These allochthonous species are most likely to benefit from drier conditions and may have driven the duration of the pollen season in our study area. Consistently, in the Mediterranean region (specifically in Greece), a prolonged pollen season was recorded for the *Artemisia* genus, coinciding with warmer winter and spring temperatures[51].

The effects of precipitation on the pollen season features were less clear than those of temperature, as highlighted in other studies[24]. Besides *Artemisia*, only *Ambrosia* significantly correlated to this parameter, with an increase in precipitation and relative humidity causing an anticipated end of the pollen season. This result complements findings on *Ambrosia* ecology; while plant establishment and flowering are often positively related to water availability, our data indicate that, in this specific context, increased precipitation is associated with a shorter duration of the atmospheric pollen season[48,52]. However, another study carried out in the Milan area found a negative relationship between *Ambrosia* pollen load and lower rainfall in the pre-and during the flowering season[53]. Multiple factors may be on the basis of these results, among which the removal effect on bioaerosols from the air performed by precipitation[54] and the presence of the allochthonous leaf beetles *Ophraella communa* in the Milan area. *O. communa* preferentially feeds on *Ambrosia* and, firstly recorded in northern Italy in 2013 as an accidental introduction, it has been related to a drastic decrease in *Ambrosia* pollen[53,55].

Year	Temperature (°C)	Duration	Days conc. >1
2022	14.1, [13.8, 14.4]	114, [87.7, 140]	105, [80.4, 130]
		116, [90.9, 141]	107, [83.7, 131]
2040	15.0, [14.5, 15.5]	120, [97.3, 142]	112, [90.3, 133]
		123, [102.6, 143]	115, [95.9, 134]
2060	16.0, [15.3,16.8]	126, [107.9, 144]	119, [101.4, 136]
		131, [116.3, 146]	124, [110.2, 138]
2080	17.1, [16.1, 18.0]	133, [119.5 147]	126, [113.4, 139]
		139, [128.9, 149]	133, [123.2, 142]
Year	**Solar Radiation (J/m^2)**	**Duration**	**Days conc. >1**
2022	596042, [577097, 614987]	119.9, [87.0, 152.9]	110.3, [76.5, 144.0]
		119.9, [86.9, 152.9]	112.1, [79.9, 144.2]
2040	584266, [572974, 595557]	121.9, [90.8, 152.9]	112.2, [80.1, 144.3]
		122.7, [92.5, 152.9]	115.2, [85.7, 144.6]
2060	609127, [581218, 637036]	118.2, [83.6, 152.8]	114.2, [84.0, 144.5]
		125.9, [98.9, 152.9]	118.7, [92.3, 145.0]
2080	622211, [585193, 659229]	123.8, [94.6, 152.9]	116.3, [87.9, 144.7]
		129.1, [105.3, 152.9]	122.2, [99.0, 145.4]

Table 7. Forecasts for the Urticaceae pollen season duration and the number of days with a concentration value greater than 1 within a season (prediction and confidence bounds at 95% level) as a function of the standard temperature at 2m above the surface – the "nose-level" temperature and of the mean value of surface short-wave solar downward radiation accumulated over the last hour (J/m^2).

The absence of a significant relationship between SPIn, season peak day and value of the analyzed taxa, and meteorological parameters in the Milan area may be due to the implementation of management programs designed to reduce *Ambrosia* populations, which may have interfered with the airborne pollen of herbaceous species in general[24,53]. Specifically, preventive measures aimed at protecting citizens' health from *Ambrosia* pollinosis were initiated in the northwest Milan area since 1999, following the first regulation promulgated by the Lombardy Region[30]. The main recommendation was to carry out consecutive mowing prior to plant blossom. This type of human intervention is significant because changes in land use caused by human activities have been shown to strongly influence plant distribution and airborne pollen concentrations across the Mediterranean region[56,57].

Meteorological variables, projections and effects on pollen season features

The warmer climate in the study area (corresponding to +3°C in the annual average temperature) will lead to an earlier start of the pollen season for Urticaceae by 13-16 days compared to the last year of observation (2022), depending on the scenario, and by 12-14.6 days for Poaceae. Moreover, exacerbation of dry weather (i.e. increased solar radiation and decreased relative humidity) may cause the extension of *Artemisia* pollen season, perhaps due to more suitable conditions for the allochthonous species belonging to the genus (see previous paragraph), with the end date postponed by 2.4-4 days in the medium scenario and by 5-6.6 days in the worst one. These findings are consistent with the few studies that investigate the effect of future climatic scenarios on pollen emission duration. Models of[41] resulted in a shift of the future start and end of the flowering season to an earlier date than the historical period, with the starting date showing a stronger temperature dependence than the end date and, thereby, increasing the length of the pollen season duration for several deciduous tree genera and grasses. Similar trends were obtained by[11], with higher sensitivity of grass pollen to changes in temperature over time with respect to the analyzed tree species (i.e., oak and birch). Also, the pollen season of *Ambrosia* is projected to elongate with increasing temperature (by 6.5-7.8 days, depending on the scenario), while precipitation is projected to decrease its duration. As stated above, precipitation is a more complex factor to analyze in relation to plant phenology, as it is both linked to short-term effects on pollen production (i.e., by washing out particles from the air) and to the long-term impacts, with benefits and detriments for plant growth depending on the species' ecology[58]. The results of this study could certainly be improved by models that relate meteorological variables to pollen season parameters during specific phases of plant phenology (e.g., before or during flowering), rather than to the pollen season as a whole. However, to the best of our knowledge, the present study is one of the few that investigate the projection of meteorological parameters onto pollen season features worldwide.

Year	Humidity (%)	Ending day	Duration
2022	70.9, [69.2, 72.6]	282.7, [280.1, 285.4]	64.3, [60.8, 67.8]
		283.8, [281.7, 285.9]	65.5, [62.6, 68.3]
2040	69.8, [66.9, 72.6]	283.4, [281.2, 285.7]	65.0, [62.0, 68.1]
		285.3, [283.3, 287.3]	67.1, [64.7, 69.5]
2060	68.5, [64.3, 72.6]	284.3, [282.3, 286.3]	66.0, [63.3, 68.6]
		287.1, [284.2, 289.9]	68.9, [66.0, 71.8]
2080	67.2, [61.7, 72.7]	285.1, [283.2, 287.1]	66.9, [64.4, 69.3]
		288.8, [284.7, 292.8]	70.8, [66.8, 74.8]
Year	**Solar radiation (J/m^2)**	**Ending day**	
2022	596042, [577097, 614987]	274.8, [266.7, 282.9]	
		276.0, [268.8, 283.2]	
2040	584266, [572974, 595557]	276.0, [268.9, 283.2]	
		278.0, [272.3, 283.7]	
2060	609127, [581218, 637036]	277.4, [271.3, 283.5]	
		280.3, [276.3, 284.3]	
2080	622211, [585193, 659229]	278.8, [273.6, 283.9]	
		282.6, [280.1, 285.2]	

Table 8. Forecasts for the *Artemisia* pollen season duration and ending day, including predictions and 95% confidence bounds, as a function of relative humidity from the dew point (left) and the mean surface short-wave solar downward radiation accumulated over the last hour (J/m^2) (right).

While these linear extrapolations do not account for non-linear climate feedback loops, they provide a necessary baseline to understand the magnitude of potential pollen shifts under the assumption of stable environmental trends.

Conclusions

In the Milan area, the warming climate observed over recent decades has led to significant shifts in the pollen season of several herbaceous taxa, with earlier onset and longer duration. Our analysis indicates that temperature is the primary driver of these phenological changes, while the effects of precipitation appear more complex, with increased rainfall generally associated with an earlier end of the main pollen season. These trends suggest that climate change may have a particularly strong impact on grasses, potentially increasing the frequency and associated costs of pollen-related healthcare visits. Additionally, certain weed species, such as *Artemisia* and *Ambrosia*, may find more favorable conditions under the projected increases in temperature or drier conditions. The effects of precipitation on flowering and pollen release were more complex even if, generally, increasing rainfall contributes to a shortening of the end of the main pollen season.

While these findings provide a consistent preliminary assessment, a primary limitation lies in the linear extrapolation of historical temperature-phenology relationships. Such models may not capture potential non-linearities or physiological thresholds when projecting beyond observed temperature ranges. Furthermore, our analysis–focused on meteorological drivers–does not account for the high degree of uncertainty inherent in long-term atmospheric shifts, nor for non-climatic factors such as land-use changes, CO_2 fertilization effects on pollen production, or complex biological responses like dormancy delays, which could significantly alter the projected trends

These findings highlight the importance of maintaining long-term aerobiological monitoring networks to support both ecological research and public health planning. Further studies are needed to quantify the epidemiological impacts of changing pollen loads under future climate scenarios.

Year	Humidity (%)	Duration	Days conc. >1
2022	70.9, [69.2, 72.6]	40.5, [35.6, 45.3]	38.2, [33.7, 42.7]
		41.5, [37.5, 45.6]	39.3, [35.6, 43.1]
2040	69.8, [66.9, 72.6]	41.2, [36.8, 45.5]	38.9, [34.9, 42.9]
		43.0, [39.9, 46.1]	40.8, [37.9, 43.7]
2060	68.5, [64.3, 72.6]	42.0, [38.2, 45.7]	39.7, [36.3, 43.2]
		44.6, [42.1, 47.1]	42.5, [40.1, 44.8]
2080	67.2, [61.7, 72.7]	42.8, [39.6, 46.0]	40.6, [37.6, 43.6]
		46.2, [43.4, 49.0]	44.1, [41.5, 46.7]

Year	Precipitation (mm)	Duration	Days conc. >1
2022	0.044, [0.038, 0.050]	47.5, [44.5, 50.5]	44.9, [42.0, 47.9]
		48.5, [45.0, 51.9]	45.7, [42.3, 49.1]
2040	0.048, [0.039, 0.058]	46.9, [44.1, 49.6]	44.4, [41.7, 47.1]
		48.3, [44.9, 51.7]	45.6, [42.3, 48.9]
2060	0.053, [0.039, 0.067]	46.1, [43.6, 48.6]	43.7, [41.3, 46.2]
		48.3, [44.9, 51.7]	45.6, [42.3, 48.9]
2080	0.057, [0.038, 0.076]	45.5, [43.0, 47.9]	43.2, [40.9, 45.6]
		48.5, [45.0, 51.9]	45.7, [42.3, 49.1]

Year	Temperature (°C)	Duration
2022	14.1, [13.8, 14.4]	28.7, [12.5, 44.9]
		29.4, [13.8, 44.9]
2040	15.0, [14.5, 15.5]	30.7, [16.4, 44.9]
		31.8, [18.5, 45.0]
2060	16.0, [15.3, 16.8]	32.9, [20.7, 45.0]
		34.6, [24.1, 45.1]
2080	17.1, [16.1, 18.0]	35.3, [25.4, 45.1]
		37.2, [29.2, 45.2]

Table 9. Forecasts for the *Ambrosia* pollen season duration and the number of days with a concentration value greater than 1 within a season (prediction and confidence bounds at 95% level) as a function of the relative humidity from the due point, of the standard temperature at 2m above the surface – the "nose-level" temperature, and of the convective precipitation, i.e., water level accumulated during the last one hour (mm).

Data availability
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

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MB: Conceptualization, Methodology, Data curation, Investigation, Writing original draft. EC: Data collection, Methodology, Writing original draft. MF: Resources. MS: Data collection. JP: Data collection. MMP: Methodology, Software, Formal analysis, Data curation. GSM: Methodology, Software, Formal analysis, Data curation, Writing original draft – review & editing. All authors reviewed the manuscript.

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Declarations

Competing interests

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