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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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ABSTRACT

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 pollen season and climate parameters. Furthermore, future scenarios were developed to forecast trends in pollen season features based on the analyzed meteorological variables. 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 earlier onset of the pollen season, while precipitation and relative humidity to an earlier end date. Moreover, in the study area, a strong increase in annual average temperature has been observed since 1975, projected to continue over the next 60 years. This increase is 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.

1 Introduction

Allergic respiratory diseases are increasing worldwide in both school-age children and adults¹⁻⁴. 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 impacts⁴, 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 year⁴).

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 worldwide⁶⁻⁸. As a consequence, investigating temporal trends in pollen concentration is crucial to better understand their impact on human health⁹. 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/m³) 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 production¹². 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 Spain²¹. 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 August²².

The impact of climate change on plant phenology may vary among geographical areas²³. In Italy, Tagliaferro et al.²⁴ observed different trends in the Seasonal Pollen Integral (SPI_n) 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/m³)) SPI_n, while the subcontinental eastern area showed the most pronounced decreases in Urticaceae (-625 p/m³) and *Artemisia* (-47 p/m³) SPI_n 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 population²⁵. 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.

2 Materials and Methods

2.1 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 Europe³⁰. 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.

2.2 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 Control³¹. Daily pollen concentrations are expressed as particles per cubic meter of air (p/m³). 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 total³²), 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/m³, Annual Pollen Integral (API_n, sum of daily pollen concentrations over the year³³), and Seasonal Pollen Integral (SPI_n, sum of daily pollen concentration over the main pollen season). Given the extremely high correlation observed between the Annual Pollen Integral (API_n) and the Seasonal Pollen Integral (SPI_n) across all taxa (Pearson correlation $\hat{\rho} = 0.9999734$), we elected to use only the SPI_n 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.

84 Defining the start and end of the pollen season is challenging. The phenological season is influenced by local landscape
 85 heterogeneity (e.g., shadows from slopes, trees, buildings), which introduces uncertainty and can “blur” the aerobiological
 86 season recorded by pollen traps³⁴. Long-range transport can also produce peaks before or after the local season. Moreover, the
 87 clinical relevance of a pollen season depends on both timing and intensity, specifically when pollen concentrations exceed
 88 established biological thresholds known to trigger allergic symptoms⁹; low overall concentrations may prevent the emergence
 89 of a medical season, even when aerobiological and phenological seasons occur. To account for these complexities, we used the
 90 2.5%-97.5% percentile criterion to define season timing, following the approach of previous studies³². Absolute concentration
 91 thresholds are less reliable due to high inter-annual variability³⁵. While the percentile method could, in principle, be influenced
 92 by long-range transport trends, the Milan region is primarily protected by the Alps (north) and the sea (south-west and east).
 93 Therefore, this criterion provides a robust and appropriate measure for defining the pollen season in this study. In parallel,
 94 our analysis of local meteorological data revealed a clear warming trend in the Milan area over the past decades, consistent
 95 with observations across Italy and Europe. Mean annual temperatures have increased and are projected to continue rising over
 96 the next 60 years. Solar radiation is expected to increase with temperature, consistent with their usual association. Observed
 97 and projected precipitation trends indicate a general increase, particularly in spring and winter, in line with continental-scale
 98 patterns. These climate trends provide the basis for interpreting observed shifts in airborne pollen seasonality, such as earlier
 99 onset dates and extended pollen seasons. While direct phenological observations of plants were not conducted, changes in the
 100 timing of airborne pollen concentrations serve as a reliable proxy for understanding the response of plant reproductive cycles to
 101 climate variability, especially in anemophilous plants^{20,36,37}.

102 2.3 Meteorological data

103 Daily meteorological data were extracted from the ERA5 reanalysis³⁸, within the Copernicus Climate Change Service (C3S).
 104 The data were aggregated by considering the daily mean value of each time series. The following weather parameters were
 105 selected: daily average of standard air temperature (°C) at 2m above the surface, i.e., the “nose-level” temperature, and relative
 106 humidity (%) at 2m above the surface; wind speed (m/s); convective precipitation, i.e., water level accumulated during the
 107 last one hour (mm); surface short-wave solar radiation downwards, which comprises both direct and diffuse solar radiation
 108 accumulated during the last hour (J/m²).

109 2.4 Statistical Analysis

110 To analyse the association between pollen-season descriptors (start date, end date, duration, peak day, peak value, APIn,
 111 SPIn, and number of days with concentration > 1) and the meteorological variables described in Section 2.3, we used two
 112 complementary correlation coefficients. Pearson’s ρ was applied to quantify linear relationships, as it is particularly effective
 113 when variables exhibit approximate normality and linear dependence. In contrast, Spearman’s rank correlation coefficient (ρ_S)
 114 was used to detect monotonic associations that may not follow a linear pattern, without requiring assumptions regarding the
 115 distribution or linearity of the data. This dual approach allows us to distinguish linear from purely monotonic associations and
 116 to understand better how different types of relationships manifest in the data.

117 For each taxon, we calculated the pollen season (start and end) according to the definition provided in Section 2.2. For the
 118 correlation analysis, we used the daily average of each meteorological variable calculated over the specific pollen season period.
 119 This approach was chosen to capture the average environmental intensity during the season, ensuring that the indicators remain
 120 independent of the varying duration of the pollen seasons across years and taxa.

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

129 3 Results

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

136 that both measures convey essentially the same information and provide consistent evidence of the linear associations between
137 meteorological variables and pollen season characteristics.

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

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.

Meteo feature	Pollen specie	$\hat{\rho}$	p-val (ρ)	$\hat{\rho}_S$	p-val (ρ_S)
temperature	<i>Ambrosia</i>	-0.325	0.092	-0.346	0.071
	<i>Artemisia</i>	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	<i>Ambrosia</i>	0.194	0.323	0.213	0.276
	<i>Artemisia</i>	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	<i>Ambrosia</i>	-0.056	0.766	-0.086	0.663
	<i>Artemisia</i>	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	<i>Ambrosia</i>	-0.215	0.272	-0.310	0.109
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	-0.049	0.736	-0.043	0.826
	<i>Artemisia</i>	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

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

148 Regarding the duration of the pollen season (Table 3), significant correlations emerge for a limited subset of taxa and
149 meteorological variables. *Ambrosia* and Urticaceae show a positive association with temperature, suggesting longer seasons
150 in warmer years. *Ambrosia* and *Artemisia* also respond significantly to wind speed (positive) and to relative humidity and
151 precipitation (negative), indicating that drier and windier conditions tend to prolong their seasons. Solar radiation shows
152 a weaker but still significant effect, with positive correlations for *Ambrosia* and *Artemisia*. No significant relationships are
153 detected for Cannabaceae, Chenopodiaceae/Amaranthaceae, or Poaceae regarding season duration. This lack of significance,
154 contrasted with the results found for other taxa, highlights that the response of pollen season timing to meteorological drivers is

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.

Meteo feature	Pollen species	$\hat{\rho}$	p-val (ρ)	$\hat{\rho}_S$	p-val (ρ_S)
temperature	<i>Ambrosia</i>	-0.074	0.709	-0.122	0.537
	<i>Artemisia</i>	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	<i>Ambrosia</i>	-0.087	0.660	-0.011	0.956
	<i>Artemisia</i>	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	<i>Ambrosia</i>	0.054	0.784	0.076	0.701
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	-0.050	0.800	-0.068	0.732
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	-0.036	0.854	0.030	0.880
	<i>Artemisia</i>	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 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.

Meteo feature	Pollen species	$\hat{\rho}$	p-val (ρ)	$\hat{\rho}_S$	p-val (ρ_S)
temperature	<i>Ambrosia</i>	0.379	0.047	0.418	0.027
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	-0.155	0.430	-0.067	0.735
	<i>Artemisia</i>	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	<i>Ambrosia</i>	-0.396	0.037	-0.440	0.019
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	-0.490	0.008	-0.530	0.004
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	0.311	0.107	0.387	0.042
	<i>Artemisia</i>	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 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.

Meteo feature	Pollen species	$\hat{\rho}$	p-val (ρ)	$\hat{\rho}_S$	p-val (ρ_S)
temperature	<i>Ambrosia</i>	0.277	0.153	0.306	0.114
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	0.019	0.922	0.104	0.597
	<i>Artemisia</i>	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	<i>Ambrosia</i>	-0.430	0.022	-0.449	0.017
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	-0.432	0.022	-0.441	0.019
	<i>Artemisia</i>	-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	<i>Ambrosia</i>	0.223	0.254	0.243	0.213
	<i>Artemisia</i>	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

155 not uniform across all species.

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

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

164 A linear trend was then estimated for each meteorological variable to explore hypothetical scenarios for pollen levels
 165 for the different species at 20, 40, and 60 years into the future. We acknowledge that the linear trends estimated for the
 166 meteorological variables cannot capture all the variability present in the data, as also reflected in Table 5. Nevertheless, the
 167 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
 168 metrics: start, end, duration, and number of days with concentration above 1) indicates that both linear and monotonic trends
 169 point in the same direction. This supports the use of a linear approximation as a first-order representation of the underlying
 170 relationships. Our intention is not to predict exact future weather values, but to provide insight into the direction and relative
 171 magnitude of historical trends, which form a consistent basis for assessing potential changes in pollen seasonality under
 172 different meteorological scenarios. The uncertainty in these trend-based scenarios is explicitly acknowledged and taken into
 173 account in the interpretation of results.

Figure 1. Plot of the annual mean value of 2m temperature ($^{\circ}\text{C}$) (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.

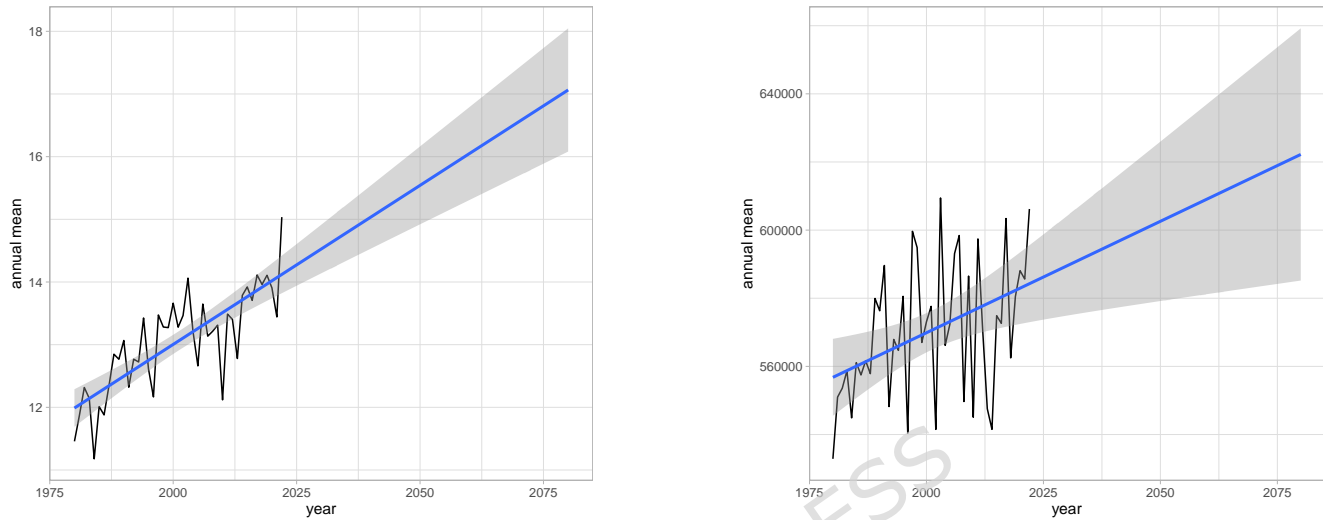


Figure 2. Plot of the annual mean value of relative humidity from the due point (%) (left) and the annual mean value of convective precipitation, water level accumulated during last one hour (mm) (right), both shown as black solid lines. The regression line (blue solid line) is displayed with 95% confidence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

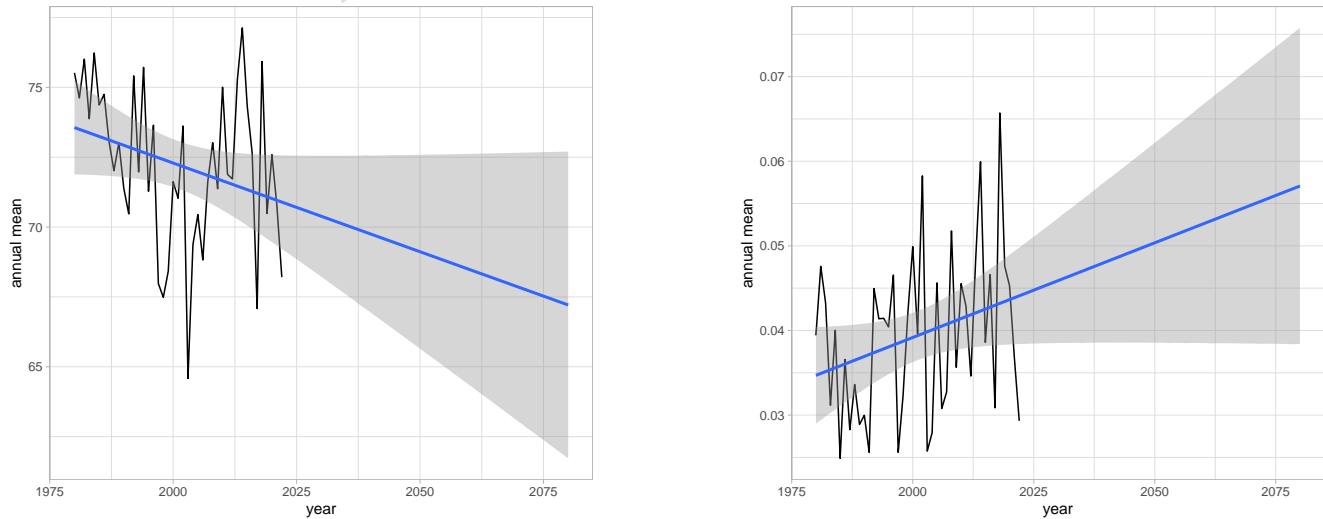


Table 5. Summary of the linear regression model for the mean annual value of each meteo variable as a function of the year, including estimated coefficients, standard errors, t-values, p-values, and goodness-of-fit measures. P-values ≤ 0.05 are shown in bold.

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			

174 The results of the estimated linear models are presented in Table 5. The estimated models show a clearly increasing trend
 175 (p-value < 0.01) for the average standard temperature at 2m above the surface and for the average surface short-wave solar
 176 downwards radiation accumulated during the last one hour (J/m²) (see Figure 1). A weakly increasing trend is also observed for
 177 annual mean convective precipitation, i.e., water level accumulated during the last one hour (mm), although with substantial
 178 interannual variability (p-value < 0.1). Conversely, relative humidity shows a slightly decreasing trend (p-value < 0.1), while no
 179 statistically significant linear trend is detected for wind speed (see Figure 2). This indicates that long-term meteorological
 180 change in the study area is driven primarily by temperature.

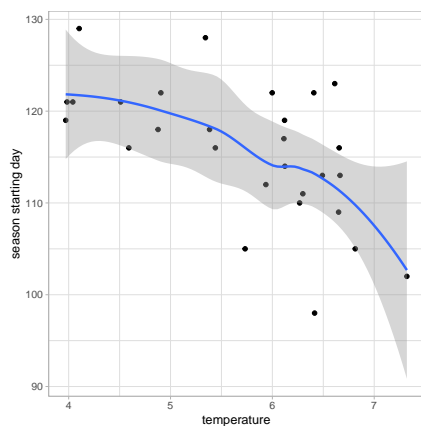
181 For meteorological variables with a significant or marginally significant linear trend (specifically temperature, solar radiation,
 182 and with *p* - value < 0.07, humidity and precipitation), the extrapolated values were used as inputs to estimate potential pollen
 183 levels. Two sensitivity scenarios were considered: a 'Trend-Persistence' scenario, based on the projected value at 20, 40, and 60
 184 years from the last observation, and a 'Pessimistic' scenario, representing the most adverse climate conditions. These scenarios
 185 are intended as sensitivity analyses rather than deterministic forecasts, providing a framework to assess the potential response
 186 of pollen seasons under the assumption of continued linear climatic shifts. Specifically, for temperature, the upper bound of the
 187 95% confidence interval of the estimated mean was used to estimate pollen levels, whereas for relative humidity, the lower
 188 bound was applied to simulate a worst-case scenario.

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

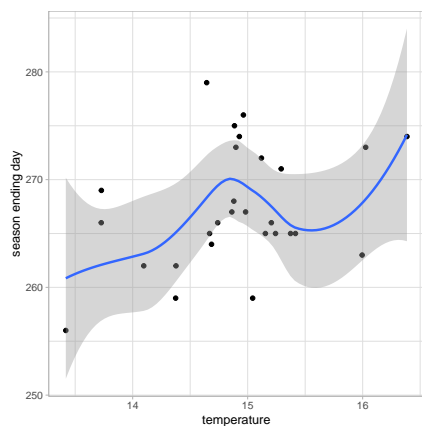
192 As shown in Figure 3, the start and end dates of the Urticaceae pollen season exhibit clear linear relationships with
 193 temperature: panel (a) shows a negative linear association between temperature and the start of the season, indicating earlier
 194 onset in warmer years, while panel (b) shows a positive linear relationship between temperature and the end of the season,
 195 suggesting delayed termination. In contrast, the relationship between temperature and the overall duration of the pollen season,
 196 shown in panel (c), does not appear to be linear. The duration increases with temperature up to a certain point, but then seems
 197 to decline at higher temperature values. A similar pattern is observed for Poaceae, as shown in Figure 4, which follows the
 198 same panel structure. For this species, the relationship between temperature and the start of the pollen season remains clearly
 199 negative and linear, whereas the association with the end of the season appears non-linear. Regarding the season's duration, it
 200 exhibits a similar inverted U-shaped pattern, as illustrated for Urticaceae. Graphical representations of the temperature–pollen
 201 relationships are shown only for Poaceae and Urticaceae, which exhibited the strongest and most consistent associations. For
 202 the remaining taxa, correlations were weak or non-significant, and additional plots were omitted to avoid redundancy with the
 203 correlation tables.

204 Table 6 presents projections for the pollen season starting day (predictions with 95% confidence intervals) based on

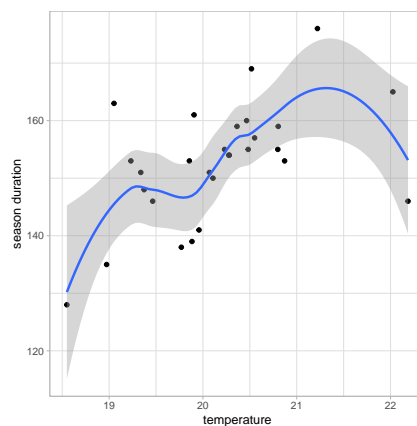
Figure 3. Relationship between mean seasonal temperature and characteristics of the Urticaceae pollen season. The three panels show: (a) start day of the pollen season, (b) end day of the pollen season, and (c) duration of the pollen season, each as a function of mean temperature ($^{\circ}\text{C}$).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



(a) Pollen season starting day vs. temperature.

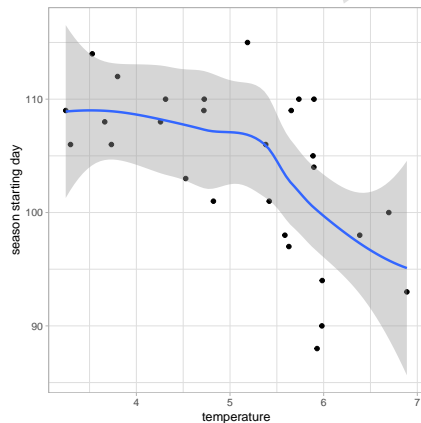


(b) Pollen season-ending day vs. temperature.

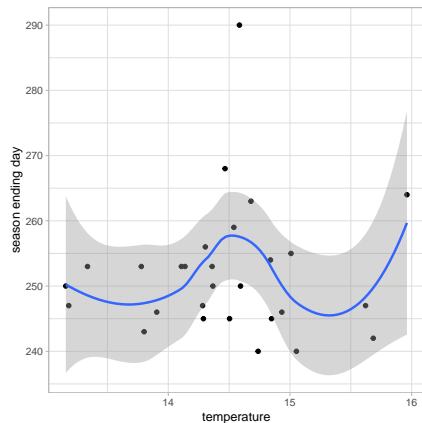


(c) Pollen season duration vs. temperature.

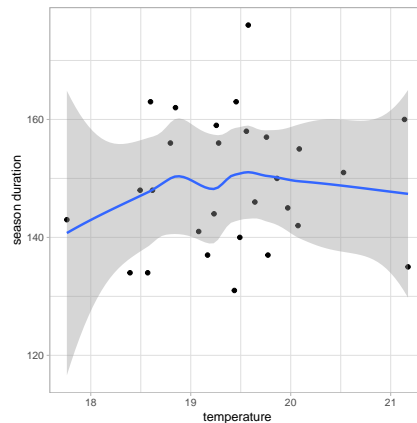
Figure 4. Relationship between mean seasonal temperature and characteristics of the Poaceae pollen season. The three panels show: (a) start day of the pollen season, (b) end day of the pollen season, and (c) duration of the pollen season, each as a function of mean temperature ($^{\circ}\text{C}$). Points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



(a) Pollen season starting day vs. temperature.



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



(c) Pollen season duration vs. temperature.

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/m³ (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/m²). 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 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.

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.

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 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/m²).

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 8 presents projections for the *Artemisia* pollen season duration and ending day, including 95% confidence bounds, as

219 a function of relative humidity from the dew point (left) and surface short-wave solar radiation (right). Following the same
 220 scenario convention as above, a projected decrease in average annual humidity is associated with a 3-day delay in the end of the
 221 pollen season over 60 years in the ‘Trend-Persistence’ scenario and up to 5 days in the ‘Pessimistic’ scenario. This would result
 222 in an average estimated extension of the season of 5 days. Solar radiation shows a smaller but consistent modeled effect on
 223 season duration under these linear assumptions.

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).

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]	

224 Table 9 presents projections for *Ambrosia* pollen season duration and the number of days with concentrations above 1 p/m^3 ,
 225 as a function of relative humidity from the dew point, 2m temperature, and convective precipitation (mm). According to the
 226 observed negative correlation between precipitation and season duration ($\hat{\rho} = -0.49$, $p = 0.008$), an increase in precipitation is
 227 projected to potentially reduce the mean season length from 47.5 days in 2022 to 45.5 days in 2060 under the ‘Trend-Persistence’
 228 scenario.. Temperature increases are associated with a potential trend toward longer pollen seasons, while the modeled effect of
 229 precipitation under the ‘Pessimistic’ scenario remains minimal. For a more in-depth discussion on the necessity of considering
 230 these drivers for the ragweed pollen season, please refer to Section 4.

231 4 Discussion

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

239 4.1 Relationship between meteorological variables and pollen season features

240 Our study provided clear evidence of climate warming in the Milan area, consistent with trends registered across Italy and
 241 Europe^{13,20,24,39,40}. An observed significant increase in mean annual temperature was registered over the last decades. Similarly,
 242 precipitation amounts also increased during this period, mirroring regional findings, such as those noted for spring and winter
 243 seasons in the continental US⁴¹. Looking forward, significant warming is predicted: our projection of a $+3^\circ\text{C}$ increase in the
 244 annual average temperature over the next 60 years aligns with estimates for other Mediterranean cities, such as the increase
 245 of up to $0.5^\circ\text{C}/\text{decade}$ estimated for Barcelona between 2024–2100⁴⁰. Furthermore, considering the observed local trends

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).

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]	

and the statistical association between these variables⁴², 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 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 regions⁴⁶. 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 settings⁴⁶⁻⁴⁸. 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* 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 rainfall²². 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 areas²² 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 temperatures⁵¹.

The effects of precipitation on the pollen season features were less clear than those of temperature, as highlighted in other studies²⁴. 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 season⁵³. Multiple factors may be on the basis of these results, among which the removal effect on bioaerosols from the air performed by precipitation⁵⁴ 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}.

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 Region³⁰. 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}.

4.2 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

300 climatic scenarios on pollen emission duration. Models of⁴¹ resulted in a shift of the future start and end of the flowering
301 season to an earlier date than the historical period, with the starting date showing a stronger temperature dependence than
302 the end date and, thereby, increasing the length of the pollen season duration for several deciduous tree genera and grasses.
303 Similar trends were obtained by¹¹, with higher sensitivity of grass pollen to changes in temperature over time with respect to
304 the analyzed tree species (i.e., oak and birch). Also, the pollen season of *Ambrosia* is projected to elongate with increasing
305 temperature (by 6.5-7.8 days, depending on the scenario), while precipitation is projected to decrease its duration. As stated
306 above, precipitation is a more complex factor to analyze in relation to plant phenology, as it is both linked to short-term effects
307 on pollen production (i.e., by washing out particles from the air) and to the long-term impacts, with benefits and detriments
308 for plant growth depending on the species' ecology⁵⁸. The results of this study could certainly be improved by models that
309 relate meteorological variables to pollen season parameters during specific phases of plant phenology (e.g., before or during
310 flowering), rather than to the pollen season as a whole. However, to the best of our knowledge, the present study is one of the
311 few that investigate the projection of meteorological parameters onto pollen season features worldwide.

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

314 5 Conclusions

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

323 While these findings provide a consistent preliminary assessment, a primary limitation lies in the linear extrapolation
324 of historical temperature-phenology relationships. Such models may not capture potential non-linearities or physiological
325 thresholds when projecting beyond observed temperature ranges. Furthermore, our analysis—focused on meteorological
326 drivers—does not account for the high degree of uncertainty inherent in long-term atmospheric shifts, nor for non-climatic
327 factors such as land-use changes, CO₂ fertilization effects on pollen production, or complex biological responses like dormancy
328 delays, which could significantly alter the projected trends

329 These findings highlight the importance of maintaining long-term aerobiological monitoring networks to support both
330 ecological research and public health planning. Further studies are needed to quantify the epidemiological impacts of changing
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335 The authors declare no competing interests.

336 Author contributions statement

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

341 Data Availability

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

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