



Long-term changes in the timing and intensity of the pollen season in Slovenia (2002–2024)

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Received: 29 January 2026 / Accepted: 1 June 2026
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Abstract Climate change is reshaping pollen season dynamics across Europe, with significant implications for allergic populations. This study presents the first comprehensive long-term analysis of pollen season trends in Slovenia, a region characterized by high phytogeographic diversity at the intersection of Mediterranean, Alpine, Dinaric, and Pannonian climatic influences. Daily airborne pollen concentration data from three monitoring stations were analyzed for

14 allergenic taxa over 23 years (2002–2024). Pollen season timing was determined using a normalized cumulative-sum approach, and linear regression quantified temporal trends in season onset, termination, duration, and total annual pollen load. Results reveal general advancement in season onset across most taxa, particularly pronounced for arboreal species in the Mediterranean region. Season termination exhibited asymmetric patterns: earlier endings for spring-flowering trees and delayed termination for herbaceous taxa, especially Poaceae. Notably, trees showed compressed seasons due to faster advancement of season end relative to onset, potentially leading to more intense allergen exposure despite shorter duration. Significant increases in annual pollen load were detected for Poaceae, Urticaceae, and *Plantago*, while *Artemisia* showed widespread decline. The coastal Mediterranean site exhibited significantly earlier onset, later termination, and longer seasons compared to continental stations, which showed strong inter-site synchrony. These findings demonstrate asymmetric seasonal responses to climate forcing across small spatial scales, with important implications for region-specific public health strategies.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10453-026-09924-x>.

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Keywords Airborne pollen · Pollen trends · Pollen season · Slovenia · Mediterranean climate · Continental climate

1 Introduction

The global climate has changed considerably, with impacts already observed across a wide range of physical and biological systems, including shifts in phenological events (Calvin et al., 2023). One approach to assessing the impact of climate change on vegetation is the analysis of long-term airborne pollen monitoring, which is a valuable tool for studying the reproductive phenology of anemophilous plants (Clot, 2003; Galán et al., 2016).

Climate change, characterized by elevated atmospheric CO₂ and rising temperatures, represents the primary force reshaping phenological patterns across taxa (D'Amato et al., 2020; Schramm et al., 2021; Zhang & Steiner, 2022; Ziska & Beggs, 2012). However, local factors—including urbanization, urban heat islands, ornamental tree plantings, and the introduction of invasive allergenic species—modulate these climate signals and contribute to the regional variability (Damialis et al., 2019; Schramm et al., 2021). All of aforementioned variables can influence the timing, duration, and intensity of pollen seasons, with effects varying by region and plant species. Consequently, alterations in pollen seasons can affect health, as pollen exposure is a recognized trigger for adverse symptoms in sensitized individuals (Beggs, 2021; Berezhanskiy et al., 2025; Guilbert et al., 2018; Sapkota et al., 2019).

Numerous studies have reported a general tendency toward an earlier start of pollen seasons for a wide range of taxa across Europe, with the most pronounced advances observed in early-season tree taxa such as *Corylus*, *Alnus*, *Quercus*, and members of the Cupressaceae family. Earlier season starts have also been documented for herbaceous taxa, particularly the Poaceae and Urticaceae families (Adams-Groom et al., 2022; Cristofolini et al., 2020; Glick et al., 2021; Hoebeke et al., 2018; Rojo et al., 2021). However, these responses show considerable spatial variability, as trends in the timing of pollen season onset differ among regions and are not statistically significant at all monitoring sites. Furthermore, long-term studies focusing on seasonal breakpoints indicate that trends for several species in Switzerland have been less pronounced or absent over the past two decades (Eeftens & Gehrig, 2019). Comparable results have been reported for *Betula* pollen in France, Belgium, and Switzerland, where the timing of season onset

shifted after the late 1990s and early 2000s, suggesting a trend toward a later start (Besancenot et al., 2019; Hoebeke et al., 2018; Jochner-Oette et al., 2019).

Predominantly negative trends in pollen season end dates have been reported, with variations associated with the taxa examined and the definitions of the pollen season applied (Gehrig & Clot, 2021). Earlier pollen season endings are reported mainly for arboreal taxa, whereas later end dates are more frequently observed for herbaceous species (Bogawski et al., 2014; Lind et al., 2016; Rojo et al., 2021). Alterations in pollen season start and end dates can impact the season's overall duration. Several studies indicate that the duration of pollen season has increased over time for various taxa (Anderegg et al., 2021; Tagliaferro et al., 2024; Ziska et al., 2019). Other studies, however, report generally stable season durations with no significant trends, with late-flowering herbaceous taxa, such as Poaceae and Urticaceae, often emerging as exceptions and exhibiting a tendency toward season extension (Lind et al., 2016; Makra et al., 2011; Rojo et al., 2021).

Despite regional variability, increases in the seasonal pollen integral (SPIn) or the annual pollen integral (APIn) were consistently observed across the Northern Hemisphere (Ziska et al., 2019). In their review article, Ziello et al. reported that the APIn value has been increasing across Europe, particularly for arboreal taxa, whereas many herbaceous species tend to show a decreasing trend (Ziello et al., 2012). Similar outcomes have also been reported in several later studies, with most research indicating increasing pollen trends among arboreal taxa of the Betulaceae, Fagaceae, Cupressaceae, and Oleaceae families, in contrast to declining or stable trends observed for herbaceous taxa such as *Artemisia*, Urticaceae, and Poaceae (de Weger et al., 2021; Galán et al., 2016; Rojo et al., 2021).

In this study, we focus on identifying potential long-term changes in the timing, duration and intensity of the pollen season for 14 taxa in Slovenia over the twenty-three years (2002–2024). This period coincides with documented climate change trends, during which temperatures in Slovenia have been rising faster than the global average, alongside observable shifts in precipitation patterns (Slovenian Environment Agency [ARSO], 2022). This is particularly relevant, as temperature is considered the primary

driver of phenological change (Bonini et al., 2026). Furthermore, the presented article is the first comprehensive aerobiological study in Slovenia that explicitly addresses both regional differentiation and inter-regional coherence within a climatically transitional zone.

2 Methods

2.1 Study area and phytogeographic context

Slovenia is situated within the temperate zone at the convergence of four major European geographic regions: the Mediterranean, the Alps, the Dinaric Alps, and the Pannonian Plain. Climatic contact and transition represent a challenge for climate classifications, as the identified climate types are atypical compared to true continental, Mediterranean or mountain climates. This positioning results in a transitional climate classified into moderate continental, moderate Mediterranean, and mountain climate types (Ogrin et al., 2023).

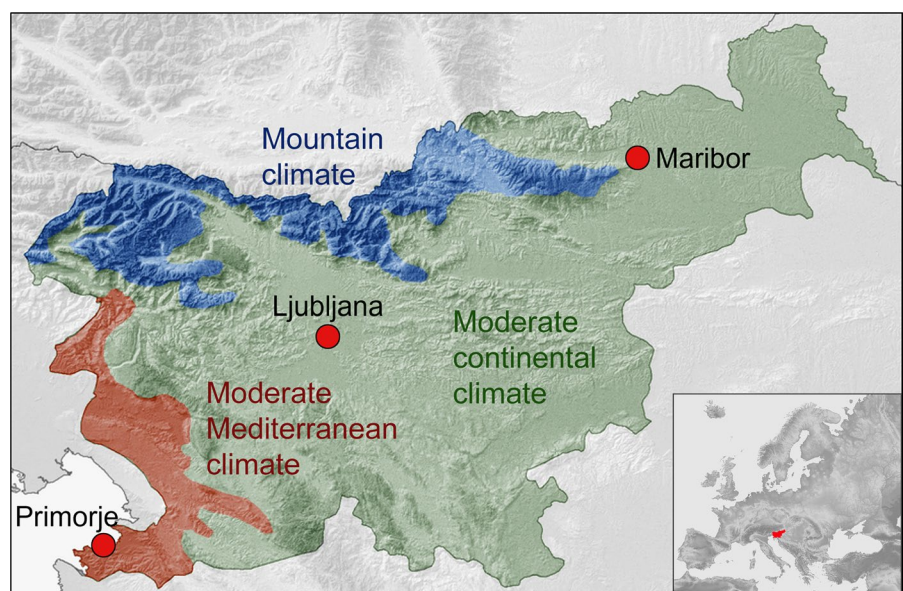
The monitoring sites were selected to represent these distinct environmental profiles: Primorje (45.5333° N, 13.6500° E), Ljubljana (48.1482° N, 16.0385° E) and Maribor (46.5646° N, 15.6460° E), (see Fig. 1). The Ljubljana and Maribor sites are situated in densely populated areas and are influenced

by urban heat island effects (Komac et al., 2016; Žiberna, 2006), whereas the station in the Primorje region is embedded in a rural landscape. The climatic conditions of the specific study areas are further differentiated by regional gradients. Primorje is characterized by a moderate Mediterranean climate (mean annual temperature: 14.1 °C; annual precipitation: 1149.8 mm). Ljubljana represents a moderate continental climate (mean temperature: 11.8 °C; precipitation: 1251.8 mm). Maribor also reflects a moderate continental climate (mean temperature: 11.1 °C; annual precipitation: 918.3). A more detailed description of the climatic condition is also provided in the Supporting Information file in Figure S1 and Figure S2. Daily weather data from the year 2002 and till 2024 have been obtained from the Slovenian Environment Agency (“Slovenian Environment Agency [ARSO]” 2026).

These climatic gradients contribute to the spatial differentiation of vegetation patterns across Slovenia. Slovenian forests cover more than half of the country (58.07%) and represent an essential landscape element (Železnik, 2021).

In general, Slovenia is classified within the continental biogeographical region (EEA, 2026), but with increasing proximity to the Adriatic Sea, it exhibits certain climatic conditions that favour thermophilous, drought-adapted deciduous forests, dominated by *Quercus pubescens*, *Ostrya carpinifolia*, and

Fig. 1 Location of the study area in Europe and Slovenia. Red dots indicate the locations of the three main pollen monitoring sites: Maribor and Ljubljana (Moderate continental climate) and Primorje (Moderate Mediterranean climate)



Fraxinus ornus. *Pinus nigra* is widespread in this region due to afforestation (Repe, 2020), while cultivated species, such as *Olea europaea*, are also well represented. In the continental part of Slovenia, humid lowland areas are dominated by forest vegetation consisting of *Quercus robur*, *Alnus glutinosa*, *Alnus incana*, and *Fraxinus excelsior*, together with other hygrophilous tree species. The drier lowland areas were formerly dominated by *Quercus petraea* and *Carpinus betulus* forests, which are still locally present. On slopes, *Fagus sylvatica* dominates, with *Castanea sativa*, *Betula pendula*, and *Pinus sylvestris* occurring sporadically (Ogrin et al., 2023).

2.2 Aerobiological monitoring and sampling protocol

The herein analyzed dataset spans over the period 2002–2024 and was provided by the National Laboratory of Health, Environment and Food (National

Laboratory of Health, Environment and Food, 2025), which operates the national aerobiological monitoring network in accordance with European Aerobiology Society (EAS) methodological requirements (Galán et al., 2014). Daily airborne pollen concentrations were monitored for 14 pollen taxa: *Ambrosia* spp. (ragweed), *Artemisia* spp. (mugwort), *Betula* spp. (birch), *Castanea* spp. (sweet chestnut), *Fagus* spp. (beech), *Fraxinus* spp. (ash), *Carpinus* spp./*Ostrya* spp. (hornbeam/hop-hornbeam), *Pinus* spp. (pine), *Plantago* spp. (plantain), *Platanus* spp. (plane tree), Poaceae (grasses), *Quercus* spp. (oak), *Rumex* spp. (dock), and Urticaceae (nettle). The mean, minimum, and maximum Annual Pollen Integrals (APIIn) for these taxa across the three monitoring sites are summarized in Table 1, reflecting their relative abundance and dominance within the studied regions.

Taxonomic resolution follows morphological identification limits, with taxa identified at the family or genus level, each comprising different species (Makra

Table 1 Summary of Annual Pollen Integrals (APIIn) for the analyzed pollen taxa across three monitoring sites in Slovenia (2002–2024). The table presents the mean, minimum, and maximum annual values (expressed as pollen grains day/m³) for each taxon

Pollen taxa	Ljubljana			Maribor			Primorje		
	Mean (APIIn)	Min (APIIn)	Max (APIIn)	Mean (APIIn)	Min (APIIn)	Max (APIIn)	Mean (APIIn)	Min (APIIn)	Max (APIIn)
<i>Ambrosia</i> spp.	804	367	1434	1187	658	1832	623	223	1277
<i>Artemisia</i> spp.	217	88	468	315	140	594	135	67	189
<i>Betula</i> spp.	4208	1378	8847	4575	1051	9207	293	24	647
<i>Carp.</i> spp./ <i>Ostr.</i> spp.	5135	1134	22,122	3953	1100	13,364	6764	1211	28,230
<i>Castanea</i> spp.	2482	1106	4038	2904	1670	4275	800	315	1636
<i>Fagus</i> spp.	1112	20	4443	1519	24	7136	351	19	1570
<i>Fraxinus</i> spp.	1811	346	4745	1641	574	3226	3871	344	18,030
<i>Pinus</i> spp.	3369	1908	5486	5343	2609	7751	3795	1133	9782
<i>Plantago</i> spp.	597	282	1287	666	252	1457	416	210	852
<i>Platanus</i> spp.	1621	103	5028	532	70	1236	467	127	1043
Poaceae	3480	2304	4989	3820	2625	5589	2417	1115	3992
<i>Quercus</i> spp.	2212	550	4617	3049	727	7226	2932	585	6594
<i>Rumex</i> spp.	122	43	212	127	62	202	66	23	116
Urticaceae	4119	2406	5893	7104	3678	10,688	3550	1433	7934

et al., 2011). Airborne samples were collected using volumetric pollen samplers of the Hirst type (Hirst, 1952).

2.3 Data preprocessing

Data management and preprocessing were performed using a Python based workflow (The pandas development team 2026) to ensure a consistent preparation of raw datasets. A systematic assessment of monthly data completeness, particularly for the Maribor monitoring site, identified persistent gaps during the shoulder seasons (early spring and late autumn). Consequently, to maintain inter-regional comparability and seasonal integrity, the months of January, November, and December were excluded from all subsequent analyses. Furthermore, the year 2011 was removed due to excessive measurement discontinuities.

Detailed annual and monthly completeness metrics for each monitoring site—Ljubljana (Figures S3, S6a), Maribor (Figures S4, S6b), and Primorje (Figures S5, S6c)—are provided in the Supporting Information. Within the synchronized sampling window, the percentage of missing data remained low, at 0.4% for Ljubljana, 5.2% for Maribor, and 4.1% for Primorje. The average duration of these gaps was 2.27 days, 5.47 days, and 6.47 days, respectively. More details are provided in the Supporting Information File.

2.4 Time series imputation

Data continuity was maintained through a dual-stage hybrid imputation framework, developed to address the inherent non-linearity and zero-inflation of aerobiological time series without requiring external meteorological drivers (see Supporting Information file). We have tested the performance of the dual-stage hybrid model with 3 other gap filling methods (see Figure S8 and Table S1), whereby the dual-stage hybrid imputation framework outperformed the other used methods. The imputation strategy differentiates between short-term and long-term absences. Measurement gaps shorter than five consecutive days were filled using Akima 1D interpolation (Akima, 1991). For gaps equal to or exceeding five days, the algorithm utilizes a phenologically informed decision process. A taxon-specific flowering season was defined as the set of days-of-year (DOY) where the

7-day smoothed climatological mean concentration, calculated from the station's historical record, exceeded 1 grains/m³. Missing values falling outside this window were assigned a value of zero. Conversely, in-season gaps were filled using a ratio-to-climatology approach. To account for inter-annual variability in season intensity, the climatological DOY mean was scaled by a local intensity factor derived from observed concentrations in the three-day context windows immediately adjacent to the gap. All imputed values were clipped at a lower bound of zero to ensure physical plausibility. The hybrid approach was adopted as the imputation method for final dataset construction.

2.5 Definition of the main pollen season (MPS)

To identify the onset and cessation of pollen seasons, we employed a normalized cumulative-sum approach, a widely recognized standard in long-term aerobiological research (Bastl et al., 2018; Gehrig & Clot, 2021). For each taxon-site-year combination, daily pollen concentrations were normalized by the Annual Pollen Integral (API_n) (Galán et al., 2017). The season start (T_{start}) and season end (T_{end}) were defined as the ordinal days when the cumulative normalized curve reached 2.5% and 97.5% of the annual total, respectively (the 95% method) (Andersen, 1991). The 95% cumulative method was selected for defining the main pollen season (MPS) to ensure methodological consistency with long-term aerobiological studies across Europe (Galán et al., 2016; Gehrig & Clot, 2021; Tagliaferro et al., 2024). While percentage-based definitions are widely considered the standard for describing the MPS and constructing pollen calendars, they are primarily designed to delineate the core pollen season. By excluding sporadic early or late pollen grains, which often originate from long-distance transport, secondary flowering, or resuspension (Gehrig & Clot, 2021; Rojo et al., 2020). However, percentile methods may be less effective for evaluating clinical exposure and patient symptomatology, where threshold-based definitions (e.g., fixed concentrations of grains/m³) remain the standard for identifying clinically relevant aeroallergen levels. Throughout the manuscript, we have implemented the percentage-based definition of MPS, which is widely recognized as a standard in long-term aerobiological research.

By referencing each season to its own APIn, the approach isolates phenological responses from inter-annual fluctuations in emission intensity, allowing for statistically valid comparisons between years of high and low pollen integral. Furthermore, the use of uniform percentile boundaries supports the standardized inter-regional and inter-annual comparisons required for multi-site trend analysis. Adherence to this standardized framework and Hirst-type sampling protocols ensures that results are reproducible and comparable across monitoring networks (Galán et al., 2014).

The implementation of this analysis pipeline is demonstrated in Fig. 2, using *Platanus* data from the Ljubljana monitoring site as a representative example. The implementation of the analysis pipeline for all other taxa across the three regions is provided

in the Supplementary Material (Figures S13–S26, S30–43, and S47–S60).

2.6 Inter-regional correlation analysis

To evaluate the spatial coherence of pollen dynamics across Slovenia's distinct phytogeographic regions, we performed a pairwise correlation analysis of the daily pollen concentrations. This step is essential for determining whether the observed seasonal shifts are localized phenomena or part of a synchronized regional response to climatic forcing.

For each taxon, pairwise Pearson correlation coefficients (r) were computed between the synchronized daily time series (restricted to the February–October window to ensure regional comparability) for the three monitoring sites: Ljubljana, Maribor, and

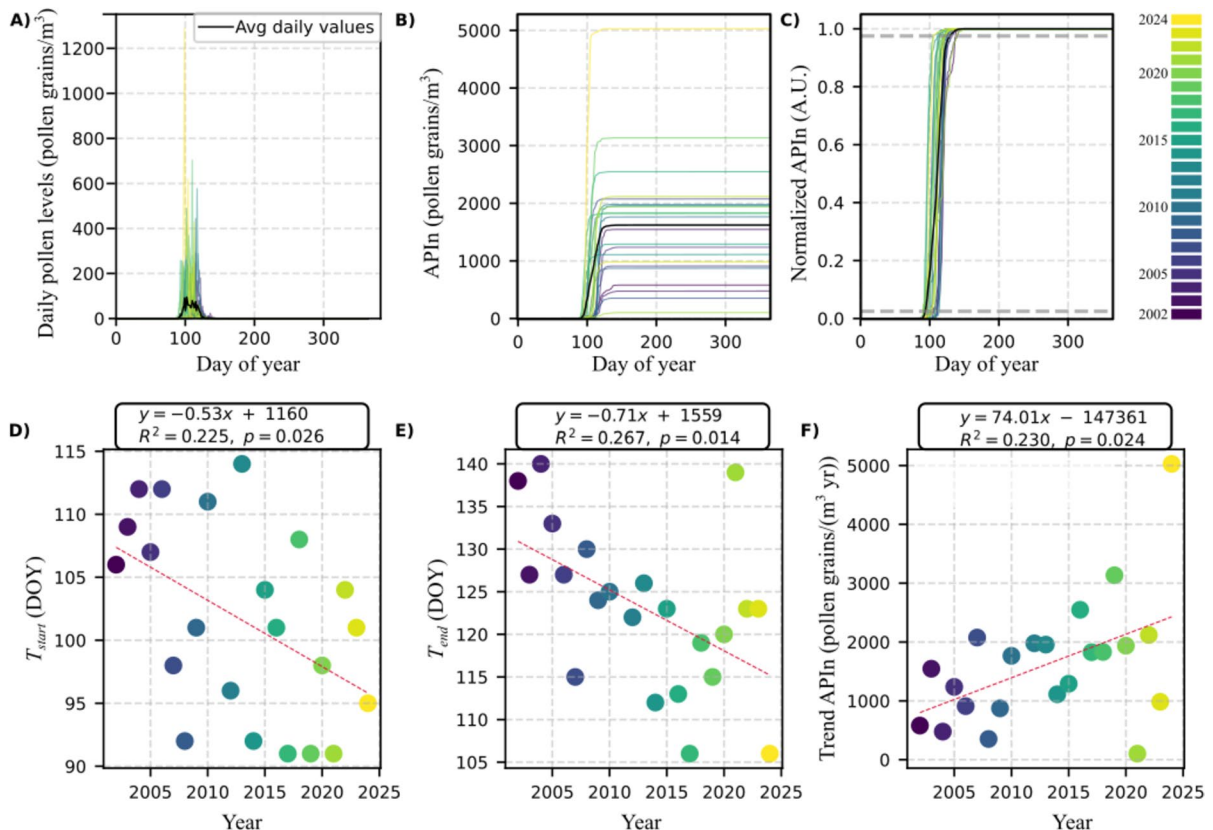


Fig. 2 Example of the pollen season analysis pipeline applied to *Platanus* in Ljubljana. The top row presents the seasonal dynamics and data normalization: **A** daily pollen concentrations showing average values (black) and 7-day smoothing (red dashed line); **B** cumulative annual pollen totals; and **C** normal-

ized cumulative sums used for thresholding. The bottom row illustrates inter-annual trends over 23 years for **D** T_{start} , **E** T_{end} , and **F** the APIn. The year of the measurement is color coded as shown by the bar

Primorje. Unlike the regression analysis used for long-term trends, this spatial-correlation analysis quantifies the inter-regional synchrony of temporal fluctuations—specifically, how closely the day-to-day variations in collected pollen levels align across the sites.

Correlations were calculated independently for each taxon using non-detrended data to preserve the biological structure of year-to-year variability. High correlation coefficients (r) indicate a synchronized response between sites, suggesting that regional differences in T_{start} or APIn are secondary to broad climatic forcing. Conversely, lower correlations indicate a decoupling of measured pollen levels, highlighting the dominance of local environmental factors, distinct regional vegetation compositions, or topographical barriers. Detailed inter-regional correlation matrices and comparative time series for each taxon are provided in the Supplementary Material (Figures S61–S74).

2.7 Statistical tests

Temporal trends for each pollen metric (T_{start} , T_{end} , ΔT , and APIn) were quantified using ordinary least squares (OLS) linear regression to determine annual rates of change (slope), with the non-parametric Mann–Kendall test applied to verify trend direction and significance under conditions of non-normality. Furthermore, to evaluate regional differentiation,

a Mann–Whitney U test was employed to compare the distribution of pollen metrics between individual monitoring sites (e.g., Maribor vs. Ljubljana). This non-parametric approach was selected to account for the heteroscedasticity and non-normal distributions characteristic of long-term aerobiological data. OLS-derived statistics are reported throughout the text to facilitate direct comparison with prior literature, with statistical significance defined at $\alpha = 0.05$. Significant trends and inter-site differences ($p < 0.05$) are reported where phenologically or biologically relevant. To account for simultaneous testing across multiple taxa and monitoring sites, Bonferroni correction was applied to all trend p -values; only corrected values meeting the significance threshold are reported in Tables 2–4. All statistical analyses were performed using the SciPy and Statsmodels libraries in Python 3.10.

3 Results

3.1 Pollen season characteristics

3.1.1 Season start

To assess regional variability in the temporal onset of pollen seasons across Slovenia, T_{start} was compared among the three monitoring sites: Ljubljana, Maribor, and Primorje. Figure 3 illustrates the inter-annual

Table 2 Statistically Significant Trends in Pollen Season Start Time (T_{start}) measured with day of year (DOY). Listed pollen exhibit a significant trend. Trend shows the linear change in T_{start} , expressed in days per year (negative values signify an earlier onset). STD is the standard deviation of the observed

T_{start} values (in days). Min, avg, and max represent the minimum, average, and maximum Day of the Year (DOY) when the pollen season started across the entire observation period, respectively

Location	Pollen taxon	Trend (D/Y)	p -value	STD (days)	R^2	Min (DOY)	Avg (DOY)	Max (DOY)
Primorje	<i>Carp. spp./Ostr. spp.</i>	-0.60	0.026	5.3	0.23	76	88	104
Ljubljana	<i>Carp. spp./Ostr. spp.</i>	-0.62	0.032	9.2	0.21	73	90	105
Maribor	<i>Fagus spp.</i>	-0.44	0.011	5.6	0.28	93	102	114
Primorje	<i>Pinus spp.</i>	-1.14	0.001	11.7	0.43	71	94	113
Ljubljana	<i>Pinus spp.</i>	-0.59	0.039	9.0	0.20	89	118	133
Primorje	<i>Platanus spp.</i>	-0.72	0.001	7.6	0.41	83	95	108
Ljubljana	<i>Platanus spp.</i>	-0.53	0.026	7.5	0.23	91	102	114
Primorje	<i>Quercus spp.</i>	-0.59	0.032	8.7	0.21	85	99	112
Ljubljana	Urticaceae	-1.46	0.002	15.9	0.39	103	134	165
Primorje	Urticaceae	-1.01	0.036	15.2	0.20	95	114	159
Maribor	Urticaceae	-0.29	0.040	4.5	0.19	150	158	168

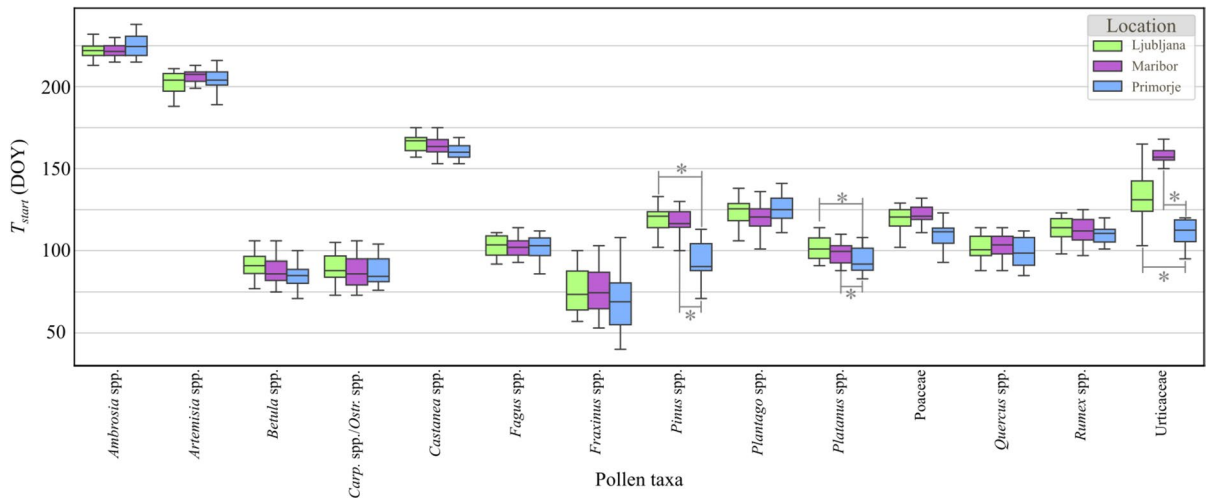


Fig. 3 Comparison of the Start Time (T_{start} , Day of Year) for the Main Pollen Season (MPS) across different pollen taxa and three monitoring locations (Ljubljana, Maribor, and Primorje). Each box represents the interquartile range (IQR), the central

line indicates the median duration, and whiskers extend to the full range of observed values (2002–2024). Variations in box height reflect the inter-annual variability of the T_{start} for each specific taxon at each location

variability and median onset dates for the 14 analyzed taxa. The visual comparison reveals distinct regional clustering, primarily separating the coastal site (Primorje) from the continental interior (Ljubljana and Maribor).

The Primorje region exhibited a significantly earlier onset for several taxa, such as *Pinus*, *Platanus*, and *Urticaceae*. Pairwise statistical comparisons using Mann–Whitney U tests confirmed that these regional differences were most pronounced for *Pinus*, *Poaceae*, and *Urticaceae*, where the coastal site consistently preceded the inland stations. This advancement was most significant when comparing the Mediterranean coast to Maribor, which is the most distant and continental station in the network. Conversely, late-summer taxa like *Ambrosia* and *Artemisia* showed minimal regional variation in onset.

Statistically significant temporal trends in T_{start} (summarized in Table 2) reveal a general nationwide tendency toward advancement. In Ljubljana, the most substantial advancement was recorded for *Urticaceae* (−1.46 days/year). Significant advancements were also observed in Ljubljana for *Carpinus/Ostrya* (−0.62 days/year), *Pinus* (−0.59 days/year), and *Platanus* (−0.53 days/year). The coastal region of Primorje showed even more aggressive advancements for specific arboreal groups, notably *Pinus* (−1.14 days/year), *Quercus* (−0.59 days/year), and

Platanus (−0.72 days/year). In the continental station of Maribor, trends were generally lower, though significant advancements were confirmed for *Fagus* (−0.44 days/year).

The highest standard deviation of T_{start} is observed for *Urticaceae* in Ljubljana (STD=15.9 days) and *Urticaceae* in Primorje (STD=15.2 days).

3.1.2 Season end

Analysis of inter-site variability of season end times, T_{end} , shown in Fig. 4 indicates that the coastal region of Primorje predominantly experiences later season endings for multiple taxa compared to the continental interior. Pairwise statistical comparisons confirmed significant regional differences, particularly for *Poaceae* and *Urticaceae*. Conversely, arboreal taxa such as *Betula* and *Quercus* generally conclude their seasons significantly earlier at continental sites.

Statistically significant trends in the pollen season end time (T_{end}) are summarized in Table 3, highlighting an asymmetric restructuring of the seasonal timeline across different taxa. Arboreal species generally exhibited an earlier termination; significant negative trends were observed for *Carpinus/Ostrya* at all sites, with the most pronounced shift recorded in Ljubljana (−0.76 days/year). Similarly, *Platanus* showed a significant advancement of the season end

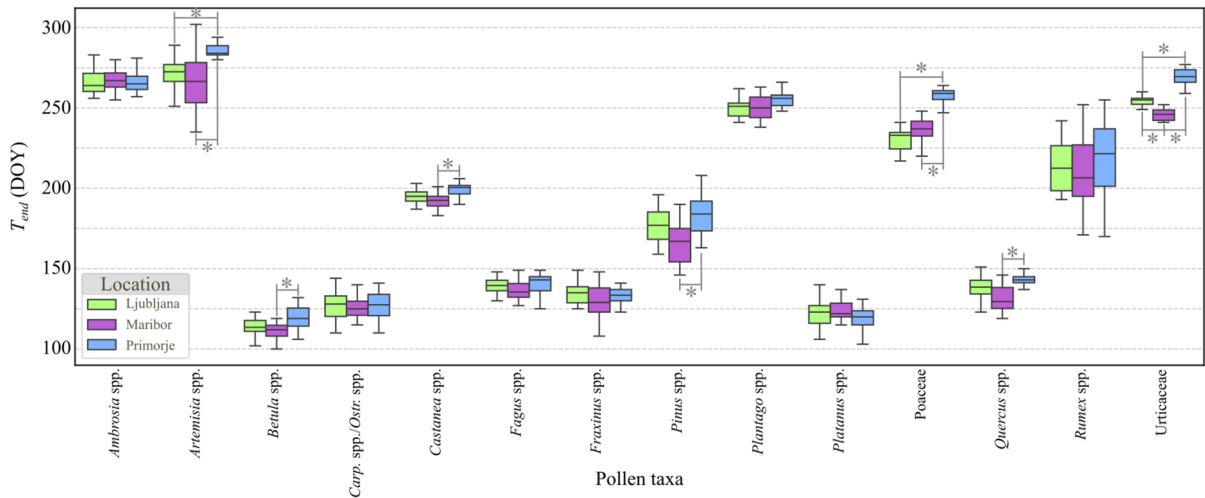


Fig. 4 Comparison of the Pollen Season End Time (T_{end} , Day of Year) across different pollen taxa and three monitoring locations (Ljubljana, Maribor, and Primorje). Boxplots illustrate inter-annual variability and median termination dates. The

central line indicates the median termination day, and whiskers represent the full range of observed values. Variations in box height reflect the inter-annual variability of T_{end} for each specific taxon at each location

Table 3 Statistically significant trends for ends of MPS (T_{end}). Values represent the temporal shifts in the Day of the Year (DOY) when the MPS concludes for specific taxa across the three monitoring sites (2002–2024). Trend denotes the change in days per year (D/Y), where negative values indicate an ear-

lier season termination and positive values indicate a delay. STD (DOY) is the standard deviation of observed end dates, and R^2 is the coefficient of determination. Min, Avg, and Max provide the earliest, average, and latest Day of the Year recorded for T_{end} during the observation period

Location	Pollen taxon	Trend (D/Y)	p -value	STD (days)	R^2	Min (DOY)	Avg (DOY)	Max (DOY)
Maribor	<i>Artemisia</i> spp.	1.60	0.002	17.4	0.39	235	266	302
Ljubljana	<i>Artemisia</i> spp.	0.75	0.012	9.6	0.28	251	272	289
Ljubljana	<i>Carp. spp./Ostr. spp.</i>	-0.76	0.002	8.5	0.38	110	128	144
Primorje	<i>Carp. spp./Ostr. spp.</i>	-0.68	0.006	8.1	0.32	110	127	141
Maribor	<i>Carp. spp./Ostr. spp.</i>	-0.49	0.021	6.9	0.24	106	125	140
Ljubljana	<i>Platanus</i> spp.	-0.71	0.014	9.3	0.27	106	123	140
Maribor	Poaceae	0.84	0.001	8.5	0.44	215	236	248
Primorje	Poaceae	0.53	0.025	7.5	0.23	246	259	284
Ljubljana	Poaceae	0.54	0.033	8.1	0.21	208	230	241

in both Ljubljana (-0.71 days/year) and Maribor (-0.37 days/year).

In contrast, herbaceous taxa demonstrated significant positive trends, indicating a clear delay in season termination. *Artemisia* exhibited a delayed end in Maribor (+1.60 days/year) and Ljubljana (+0.75 days/year). Poaceae followed a similar pattern, showing a synchronized nationwide delay in the end of the season, ranging from +0.53 days/year in Primorje to +0.84 days/year in Maribor. Furthermore, the standard deviation for T_{end} was notably high

for *Artemisia* in Maribor (17.4 days), suggesting that late-summer terminations are more sensitive to inter-annual climatic variability than the cessation periods of spring-flowering taxa.

3.1.3 Season duration

The duration of the main pollen season (MPS), defined as the interval between T_{start} and T_{end} , exhibited significant regional variability and taxa-specific temporal shifts across Slovenia. As illustrated in

Fig. 5, the coastal region of Primorje consistently recorded the longest pollen seasons for most taxa, reflecting the maritime influence that typically delays autumn dormancy in trees. In contrast, the continental interior of Ljubljana and Maribor generally showed shorter, more compressed seasons. Pairwise statistical comparisons highlighted significant regional differences, particularly for Poaceae, Urticaceae, and

Pinus, where durations in Primorje were markedly extended compared to continental sites.

Statistical parameters of the observed temporal trends for taxa exhibiting significant shifts in season duration are summarized in Table 4. The analysis reveals a robust nationwide trend toward the extension of the pollen season for herbaceous species. A consistent increase in duration (ΔT) was

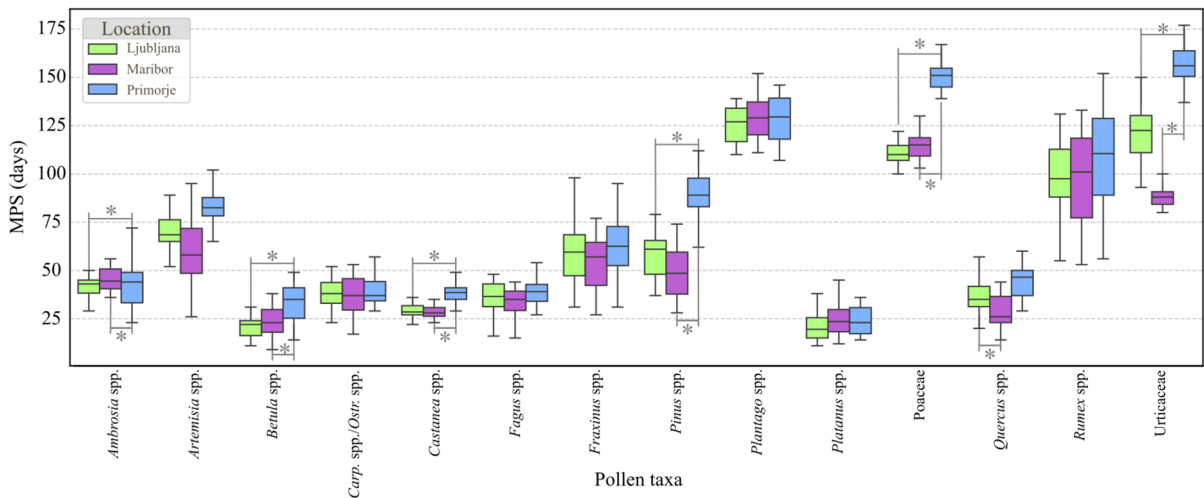


Fig. 5 Inter-site Comparison of Mean Pollen Season Duration (Duration in Days) across different pollen taxa and three monitoring locations (Ljubljana, Maribor, and Primorje). Each box represents the interquartile range (IQR), the central

line indicates the median duration, and whiskers extend to the full range of observed values (2002–2024). Variations in box height reflect the inter-annual variability of the MPS duration for each specific taxon at each location

Table 4 Trends in pollen season timing (T_{start} , T_{end}) and duration (ΔT) for taxa exhibiting significant shifts in season duration. Values represent the annual change expressed in days per year (D/Y) for the onset, termination, and total duration of the pollen season across the three monitoring sites (2002–2024). Location identifies the monitoring station, and Pollen taxa indicates the specific group exhibiting a significant trend in

duration. Negative trend values signify an earlier occurrence (for timing) or a shortening (for duration), while positive values signify a delay or an extension. P -values are provided for each parameter, with the table filtered to include only those taxa where the trend in season duration (ΔT) reached a significance level

Location	Pollen taxa	T_{start}		T_{end}		ΔT	
		Trend	p - value	Trend	p - value	Trend	p - value
Ljubljana	<i>Artemisia</i> spp.	0.12	0.564	0.75	0.012	0.63	0.042
Maribor	<i>Artemisia</i> spp.	-0.01	0.945	1.60	0.002	1.61	0.001
Ljubljana	Poaceae	-0.31	0.190	0.54	0.033	0.85	0.013
Maribor	Poaceae	-0.31	0.152	0.84	0.001	1.15	0.001
Primorje	Poaceae	-0.13	0.611	0.53	0.025	0.65	0.009
Primorje	<i>Quercus</i> spp.	-0.59	0.032	0.09	0.542	0.67	0.011
Ljubljana	Urticaceae	-1.46	0.002	0.05	0.694	1.52	0.002
Maribor	Urticaceae	-0.29	0.040	0.11	0.369	0.40	0.012
Primorje	Urticaceae	-1.01	0.036	0.14	0.519	1.15	0.042

observed for Poaceae across all monitoring sites, with significant trends ranging from +0.65 days/year in Primorje to +1.15 days/year in Maribor. Similarly, Urticaceae exhibited a substantial extension, most notably in Ljubljana (+1.52 days/year) and Primorje (+1.15 days/year). *Artemisia* also showed a significant prolongation of its season, particularly in Maribor, where the duration increased by 1.61 days/year. Among arboreal taxa, *Quercus* in Primorje was the only group to demonstrate a significant extension in duration (+0.67 days/year), a shift primarily driven by an advanced season onset.

This suggests an overall prolongation of the summer pollen exposure period. These patterns highlight the asymmetric response of pollen-season dynamics to climatic forcing, where the onset advances faster than the end retreats, leading to a complex restructuring of the seasonal timeline. Overall, the combined evidence suggests that Slovenian pollen seasons are gradually advancing (earlier start) and are either undergoing compression for arboreal taxa or lengthening for herbaceous taxa.

3.2 Trends in annual pollen integral (API_n)

Trends in the Annual Pollen Integral (API_n), which serves as a critical measure of overall seasonal severity, are summarized in Table 5. Across the 23-year observation period, the majority of analyzed taxa exhibited positive temporal trends, indicating a general increase in airborne pollen loads throughout Slovenia. This pattern was particularly pronounced for herbaceous species, which showed the strongest and most statistically significant increase nationwide. Urticaceae exhibited highly significant rising trends across all monitoring sites, with the most substantial growth recorded in Maribor (+187.7 pollen grains · day · m⁻³ · year⁻¹) and Primorje (+186.2 pollen grains · day · m⁻³ · year⁻¹). Similarly, Poaceae showed a robust increase at all locations, with the highest magnitude observed in Maribor (+93.4 pollen grains · day · m⁻³ · year⁻¹), followed by Ljubljana and Primorje. *Plantago* also displayed consistent significant increases across the country.

Regional specificity was observed among arboreal and herbaceous taxa. In Primorje, *Quercus* (+140.2 pollen grains · day · m⁻³ · year⁻¹) and *Ambrosia* (+24.3 pollen grains · day · m⁻³ · year⁻¹) exhibited significant upward trends, whereas *Platanus* showed

Table 5 Long-term trends in Annual Pollen Integral (API_n). Values represent the trend in the total measured annual pollen levels for specific all used taxa across the three monitoring sites (2002–2024). Trend is expressed in pollen rains · day · m⁻³ · year⁻¹ where positive values indicate an increase in the total seasonal pollen load and nega-

tive values signify a decrease. *P*-values indicate the statistical significance of linear regression; values below 0.05 represent statistically significant trends. *R*² provides the coefficient of determination, denoting the proportion of variance in API_n explained by the temporal trend

Pollen taxa	Ljubljana			Maribor			Primorje		
	Trend	<i>P</i> - value	<i>R</i> ²	Trend	<i>P</i> - value	<i>R</i> ²	Trend	<i>P</i> - value	<i>R</i> ²
<i>Ambrosia</i> spp.	-0.5	0.957	0.00	13.006	0.137	0.11	24.3	0.022	0.24
<i>Artemisia</i> spp.	-10.8	0.000	0.54	-14.594	0.000	0.52	-1.4	0.157	0.10
<i>Betula</i> spp.	109.7	0.103	0.13	22.479	0.782	0.00	6.7	0.179	0.09
<i>Carp. spp./Ostr. spp.</i>	109.7	0.481	0.03	63.633	0.530	0.02	287.7	0.138	0.11
<i>Castanea</i> sp.	-17.9	0.494	0.02	-25.214	0.361	0.04	-10.1	0.312	0.05
<i>Fagus</i> spp.	40.9	0.389	0.04	70.021	0.317	0.05	11.3	0.414	0.03
<i>Pinus</i> spp.	24.8	0.339	0.05	66.359	0.175	0.09	97.7	0.085	0.14
<i>Plantago</i> spp.	21.9	0.002	0.40	29.111	0.000	0.48	17.8	0.001	0.42
<i>Platanus</i> spp.	74.0	0.024	0.23	10.659	0.279	0.06	-20.4	0.003	0.37
Poaceae	64.4	0.008	0.30	93.374	0.000	0.48	60.4	0.003	0.37
<i>Quercus</i> spp.	39.6	0.269	0.06	88.548	0.107	0.12	140.2	0.003	0.36
<i>Rumex</i> spp.	-4.8	0.001	0.45	-2.403	0.026	0.22	-0.5	0.499	0.02
Urticaceae	112.0	0.001	0.46	187.684	0.000	0.49	186.2	0.000	0.55

a significant decrease specifically in the coastal region (-20.4 pollen grains \cdot day \cdot m $^{-3}$ \cdot year $^{-1}$) despite an increase in Ljubljana ($+74.0$ pollen grains \cdot day \cdot m $^{-3}$ \cdot year $^{-1}$). While the majority of taxa showed increasing intensity, *Artemisia* and *Rumex* exhibited significant declines in continental regions. The decrease in *Artemisia* was notably strong in both Ljubljana (-10.8 pollen grains \cdot day \cdot m $^{-3}$ \cdot year $^{-1}$) and Maribor (-14.6 pollen grains \cdot day \cdot m $^{-3}$ \cdot year $^{-1}$), with the temporal trend explaining over 50% of the variance in these locations. These findings suggest that while climate-driven warming generally favors higher APIn, localized environmental factors and management strategies contribute to divergent regional intensity patterns.

3.3 Inter-regional synchrony of pollen seasons

To examine the spatial coherence of airborne pollen variability across Slovenia, pairwise Pearson correlation coefficients (r) were calculated between synchronized daily time series of pollen concentrations at the three monitoring sites: Ljubljana, Maribor, and Primorje. These correlations quantify the inter-regional synchrony of temporal fluctuations, indicating how closely day-to-day variations in collected pollen levels align across the sites. High correlations indicate synchronized responses to broad climatic forcing, while lower correlations highlight the dominance of local environmental factors, distinct regional vegetation, or topographical barriers. Results are presented in Fig. 6.

The analysis revealed a distinct geographical structure of higher temporal coherency, with the two continental sites, Ljubljana and Maribor, exhibiting the highest degree of spatial coupling with an average correlation of $r = 0.72$. This high level of synchrony suggests that intraseasonal variations in pollen concentrations occur almost simultaneously under shared continental climatic forcing.

The resulting correlation matrices, visualized in Fig. 6, illustrate that while daily pollen dynamics are largely synchronized at a national scale, they remain regionally modulated by distinct climatic gradients and vegetation structures. In contrast to the continental interior, correlations involving the coastal Primorje station were consistently weaker, averaging $r = 0.58$ with Ljubljana and $r = 0.49$ with Maribor.

This partial decoupling reflects the buffering influence of the moderate Mediterranean climate, and distinct regional vegetation composition. Taxon-specific results showed that Poaceae demonstrated the highest nationwide coherence ($r \geq 0.73$ for all site pairs), indicating a uniform response to regional-scale meteorological drivers. Other taxa, such as *Artemisia* and *Ambrosia*, also showed strong synchrony between continental sites, with coefficients of $r = 0.80$ and $r = 0.79$, respectively. Conversely, taxa like *Fraxinus* and *Platanus* exhibited much lower coherence between coastal and inland stations ($r \leq 0.33$), highlighting their localized distribution and microclimatic dependence. The complete dataset of inter-regional correlation coefficients is presented in Table S2 in the Supplementary Material file.

In summary, the inter-regional correlations (r) represent the degree of day-to-day synchrony in pollen concentrations across Slovenia. High correlations between Ljubljana and Maribor confirm strong continental coherence, whereas the weaker association with Primorje demonstrates the buffering influence of the coastal Mediterranean climate. This pattern indicates that Slovenia's daily pollen dynamics are largely synchronized at the national scale, but are regionally modulated by climatic gradients, vegetation structure, and phenological timing.

4 Discussion

This study provides the first comprehensive analysis of long-term pollen season dynamics in Slovenia, revealing significant temporal shifts that vary by taxon, seasonal timing, and geographic region. Over the 23-year period (2002–2024), we observed an advancement in season onset across most taxa, alongside complex and often opposing trends in season termination. While arboreal species showed earlier season endings—resulting in compressed but intensified pollen periods—herbaceous taxa exhibited delayed termination and substantial increases in annual pollen load. These changes in seasonal descriptors coincide with a warming trend and changes in the precipitation regime of the studied area (Figure S2; Slovenian Environment Agency [ARSO], 2022). Notably, the coastal Mediterranean site (Primorje) consistently exhibited earlier onset,

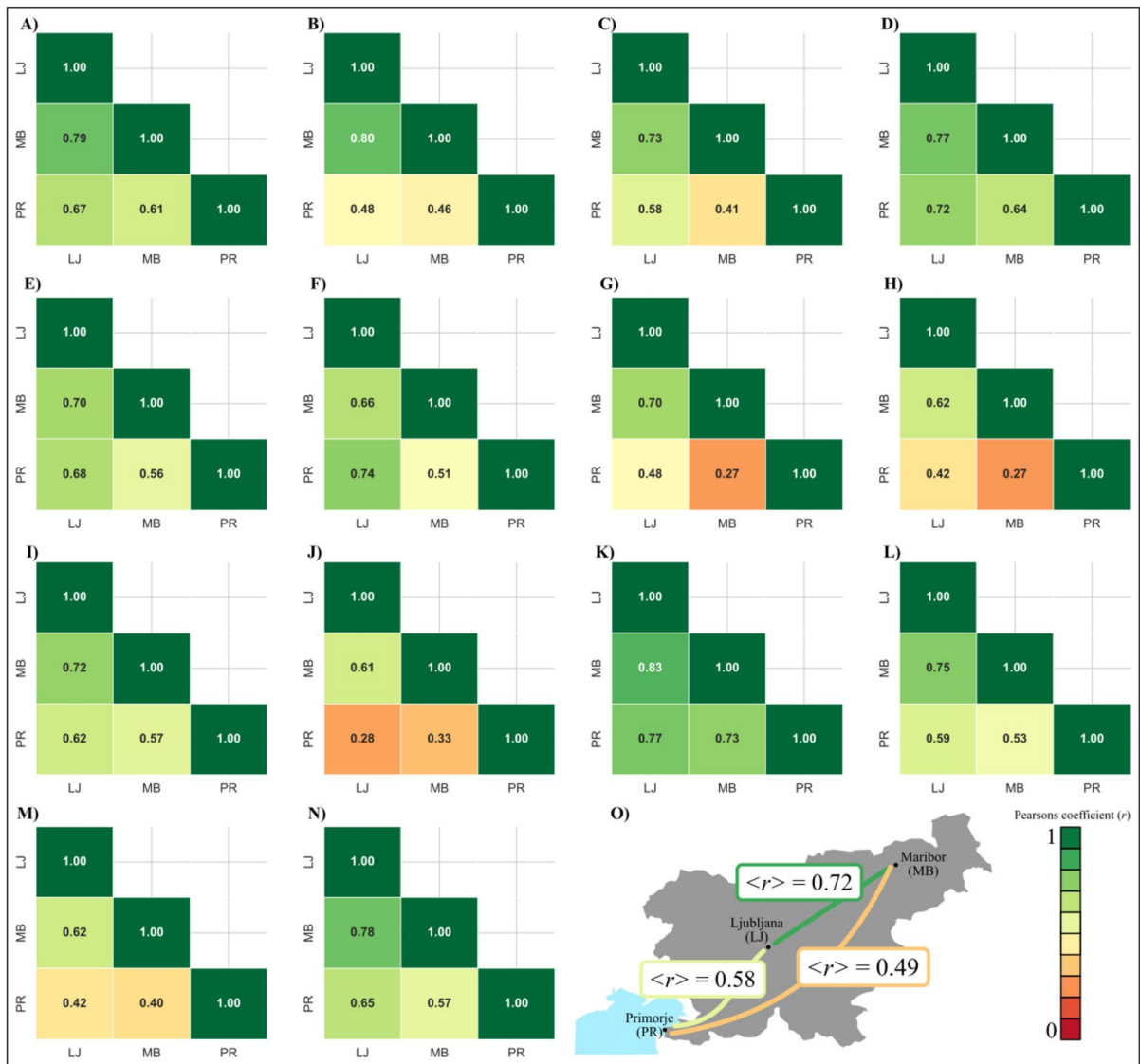


Fig. 6 Inter-site correlation of daily pollen concentrations for 14 observed taxa. Panels A–N display heatmaps of Pearson’s correlation coefficients (r) between the monitoring sites of Ljubljana (LJ), Maribor (MB), and Primorje (PR) for: **A** *Ambrosia* spp., **B** *Artemisia* spp., **C** *Betula* spp., **D** *Carpinus* spp./*Ostrya* spp., **E** *Castanea* spp., **F** *Fagus* spp., **G** *Fraxi-*

nus spp., **H** *Pinus* spp., **I** *Plantago* spp., **J** *Platanus* spp., **K** Poaceae, **L** *Quercus* spp., **M** *Rumex* spp., and **N** *Urticaceae*. Color intensity represents the strength of the correlation, ranging from 0 (red) to 1 (dark green). Panel **O** provides a geographical overview of the monitoring stations within Slovenia with average pairwise correlation values between sites

later termination, and longer overall seasons compared to continental stations, underscoring the role of regional climatic gradients in modulating pollen dynamics across relatively small spatial scales (Cristofolini et al., 2020; Rojo et al., 2021).

4.1 Pollen season onset

Across Slovenia, a tendency toward earlier pollen season onset was observed for most taxa, as previously reported by numerous European studies (Adams-Groom et al., 2022; Cristofolini et al.,

2020; Glick et al., 2021; Hoebeke et al., 2018; Rojo et al., 2021). The highest number of statistically significant trends was identified in Ljubljana and the Primorje region, whereas only a few were observed in Maribor. In Ljubljana and Primorje, an earlier season start is evident for most arboreal taxa, while among herbaceous plants, the strongest advancement was observed in the family Urticaceae. The observed onset trend may be associated with a warming trend in mean daily winter temperatures (December–February) over the study period (“Slovenian Environment Agency [ARSO]” 2026). Differences between the two continental monitoring sites may be attributed to the heat island effect, which is generally more pronounced in Ljubljana, (Komac et al., 2016), possibly contributing to earlier flowering of plants in urban areas (Jochner & Menzel, 2015). In Maribor, the effect is also present, but it is less studied and generally weaker (Žiberna, 2006).

4.2 Pollen season termination

Seasonal end dates were characterized by more complex patterns than seasonal onsets. Pollen seasons of *Carpinus/Ostrya* tended to end earlier, whereas for *Platanus* this tendency was present only at continental sites. This may be related to temperature changes, as a Swiss study has shown that higher temperatures during the flowering period of arboreal taxa can accelerate the end of pollen season (Gehrig & Clot, 2021). In contrast, herbaceous taxa generally exhibited later end dates, particularly the Poaceae family, which showed consistently delayed termination, that may be related to the high species diversity within the family, which can lead to asynchronous flowering and species-specific responses to climatic drivers, potentially contributing to a more prolonged seasonal tail (Lind et al., 2016; Rojo et al., 2021). A later end date for *Artemisia* was observed only in continental areas, potentially driven by the presence of invasive species within the genus (Kaligarič & Bakan, 2018; Strgulc Krajšek et al., 2016), which flower later than native taxa. A similar observation regarding the later end of the *Artemisia* season has also been reported in neighboring countries (Bastl et al., 2025; Cristofori et al., 2020).

4.3 Pollen season duration

Trends in season duration point to differences between herbaceous and arboreal taxa, similar to those observed for pollen season termination. Arboreal species showed heterogeneous and largely non-significant changes in season duration. An exception was *Quercus* in Primorje, where a prolongation of the season occurred. Despite a general tendency toward earlier pollen season onset, this shift did not result in extended pollen seasons in arboreal species, as also reported in previous studies (Gehrig & Clot, 2021; Lind et al., 2016). More uniform trends were found in herbaceous plants, with a lengthening of pollen seasons for Poaceae and Urticaceae and, in continental sites, also for *Artemisia*. Our results are consistent with findings in other European studies (Bogawski et al., 2014; Lind et al., 2016; Makra et al., 2011; Rojo et al., 2021). Of note, later season endings appear to have a greater influence on season lengthening than earlier season starts, as also suggested by Bogawski et al. (2014) in a Polish study on selected herbaceous taxa under conditions of atmospheric warming (Bogawski et al., 2014).

4.4 Annual pollen integral trends

Across the 23-year observation period, positive APIn trends were predominant among taxa, indicative of a general increase in airborne pollen load throughout Slovenia. Overall, trends showed clear differentiation between herbaceous and arboreal taxa. While herbaceous taxa displayed relatively consistent directional trends across study sites, with a higher frequency of statistically significant results, arboreal taxa were more variable in their regional responses.

The increases in APIn observed for certain herbaceous taxa in contrast with trends frequently reported in the literature, where APIn for tree species is typically more pronounced than in herbs and shrubs (Ziello et al., 2012). Our results indicate a significant increase in APIn for Poaceae, Urticaceae, and *Plantago* across all three monitoring sites. Comparable dynamics for Poaceae—a family comprising multiple species (Minero et al., 1998)—have also been documented in recent studies (Mousavi et al., 2024; Tagliaferro et al., 2024), in line with the increasing trends observed for Urticaceae (Gehrig & Clot, 2021; Glick et al., 2021; Makra et al., 2011). A comparable

intensifying pattern has also been described for *Plantago* (Cristofolini et al., 2020).

In contrast, other herbaceous taxa—namely *Artemisia* and *Rumex*—showed declining APIIn trends. Despite the extended *Artemisia* pollen season, our findings indicate that the lower intensity may reflect a diminished summer peak, potentially contributing to lower APIIn. This trend could be attributed to reduced ruderal vegetation driven by urban expansion, managed green spaces, and the spread of concurrent species (Ščevková et al., 2025). Although not directly assessed in our study, precipitation and high temperatures are also known to strongly influence *Artemisia* flowering, as Cariñanos et al. (Cariñanos et al., 2013) associated lower APIIn with extreme drought, whereas higher precipitation in the months preceding flowering had the opposite effect.

In agreement with a broad European study on *Ambrosia* (Sikoparija et al., 2017), no significant trends were observed at Slovenian continental sites. However, our results show an exception in the Primorje region, where an increasing trend was detected. The situation in Primorje may be attributable to its proximity to one of the main *Ambrosia* hotspot regions, the Po Plain, where this highly invasive species is widely distributed (Bonini et al., 2026).

Arboreal taxa tended to show positive trends, although these were largely non-significant. Significant increases in APIIn were found for *Quercus* in Primorje, while trends for *Platanus* differed, increasing in Ljubljana and decreasing in Primorje (de Weger et al., 2021; Gehrig & Clot, 2021; Hoebeke et al., 2018; Ziello et al., 2012). For common Slovenian forest tree species (Ogrin et al., 2023), including *Betula*, *Fagus*, *Pinus*, *Fraxinus*, and *Carpinus/Ostrya*, a slight increase in APIIn is indicated, although all calculations are non-significant.

4.5 Regional patterns and inter-site synchrony

Analysis of inter-site temporal correlations revealed the highest synchrony between the two continental sites, Ljubljana and Maribor, whereas correlations with the coastal Primorje site were consistently weaker. Despite the observed variability, *Poaceae* demonstrated the highest level of nationwide coherence.

The largest regional differences were observed in the timing of season onset and termination, whereas

trends in season intensity showed no major regional differentiation. Differences in pollen season descriptors between the Mediterranean and inland regions were observed for *Urticaceae* and *Poaceae*, which show an earlier start and a later end of the pollen season along the coast. Among arboreal taxa, *Pinus* exhibited an earlier season onset in the coastal region, whereas *Quercus* showed a later season termination compared to continental sites. These differences are primarily driven by the moderate Mediterranean climate, which facilitates the growth of thermophilic native and planted species (Ogrin et al., 2023). In contrast, a study from a neighboring region in Italy (Cristofolini et al., 2020) did not detect clear patterns in pollen-season trends across biogeographic areas.

4.6 Study limitations

This study provides the first comprehensive assessment of long-term pollen trends in Slovenia, but several limitations warrant consideration. First, the analysis is based on data from only three monitoring stations. A denser aerobiological network would provide greater spatial resolution and better characterize localized patterns across Slovenia's diverse phytogeographic regions. Second, although we identified clear temporal trends, the current analysis did not quantitatively integrate meteorological drivers (e.g., temperature, precipitation, humidity) that mechanistically underlie these seasonal pollen shifts. Third, taxonomic resolution is inherently constrained by morphological identification limits of the Hirst method—several of our taxa represent families or genera rather than individual species (e.g., *Poaceae*), potentially masking species-specific responses within these groups. Finally, systematic data gaps necessitated the exclusion of months in the cold part of the year (January, November, December), due to which early flowering taxa (*Corylus*, *Alnus*, *Cupressaceae*/*Taxaceae*) were not included in the study.

4.7 Future research directions

The findings presented here open several promising avenues for aerobiological research in Slovenia. First, the robust, quantified trends documented in this study provide an ideal foundation

for developing mechanistic predictive models that explicitly incorporate meteorological variables (temperature, precipitation, growing degree days) to predict pollen seasons with greater accuracy. Such models would be invaluable for clinical preparedness and public health interventions. Second, integrating these aerobiological findings with air quality measurements (particulate matter, nitrogen dioxide, ozone) and clinical data from Slovenian health institutions represent a critical next step to directly quantify the public health impact of changing pollen seasons and to assess the synergistic effects of pollen exposure and air pollution on allergic disease burden. Third, expanding the monitoring network to include additional urban sites across Slovenia's distinct biogeographic regions would enhance spatial resolution and enable more nuanced regional comparisons. Fourth, insights into the spectrum and dynamics of airborne allergens at the investigated monitoring sites provide a valuable basis for the selection and placement of automatic monitoring stations, which would enable public access to near-real-time pollen exposure data. Finally, investigating the physiological, genetic, and plastic responses of local plant populations could provide mechanistic insights into the drivers of the observed seasonal shifts and improve our ability to predict future trajectories under continued climate change.

5 Conclusion

In conclusion, this 23-year analysis reveals that Slovenian pollen seasons are undergoing significant restructuring, characterized by earlier onset for most taxa, divergent termination patterns between arboreal and herbaceous species, and substantial increases in allergenic pollen load—particularly for Poaceae and Urticaceae. The pronounced regional differentiation between coastal Mediterranean and continental sites underscores the importance of local climatic and ecological factors in modulating climate-driven seasonal shifts. These findings provide a comprehensive baseline for understanding aeroallergen dynamics in a climatically transitional region and offer valuable insights for the future integration of aerobiological data with broader environmental and clinical surveillance frameworks.

6 Author contributions

All authors contributed to the study conception and design. Material preparation and data collection were performed by Anja Simčič, Andreja Kofol Seliger, Urška Razboršek, and Uroš Lešnik. Data analysis was conducted by Rene Markovič. The initial draft of the manuscript was written by Rene Markovič, and all authors revised and commented on subsequent versions. All authors read and approved of the final manuscript.

Author contribution All authors contributed to the study conception and design. Material preparation and data collection were performed by A.S., A.K.S., U.R., and U.L.. Data analysis was conducted by R.M.. The initial draft of the manuscript was written by R.M., and all authors revised and commented on subsequent versions. All authors read and approved of the final manuscript.

Funding This work was supported by the Slovenian Research and Innovation Agency (ARIS) through research project V1-2566, research program P1-0055, and infrastructure program I0-0029.

Data availability Dataset generated during the current study is available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

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