Urban Ecosystems (2026) 29:141
https://doi.org/10.1007/s11252-026-02001-8

RESEARCH

Effects of land use on aeroecological patterns in a semiarid ecotone: a comparative analysis of urban and agricultural landscapes

Adem Bicakci[1] · **Semih Bekil**[1] · **Hasan Akgul**[2] · **Aycan Tosunoglu**[1]

Received: 7 November 2025 / Accepted: 28 April 2026
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Abstract
Land-use change is a critical driver reshaping aeroecological patterns in semiarid ecotones worldwide. Understanding these dynamics is essential as global biodiversity loss projections suggest that Mediterranean ecosystems are increasingly vulnerable. This study comparatively analyses the aeroecological signatures of two contrasting land-use models (urban and agricultural) within a semiarid ecotone in Southeastern Türkiye. We propose the "Aeroecological Paradox" as a conceptual framework to describe the structural divergence between these landscape types. Atmospheric pollen data from Gaziantep (2010–2011; urban) and Kilis (2018–2019; agricultural) were analysed using a space-for-time substitution approach to assess land-use effects within comparable ecological settings. Moving from the urban landscape (Gaziantep) to the agricultural landscape (Kilis), total pollen load decreased by 76%, while taxonomic diversity increased. Urban *Platanus* dominance was replaced by agricultural *Olea europaea* dominance. Key herbaceous taxa in agricultural areas exhibited longer pollen seasons (e.g., Gramineae) compared to the urban site. High-intensity peak days became less frequent, indicating a contrast in the exposure regime. Land use shapes distinct pollen dynamics, generating a "high-load, short-season" regime in urban landscapes and a "low-load, long-season, high-diversity" regime in agricultural landscapes. These findings suggest that ecological monitoring and urban–regional planning strategies in drylands should consider long-term landscape structure and land-use patterns, rather than focusing solely on short-term pollen peaks.

Keywords Aeroecological paradox · Airborne pollen · Phenology · Taxonomic diversity · Anthropogenic impact · Aerobiology

Introduction

Land-use change is widely recognized as one of the major drivers of global environmental change and is considered one of the nine planetary boundaries influencing Earth system stability (Rockström et al. 2009; Steffen et al. 2015). Changes in land use alter ecosystem structure, biodiversity patterns, and atmospheric biological particles, including airborne pollen. These changes are particularly important in Mediterranean-type ecosystems, which are globally recognized biodiversity hotspots. Although Mediterranean-type climate (MTC) regions occupy only about 2.2% of the Earth's surface, they harbor approximately one-sixth of the world's vascular plant species (Rundel 2018; Ziska et al. 2019). However, these ecosystems are increasingly vulnerable due to urbanization, agricultural intensification, climate change, and biological invasions. Projections suggest that the Mediterranean biome may experience the highest proportional biodiversity loss by the end of the twenty-first century (Sala et al. 2000).

Land-use and climate change jointly influence plant phenology, pollen production, and atmospheric transport processes (IPCC 2021). These interactions shape aeroecological patterns such as changes in pollen load, divergences

✉ Adem Bicakci
abicakci@uludag.edu.tr

Semih Bekil
bekilsemih@gmail.com

Hasan Akgul
hakgul@akdeniz.edu.tr

Aycan Tosunoglu
aycanbilisik@uludag.edu.tr

[1] Department of Biology, Faculty of Arts and Sciences, Bursa Uludağ University, Görükle Campus, Nilüfer, Bursa, Türkiye

[2] Department of Biology, Faculty Sciences, Akdeniz University, Antalya, Türkiye

Published online: 07 May 2026

in taxonomic composition, and alterations in pollen season duration (Hamaoui-Laguel et al. 2015; Ziska et al. 2019). Across Europe, long-term aerobiological studies generally report increasing pollen loads and longer pollen seasons associated with climate warming and vegetation changes (Lake et al. 2017). However, these broad trends are not universal. Regional ecological conditions, landscape structure, and atmospheric circulation may generate local aeroecological dynamics that diverge from continental patterns (García-Mozo et al. 2016).

Semiarid transition zones (ecotones) are particularly suitable for investigating such dynamics because they represent sensitive interfaces between contrasting ecological systems. These regions often function as "natural laboratories" where the interactions between vegetation structure, land use, and climate variability become especially evident (Rundel 2018; López-Orozco et al. 2023). Within these environments, relatively small changes in land management or vegetation composition can lead to significant changes in atmospheric pollen composition and seasonal dynamics.

The Southeastern Anatolia Region of Türkiye represents one such semiarid ecotone, located at the intersection of the Mediterranean and Irano–Turanian phytogeographic regions (Atalay and Efe 2012). This transitional landscape provides a suitable setting for exploring how contrasting land-use structures may influence aeroecological patterns. Similar processes linking vegetation structure, atmospheric transport, and pollen dynamics have been documented in other semiarid biodiversity regions, including Mediterranean chaparral ecosystems in California and savanna–grassland ecotones in South Africa (Rundel 2018; Neumann et al. 2025). In such systems, airborne pollen assemblages reflect the combined effects of vegetation composition, land management, and atmospheric circulation and can therefore serve as indicators of environmental change (Traidl-Hoffmann et al. 2003).

Despite increasing interest in aeroecology, relatively few studies have explicitly examined how different land-use structures shape airborne pollen dynamics in semiarid ecotones. Understanding these relationships is particularly important for Mediterranean drylands, where rapid landscape transformation and climatic variability may produce complex aeroecological responses.

Accordingly, the aim of this study is to compare the aeroecological signatures of two contrasting land-use systems within a semiarid ecotone in Southeastern Türkiye. In particular, we examine how taxonomic diversity of airborne pollen differs between contrasting land-use systems and how this diversity relates to total pollen load. We further investigate how dominant vegetation types associated with different land uses influence pollen composition and seasonal intensity patterns, and how pollen season duration and overall phenological structure vary between contrasting landscape types. To interpret these patterns, we introduce the concept of the "Aeroecological Paradox," which describes the potential divergence between pollen load, taxonomic diversity, and pollen season duration across different landscape structures.

Materials and methods

Study area and methodological framework

The study area is located in the Southeastern Anatolia Region of Türkiye within a semiarid transition zone situated at the intersection of the Mediterranean and Irano–Turanian phytogeographic regions (Fig. 1). Türkiye's flora reflects the interaction of three main phytogeographic regions—Euro-Siberian, Irano–Turanian, and Mediterranean—which contribute to the country's high botanical diversity (Davis 1965). From an aeropalynological perspective, Türkiye can be divided into five main regions, with Gaziantep and Kilis located within a transitional belt between the southern and eastern aeropalynogeographic zones (Bıçakçı and Tosunoğlu 2019).

The map illustrates the five major aeropalynogeographic regions defined by Bıçakçı and Tosunoğlu (2019) based on Davis's (1965) phytogeographic classification (N: Euro-Siberian; W and S: Mediterranean; E and C: Irano-Turanian); Gaziantep and Kilis are located within the biogeographic ecotone at the transition between the Mediterranean (S) and Irano-Turanian (E) regions; Latitude–longitude grid lines, scale bar, and north arrow are provided for geographic reference.

The region has a transitional Mediterranean–continental climate characterized by hot, dry summers and relatively cool, wet winters (MGM 2026). The landscape structure reflects the ecotonal nature of the area, where Mediterranean maquis vegetation interacts with Irano–Turanian steppe formations. Vegetation includes fragmented *Quercus* woodlands (consisting of taxa such as *Q. brantii*, *Q. infectoria*, and *Q. pubescens*), steppe vegetation, and agricultural areas dominated by olive cultivation and cereal crops (Davis 1982; Atalay and Efe 2012).

Geologically, the region is dominated by limestone and sedimentary formations typical of Southeastern Anatolia (Altinli 1966). Soils are generally calcareous and shallow in steppe areas, while deeper alluvial soils occur in agricultural valleys. Land use patterns include urban settlements, agricultural lands (particularly olive groves and cereal cultivation), and semi-natural steppe vegetation. This heterogeneous landscape structure provides a suitable setting for examining how different land-use configurations influence aeroecological patterns.

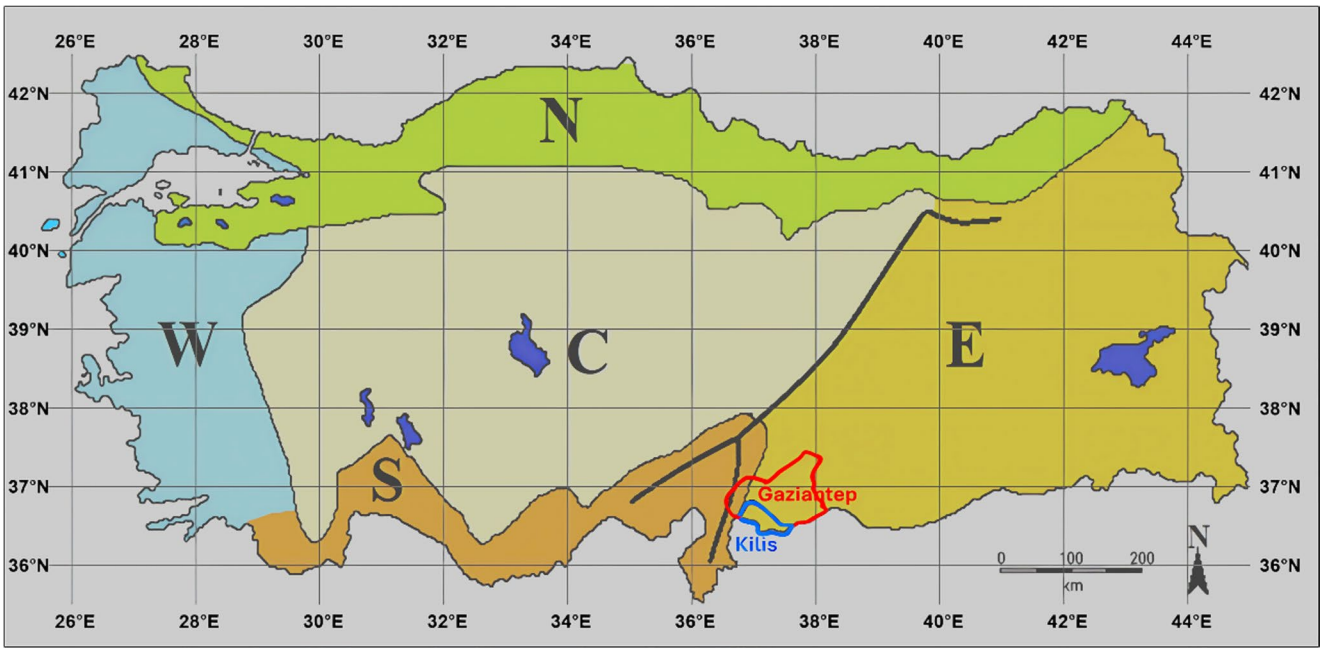


Fig. 1 Geographical location of the study sites in southeastern Türkiye

Space-for-time substitution approach

To evaluate the effects of contrasting land-use structures on airborne pollen dynamics, this study applied a space-for-time substitution approach (Pickett 1989; Blois et al. 2013). This method allows ecological processes to be examined by comparing different locations that share similar environmental conditions but differ in landscape structure.

The two study areas are geographically close and exhibit comparable climatic and topographic conditions (altitude range approximately 680–850 m) within a semiarid steppe environment. Under such comparable environmental settings, differences in airborne pollen assemblages can be interpreted primarily in relation to landscape structure and land use.

However, the space-for-time substitution approach also has methodological limitations. Comparisons between locations may not fully account for local ecological history or interannual climatic variability. Recent studies have also highlighted that space-for-time substitutions can sometimes introduce uncertainties when projecting ecological dynamics across different systems (Kreyling 2025). In this study, the approach is therefore used as a comparative framework to explore potential land-use-related differences in aeroecological patterns rather than to infer strict temporal trends.

Landscape characteristics of the study sites

The two study locations represent contrasting land-use settings within the same semiarid ecotone.

Gaziantep (37°04′N, 37°23′E) represents an urban landscape characterized by high population density (TÜİK 2023) and rapid urban development (EEA 2018). Urban vegetation includes ornamental species widely used in Mediterranean urban landscapes, particularly *Platanus orientalis*, *Cupressus sempervirens*, and several *Pinus* species. These taxa are known to contribute significantly to the atmospheric pollen spectrum of urban environments (Bıçakçı and Tosunoğlu 2019; Cariñanos et al. 2014).

Kilis (36°43′N, 37°07′E) represents a predominantly agricultural landscape with lower population density (TÜİK 2023) and extensive agricultural land use (EEA 2018). Olive groves and cereal cultivation dominate the regional landscape, and *Olea europaea* constitutes one of the principal cultivated tree species (Galán et al. 2014). Semi-natural surrounding areas include steppe vegetation and scattered forest patches dominated by *Pinus brutia* (Atalay and Efe 2012).

The close geographical proximity and broadly similar environmental conditions of these two sites allow a comparative assessment of how different landscape structures influence airborne pollen dynamics.

Pollen sampling and analysis

Atmospheric pollen sampling was conducted using volumetric pollen traps (Lanzoni VPPS 2000 type) following standard aerobiological monitoring protocols. The traps were installed on building rooftops at a height of approximately 12–15 m above ground level in open areas to minimize local

obstruction effects. Sampling procedures followed the recommendations of the International Association for Aerobiology (IAA) (Galán et al. 2014).

Although Gaziantep encompasses a larger administrative area than Kilis, a single volumetric trap installed at the standard monitoring height is considered sufficient to represent the background airborne pollen concentration within an approximate radius of 10–30 km (Galán et al. 2014). Therefore, the sampling effort is regarded as methodologically comparable for evaluating the overall aerobiological profiles of the two landscape cores.

The sampler continuously aspirates air at a flow rate of 10 L min^{-1}, depositing airborne particles onto a Melinex® adhesive tape coated with silicone. Adhesive tapes were replaced weekly, and each seven-day segment was mounted on microscope slides using glycerin gel. Slides were examined under a light microscope and pollen grains were identified to the lowest possible taxonomic level according to standard aerobiological identification criteria (Galán et al. 2007, 2014, 2017). Pollen concentrations were expressed as daily mean pollen concentrations (grains m^{-3}). The monitoring dataset consisted of two complete annual sampling periods at each site, corresponding to 2010–2011 in Gaziantep and 2018–2019 in Kilis.

Pollen season definition and statistical analysis

Meteorological data—including daily mean temperature, total daily precipitation, mean relative humidity, and mean wind speed—were obtained from the Turkish State Meteorological Service (MGM 2020). Pollen taxa contributing more than 3% of the total two-year pollen sum were classified as dominant taxa (Tosunoglu et al. 2018).

For each dominant taxon, the Main Pollen Season (MPS) was defined using the cumulative pollen method, where the start and end of the season correspond to the 2.5th and 97.5th percentiles of the cumulative annual pollen curve (Andersen 1991). Based on these values, a regional pollen calendar was constructed following the methodology of Spieksma (1991).

Relationships between daily pollen concentrations and meteorological variables were evaluated using Spearman's rank correlation analysis in IBM SPSS Statistics 23.0. This non-parametric test was selected because aerobiological datasets frequently deviate from normal distributions (Grewling et al. 2014). For each taxon, the daily pollen concentration was correlated with the meteorological variables recorded on the same day.

To evaluate seasonal intensity structure, an additional metric was applied. For each dominant taxon, days with pollen concentrations exceeding the 90th percentile (P90) of daily values within the MPS were classified as High-Intensity Days (HID). The 90th percentile is widely used in environmental statistics as a robust threshold for identifying extreme or peak events in ecological datasets (Zar 2010). This metric allows comparison of how pollen intensity is distributed within the seasonal period.

Backward air-mass trajectory analysis

To examine potential regional transport of airborne pollen, backward air-mass trajectory analysis was performed using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein et al. 2015). The analysis focused on two representative taxa: *Pinus*, representing regionally distributed forest pollen sources, and *Olea*, representing an important agricultural pollen source with potential for regional atmospheric transport.

For days with the highest recorded pollen concentrations, 48-hour backward trajectories were calculated at three arrival heights (100 m, 500 m, and 1500 m above ground level). The trajectory endpoint was set at 23:00 UTC, corresponding to the end of the 24-hour sampling period. Meteorological input data were obtained from the NOAA Global Data Assimilation System (GDAS) database. Although trajectory models provide valuable insights into potential pollen source regions, uncertainties may arise due to atmospheric variability and particle transport dynamics.

Results

The comparison between the two study sites—an urban landscape (Gaziantep, 2010–2011) and an agricultural landscape (Kilis, 2018–2019)—revealed clear differences in atmospheric pollen characteristics. These differences were observed in four main aspects: total pollen load, species richness, dominant pollen taxa composition, and seasonal phenological patterns. The following sections present the quantitative results of these comparisons.

Comparative analysis of pollen load and species richness

The comparative analysis revealed an inverse pattern between total pollen load and species richness. From the urban landscape (Gaziantep) to the agricultural landscape (Kilis), the total atmospheric pollen load decreased by approximately 76% (Table 1).

Table 1 Comparison of pollen taxon richness and annual total pollen counts recorded in Gaziantep (2010–2011) and Kilis (2018–2019)

Parameter	Gaziantep	Kilis
Number of Arboreal Taxa	26	26
Number of Non-arboreal Taxa	21	26
Total Number of Taxa	**47**	**52**
Total Pollen Count	**58,241**	**13,912**

Table 2 Proportional Distribution (%) of Dominant Airborne Pollen Taxa in Gaziantep (2010–2011) and Kilis (2018–2019)

Gaziantep (2010–2011)	%	Kilis (2018–2019)	%
Cupressaceae	47.97	Cupressaceae	35.31
Quercus	10.18	*Olea*	15.45
Pinus	10.01	Gramineae	10.15
Morus	6.50	*Pinus*	7.43
Gramineae	5.56	*Quercus*	7.00
Platanus	4.45	*Morus*	3.86
Olea	2.03	Chenopodiaceae/Amaranthaceae	3.66
		Urticaceae	3.46

Despite this reduction, the total number of identified taxa increased slightly from 47 to 52 taxa (the complete list of all identified taxa and their annual total counts is provided in Online Resource 1, Table S1). This increase was mainly associated with a rise in herbaceous taxa (from 21 to 26 taxa), while the number of arboreal taxa remained constant (26 taxa).

The increased representation of herbaceous pollen types was particularly evident in groups such as Compositae, Gramineae, and Chenopodiaceae/Amaranthaceae.

Land-use differences in dominant taxa composition

Dominant taxa were defined as those contributing at least 3% of the total annual pollen count in either location. The dominant taxa for both sites are summarized in Table 2; Fig. 2.

In the urban landscape (Gaziantep), the atmospheric pollen spectrum was dominated by Cupressaceae (47.97%),

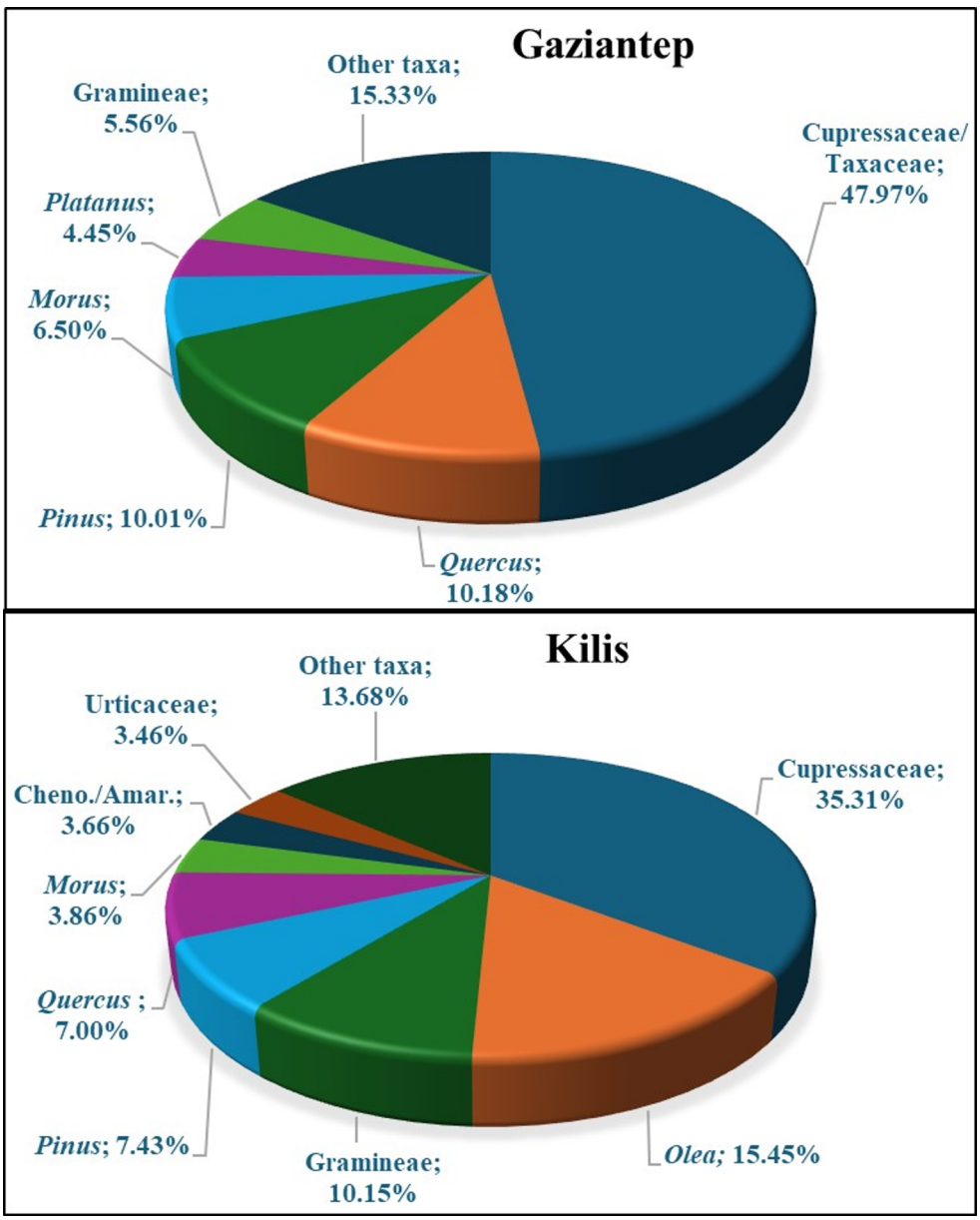


Fig. 2 Structural differences of the aeroecological landscape driven by urban and agricultural land use. While the atmosphere of the urban landscape (Gaziantep, 2010–2011) was dominated by urban taxa such as *Platanus*, the agricultural landscape (Kilis, 2018–2019) showed dominance of agricultural taxa such as *Olea europaea*, highlighting the impact of contrasting land-use structures on airborne pollen composition

followed by *Quercus* (10.18%), *Pinus* (10.01%), *Morus* (6.50%), Gramineae (5.56%), and *Platanus* (4.45%).

In the agricultural landscape (Kilis), the relative contribution of Cupressaceae decreased from 47.97% to 35.31%. In contrast, *Olea europaea* increased from 2.03% to 15.45%, becoming the second most abundant pollen taxon. Other dominant taxa in Kilis included Gramineae (10.15%), *Pinus* (7.43%), *Quercus* (7.00%), *Morus* (3.86%), Chenopodiaceae/Amaranthaceae (3.66%), and Urticaceae (3.46%).

Contrasting phenological rhythms and season structures

Land-use differences were also reflected in the temporal structure of pollen seasons. Monthly pollen curves (Fig. 3) show that the pronounced spring peak observed in the urban landscape (Gaziantep) corresponded to a lower and later seasonal peak in the agricultural landscape (Kilis), largely associated with *Olea europaea*. In addition, a distinct autumnal pollen activity was observed only in the urban site (Fig. 4). The seasonal characteristics of the dominant taxa are presented in Fig. 5; Table 3.

Comparative pollen calendars indicate that several dominant arboreal taxa, including *Quercus*, *Pinus*, and *Morus*, exhibited broadly similar spring flowering periods in both locations. However, noticeable differences in season duration were observed for several herbaceous taxa. The pollen season of Gramineae was longer in the agricultural landscape (Kilis, 208–225 days) than in the urban landscape (Gaziantep, 167–190 days). Similarly, herbaceous taxa such as Chenopodiaceae/Amaranthaceae and Urticaceae showed extended pollen presence in Kilis, with pollen occurrence continuing into late summer and autumn. These taxa contributed 3.66% and 3.46% of the total pollen load, respectively, with season durations exceeding 160 days.

Relationships between pollen concentration and meteorological variables

Relationships between daily mean pollen concentrations and meteorological variables were evaluated using Spearman's rank correlation. The correlation coefficients are provided in Online Resource 1 (Table S2). The analyses revealed differences in the strength and direction of pollen–climate relationships between the two study sites.

Gaziantep (2010–2011)

In the urban landscape (Gaziantep), temperature showed positive correlations with *Quercus* ($p<0.01$) and Gramineae ($p<0.01$ and $p<0.05$). Negative relationships with temperature were observed for Cupressaceae ($p<0.01$) and *Pinus* ($p<0.01$). Wind speed was positively correlated with Cupressaceae ($p<0.01$) and Gramineae ($p<0.01$). Relative humidity showed positive correlations with Cupressaceae ($p<0.01$) and *Pinus* ($p<0.01$). Precipitation showed a significant negative correlation only with Cupressaceae ($p<0.05$). No statistically significant correlations were detected for *Platanus* or *Morus*.

Kilis (2018–2019)

In the agricultural landscape (Kilis), pollen–climate relationships showed a more heterogeneous pattern. Precipitation was negatively correlated with Cupressaceae ($p<0.01$ in 2018), *Quercus* ($p<0.01$ in 2019), *Morus* ($p<0.05$ in

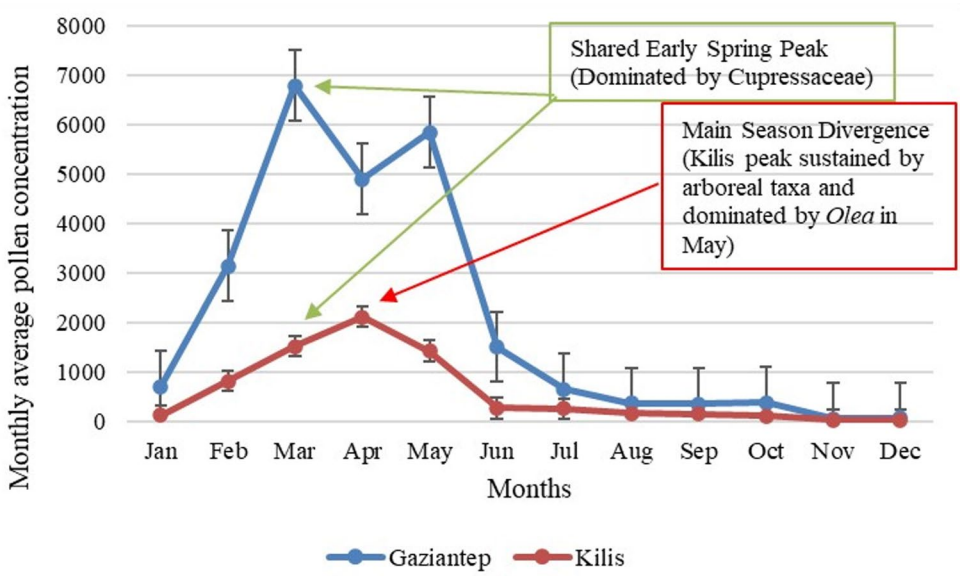


Fig. 3 Monthly average total pollen concentrations in Gaziantep and Kilis, illustrating differences in seasonal pollen load and phenology. While Gaziantep (2010–2011) exhibited sharp spring peaks, Kilis (2018–2019) exhibited a notably lower total pollen load. The divergence in the main season is distinct; the Kilis curve is sustained by several arboreal taxa in April and is ultimately defined by a late spring peak in May, primarily driven by *Olea europaea*. Data points represent two-year means; error bars indicate standard deviation. Major phenological phases are annotated

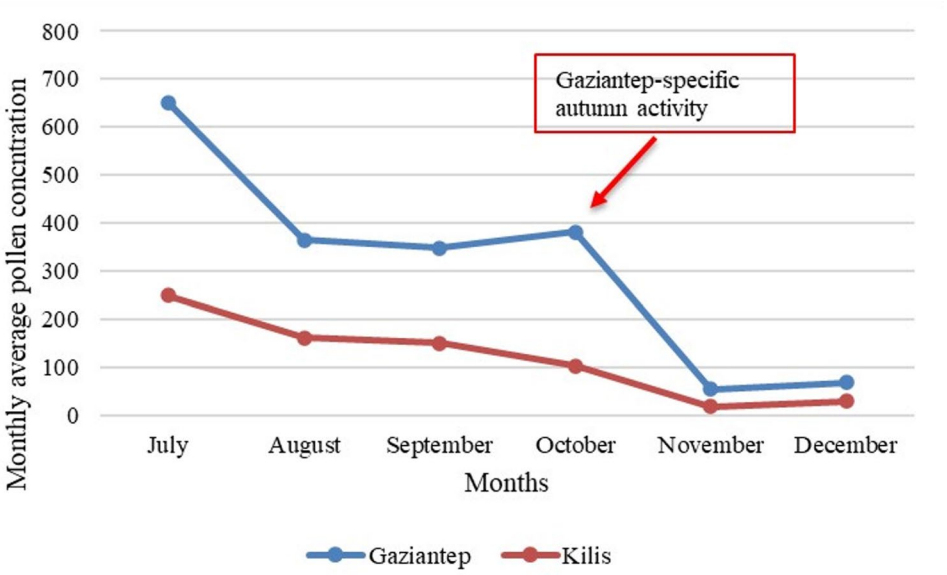


Fig. 4 Close-up comparison of late-season pollen concentrations in Gaziantep and Kilis.

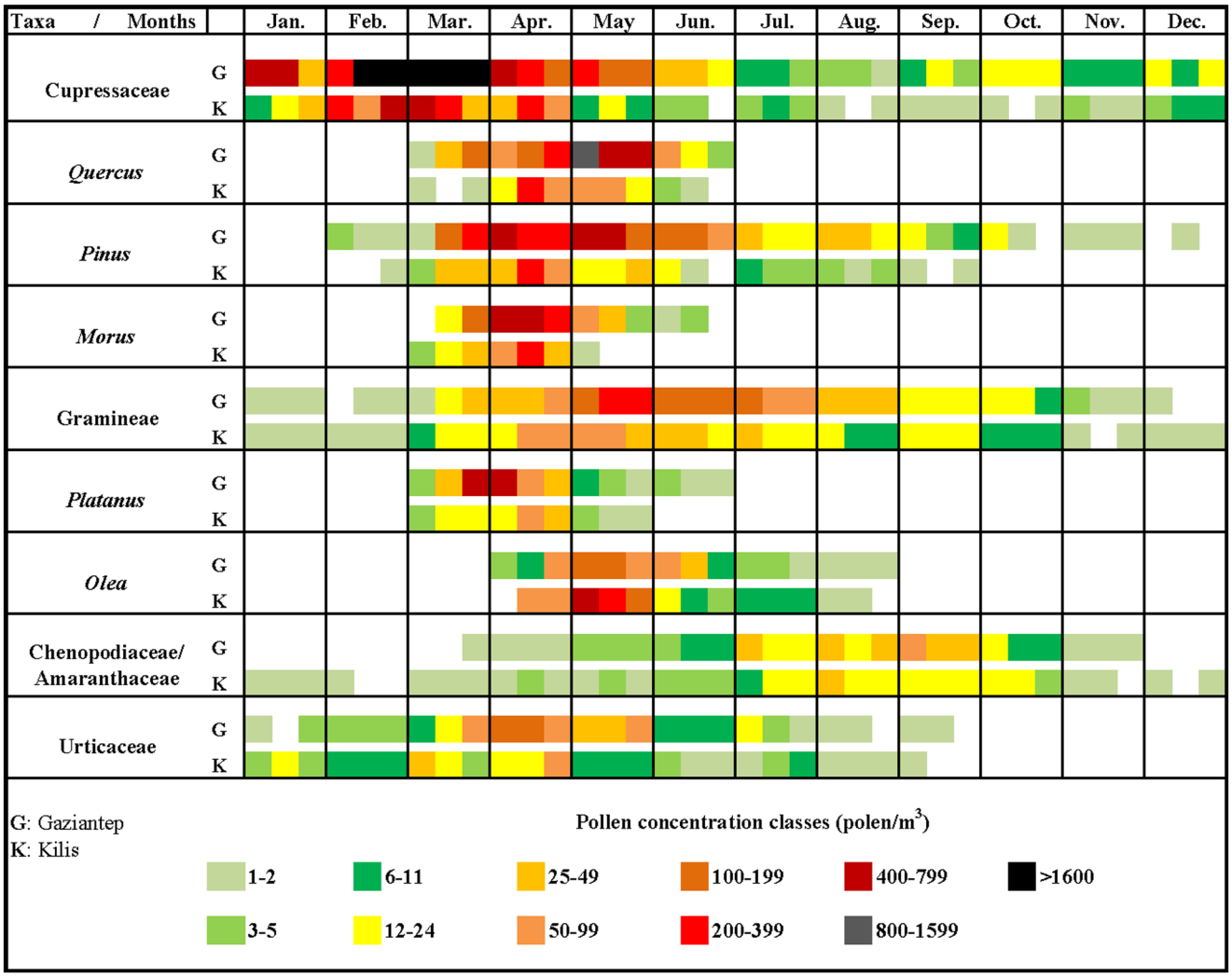


Fig. 5 Comparative pollen calendars for dominant airborne taxa in Gaziantep and Kilis. The calendars show temporally extended seasons for taxa such as Gramineae in Kilis, characterized by lower daily peaks but longer exposure periods. The agricultural landscape (Kilis) also exhibited greater taxonomic and temporal diversity, particularly due to *Olea europaea* and various herbaceous taxa

2019), and Chenopodiaceae/Amaranthaceae ($p<0.01$ in 2018). Temperature was negatively correlated with Cupressaceae ($p<0.05$ and $p<0.01$), *Olea europaea* ($p<0.01$ in 2018), and Urticaceae ($p<0.01$ in 2018), but positively correlated with Chenopodiaceae/Amaranthaceae ($p<0.01$ in 2018) and *Morus* ($p<0.01$ in 2019). Wind speed showed negative correlations with *Quercus* ($p<0.05$ in 2018), *Morus* ($p<0.01$ in 2019), and Urticaceae ($p<0.05$ in 2019). Relative humidity showed consistent negative correlations with Gramineae ($p<0.01$ and $p<0.05$) and *Pinus* ($p<0.01$) in both years.

Analysis of phenological intensity (high-intensity days)

The distribution of high-intensity pollen days was examined using the High-Intensity Day (HID) metric described in Sect. 2.5 (Table 3). The analysis revealed differences in the temporal distribution of pollen peaks between the two landscapes.

For example, Gramineae and *Quercus* showed comparable numbers of high-intensity days in the available datasets (Gramineae: 14 days in both periods; *Quercus*: 5 days in both periods). However, the temporal distribution of these

Table 3 Key indicators of the observed differences in the aeroecological pattern: Seasonal durations and high-intensity day counts for dominant taxa (Gaziantep 2010–2011 and Kilis 2018–2019)

Taxa	City	Year	Start Date	Peak Date (Day/Month)	Peak Concentration (pollen/m³)	High-Intensity Days (HID)*	End Date (Day/Month)	Season Duration (Days)
Cupressaceae	G	2010	6/1	21/2	3960	13	8/5	123
		2011	10/2	17/3	509	13	22/7	165
	K	2018	28/1	1/3	392	10	18/5	111
		2019	3/2	26/2	323	9	30/5	117
Chenopodiaceae/Amaranthaceae	G	2010	N/D	N/D	N/D	N/D	N/D	N/D
		2011	N/D	N/D	N/D	N/D	N/D	N/D
	K	2018	31/1	3/8	8	15	17/10	260
		2019	12/5	6/6	7	14	23/10	165
Gramineae	G	2010	23/3	9/5	22	18	28/9	190
		2011	28/4	21/6	45	14	11/10	167
	K	2018	10/3	25/4	24	10	20/10	225
		2019	19/3	14/4	37	14	12/10	208
Morus	G	2010	25/3	4/4	338	4	25/4	32
		2011	8/4	18/4	166	4	15/5	38
	K	2018	13/3	6/4	34	4	22/4	41
		2019	24/3	14/4	100	3	27/4	35
Olea	G	2010	N/D	N/D	N/D	N/D	N/D	N/D
		2011	N/D	N/D	N/D	N/D	N/D	N/D
	K	2018	17/4	5/5	368	6	15/6	60
		2019	3/5	20/5	124	5	20/6	49
Pinus	G	2010	15/3	10/4	196	12	27/7	135
		2011	9/4	28/4	293	13	31/8	145
	K	2018	15/3	13/4	67	7	22/7	130
		2019	25/3	15/4	101	9	22/7	120
Platanus	G	2010	15/3	30/3	412	3	14/4	31
		2011	31/3	4/4	247	3	28/4	29
	K	2018	N/D	N/D	N/D	N/D	N/D	N/D
		2019	N/D	N/D	N/D	N/D	N/D	N/D
Quercus	G	2010	18/3	9/5	292	5	17/5	61
		2011	20/4	25/5	250	5	7/6	49
	K	2018	7/4	14/4	139	3	8/5	32
		2019	14/4	13/5	29	5	31/5	48
Urticaceae	G	2010	N/D	N/D	N/D	N/D	N/D	N/D
		2011	N/D	N/D	N/D	N/D	N/D	N/D
	K	2018	20/1	4/3	10	19	28/7	190
		2019	15/1	29/4	27	16	15/7	182

Note. *High-Intensity Days (HID) are defined as days within the main pollen season (MPS) of the respective taxon when the daily pollen concentration exceeded the 90th percentile (P90) value. Abbreviations: N/D = Not Dominant; G = Gaziantep; K = Kilis

peaks differed between sites. In the agricultural landscape (Kilis), these high-intensity days were distributed across a longer pollen season, particularly for Gramineae, where the season extended to approximately 208–225 days.

In contrast, *Platanus* in the urban site showed short and concentrated seasonal peaks, whereas *Olea europaea* and herbaceous taxa such as Urticaceae showed broader seasonal distributions in the agricultural landscape.

Modelling of potential pollen sources (HYSPLIT)

Backward trajectory analyses using the HYSPLIT model were conducted to evaluate potential source regions associated with major pollen peaks. In the urban landscape (Gaziantep), major *Pinus* pollen peaks observed on 10 April 2010 and 28 April 2011 were mainly associated with local and regional air masses influencing Southeastern Anatolia and nearby regions (Fig. 6). In the agricultural landscape (Kilis), the highest *Olea europaea* pollen peaks observed on 5 May 2018 and 19 May 2019 coincided with air masses transported from distant source regions. Backward trajectory analysis indicates transport from the Mediterranean basin, including the Aegean region (Fig. 7).

Discussion

Land use as a driver of aeroecological divergence

The comparison between the two study sites suggests that contrasting land-use types may generate distinct aeroecological signatures within the same semiarid ecotone. Rather than reflecting temporal land-use change within a single location, the results highlight how different landscape structures—urban and agricultural—are associated with different pollen exposure regimes under broadly comparable climatic conditions.

Urban environments often produce highly concentrated pollen peaks associated with ornamental tree plantings and urban green-space management. In Mediterranean urban settings, species such as *Platanus*, *Cupressus*, and *Pinus* are widely used in urban landscaping and can strongly influence local airborne pollen spectra (Cariñanos and Casares-Porcel 2011). In contrast, agricultural landscapes are typically characterized by pollen profiles shaped by cultivated crops and open-field vegetation. Olive cultivation, for example, has been repeatedly identified as a dominant driver of airborne pollen dynamics in Mediterranean agricultural regions

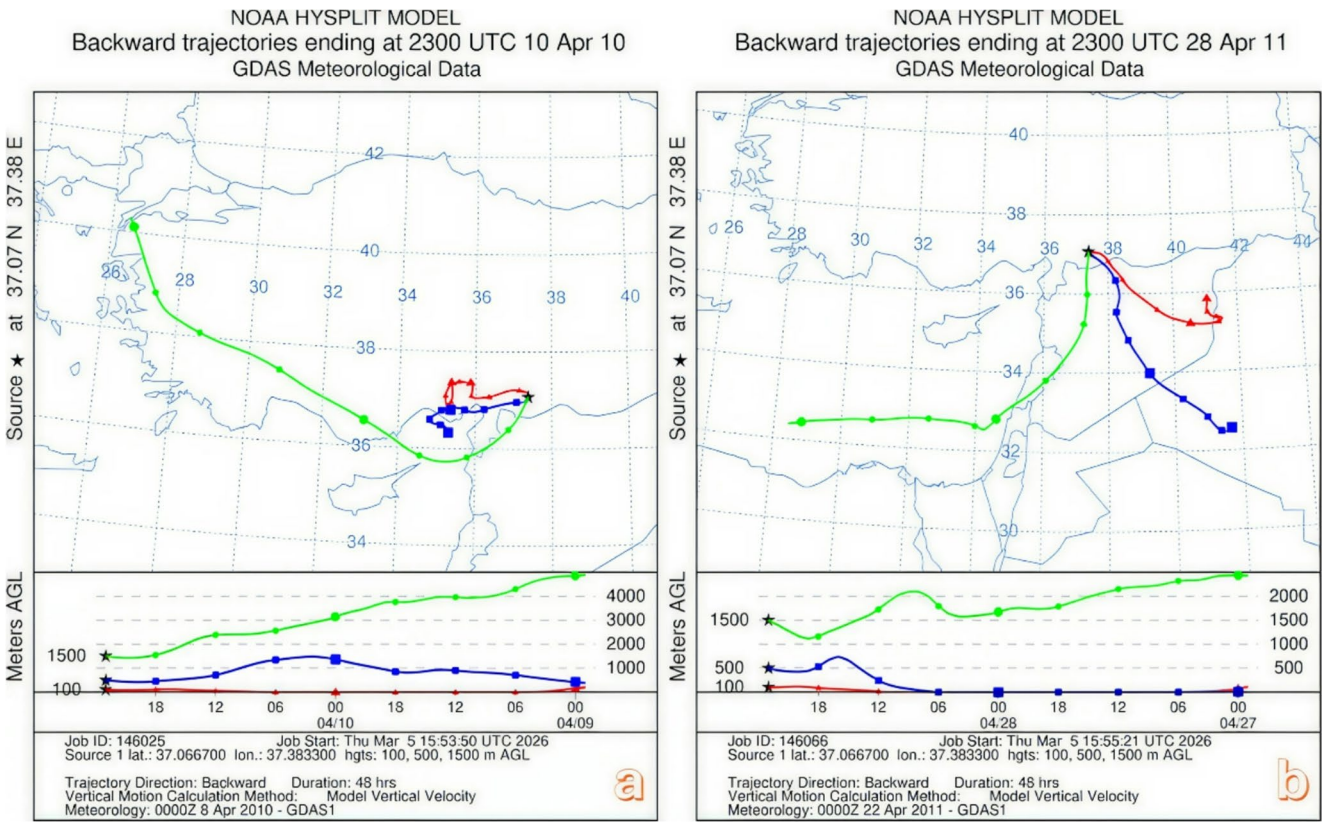


Fig. 6 HYSPLIT 48-hour back-trajectory analyses for peak *Pinus* pollen days in Gaziantep. (**a**) April 10, 2010; (**b**) April 28, 2011. Air masses associated with peak *Pinus* concentrations mainly originated from local and regional sources. The spatial extent of each trajectory plot varies depending on the distance travelled by the air masses, as determined automatically by the HYSPLIT system; therefore, slight differences in map coverage do not affect the comparability of trajectory patterns

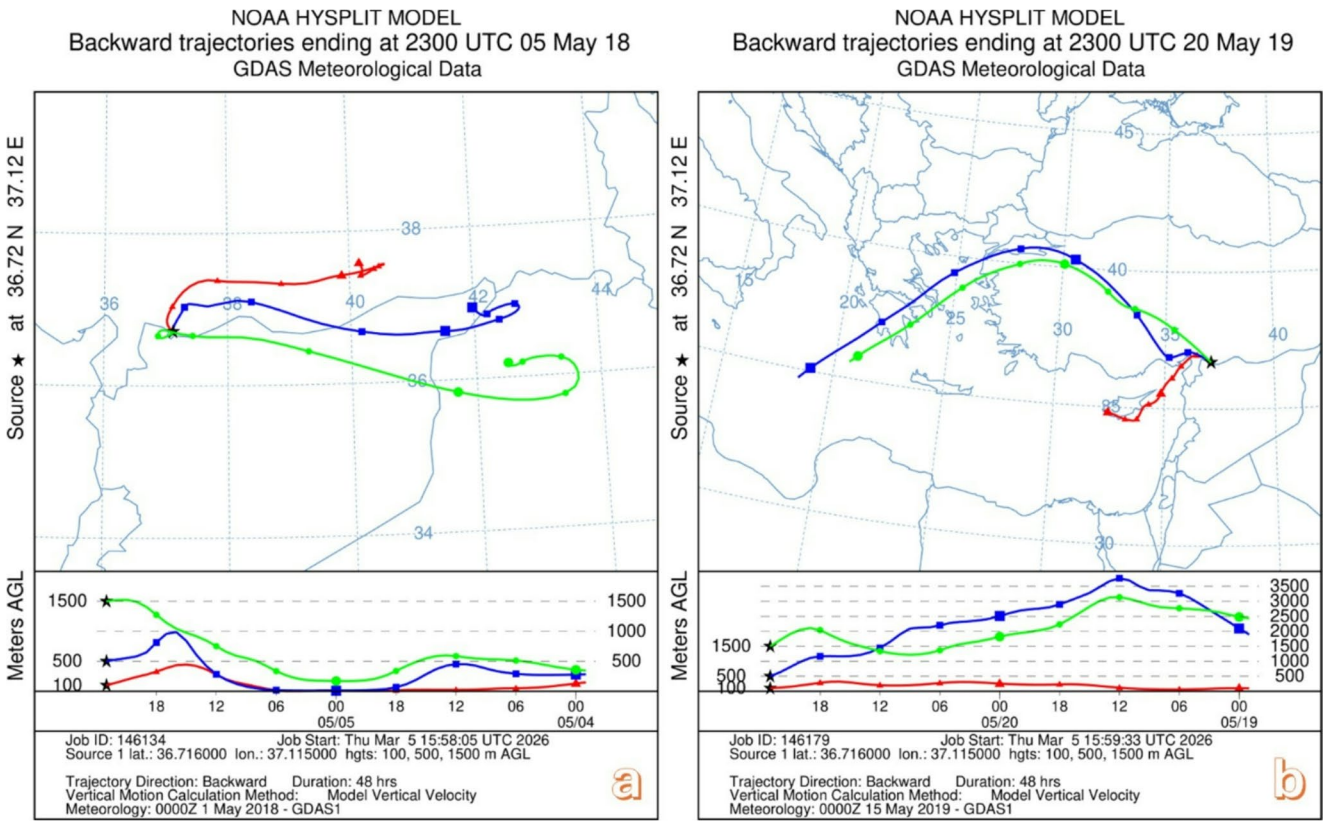


Fig. 7 HYSPLIT 48-hour back-trajectory analyses for peak *Olea* pollen days in Kilis. (**a**) May 5, 2018; (**b**) May 19, 2019. These trajectories indicate potential long-range transport contributing to *Olea* pollen peaks, highlighting the spatial dimensions of aeroecological exposure. The spatial extent of each trajectory plot varies depending on the distance travelled by the air masses, as determined automatically by the HYSPLIT system; therefore, slight differences in map coverage do not affect the comparability of trajectory patterns

(Rojo et al. 2016; Cariñanos et al. 2019). Furthermore, the volumetric dominance of specific taxa such as *Olea*, *Pinus*, and *Platanus* in both landscapes is inherently driven by their extraordinarily high biological pollen production capacity per plant and their wind-pollinated (anemophilous) reproductive strategies (Galán et al. 2014).

Within the present study area, the relative increase of *Olea europaea* in the agricultural landscape is consistent with these broader patterns. Olive pollen has been reported as a major contributor to atmospheric pollen loads in several Mediterranean agricultural regions, including southern Spain and North Africa (Cariñanos et al. 2016; El Hassani et al. 2022; Hadj Hamda et al. 2017). These studies demonstrate that regional agricultural practices can strongly influence the composition and timing of airborne pollen assemblages.

Beyond the Mediterranean Basin, similar links between land use and pollen dynamics have been reported in other parts of the world. Urban aerobiological studies have shown that city planning and ornamental plant selection can significantly shape airborne pollen spectra and allergen exposure (Haberle et al. 2014; Katz et al. 2014; Jetschni et al. 2023). Conversely, open agricultural and grassland landscapes often support a broader representation of herbaceous pollen types, leading to more temporally extended pollen seasons (Rojo et al. 2016).

In this context, the pattern observed in the present study—characterized by lower overall pollen loads combined with slightly higher taxonomic representation and extended seasonal activity in the agricultural landscape—can be interpreted as a landscape-dependent aeroecological structure. This pattern forms the basis of the conceptual framework referred to here as the Aeroecological Paradox.

Understanding these landscape-dependent pollen dynamics is particularly important for semiarid regions, where vegetation structure and land management practices can rapidly alter atmospheric pollen composition and exposure regimes. Consequently, aeroecological monitoring in dryland environments may benefit from explicitly considering land-use structure alongside climatic drivers (García-Mozo et al. 2016).

Conceptual framework: the Aeroecological Paradox

The comparison between the two study sites highlights how contrasting land-use types within the same semiarid ecotone

may produce different aeroecological regimes. Rather than representing a temporal transition within a single location, the results illustrate how two nearby landscapes with different land-use structures can generate distinct atmospheric pollen profiles. This pattern is conceptualized here as the Aeroecological Paradox, describing a contrast between a relatively concentrated pollen regime dominated by a few taxa and a more temporally extended regime characterized by broader taxonomic representation. Similar links between land use, vegetation structure, and pollen phenology have been reported in several aeroecological studies (D'Amato et al. 2007; Ziello et al. 2012; Smith et al. 2014; Hamaoui-Laguel et al. 2015; Ziska et al. 2019).

The results suggest that this pattern may arise from three interacting mechanisms. First, differences in vegetation structure associated with contrasting land-use types influence the composition of airborne pollen assemblages. Agricultural landscapes typically include a mosaic of cultivated areas, open fields, and ruderal vegetation, which can support a broader representation of herbaceous pollen taxa. Similar effects of landscape structure on pollen diversity have been documented in Mediterranean and European agricultural regions (García-Mozo et al. 2016).

Second, differences in flowering phenology among dominant taxa may contribute to changes in the temporal distribution of pollen emissions. Instead of short, highly concentrated pollen peaks, more heterogeneous vegetation structures may produce longer pollen seasons characterized by lower daily intensity but extended activity. Comparable patterns linking vegetation structure and pollen season dynamics have been reported in Mediterranean aeroecological studies (Galán et al. 2016; Ziska et al. 2019).

Finally, atmospheric transport processes may further modulate local pollen regimes. Backward trajectory analyses indicate that some pollen peaks may be associated with regional or long-distance air masses. Similar interactions between local pollen sources and atmospheric transport have been documented in aerobiological research, particularly in regions influenced by Mediterranean circulation patterns. In semiarid environments, these processes may interact with other atmospheric particles, including mineral dust, potentially influencing the dispersion and persistence of biological aerosols (D'Amato et al. 2020).

Taken together, these mechanisms suggest that aeroecological patterns in semiarid ecotones cannot be explained solely by pollen intensity. Instead, a more comprehensive perspective that considers taxonomic composition, phenological duration, and atmospheric transport processes is required. In this context, the Aeroecological Paradox provides a conceptual framework for interpreting how contrasting landscape structures may influence airborne pollen dynamics.

Synthesis of aeroecological dynamics: climate–landscape interactions

In semiarid ecotones such as Southeastern Anatolia, aeroecological patterns are shaped by the interaction of regional climatic conditions and landscape structure. The comparison of the two study areas indicates that pollen dynamics are influenced not only by climatic variability but also by the spatial configuration of vegetation associated with different land-use types. Similar interactions between climate and landscape structure have been highlighted in aerobiological studies across Mediterranean environments (García-Mozo et al. 2016).

Climate influences and phenological responses

The correlation analyses indicate that pollen–climate relationships vary among taxa and depend on local environmental conditions. Temperature, precipitation, wind speed, and relative humidity can influence pollen production, release, and atmospheric persistence in different ways. Previous studies have shown that these relationships are rarely linear and often depend on species-specific phenological strategies as well as local vegetation composition (García-Mozo et al. 2016).

Our results reflect these complexities, particularly regarding the contrasting role of meteorological drivers between the two landscapes. In the urban landscape (Gaziantep), temperature acted as a primary positive driver for several spring-flowering taxa, whereas in the agricultural landscape (Kilis), precipitation emerged as a more consistent negative factor. This negative relationship, often interpreted as the "washout" effect where rainfall physically removes biological particles from the atmosphere (García-Mozo et al. 2016; D'Amato et al. 2020), appears to be a significant factor modulating aeroecological exposure in the agricultural site. The prominence of this effect in Kilis, compared to Gaziantep, suggests that the same climatic drivers may exert different degrees of influence depending on the specific vegetation structure and regional atmospheric dynamics.

In semiarid environments, climatic stress factors such as high temperatures and seasonal water limitation may further alter flowering phenology by modifying both the timing and duration of pollen release. Some studies suggest that warming and drought conditions may reduce the intensity of pollen peaks while extending the duration of flowering periods in certain taxa (Bykova et al. 2018). Such responses highlight the complex interaction between climatic drivers and vegetation structure in determining pollen season characteristics, forming a key component of the observed aeroecological divergence.

Landscape structure and atmospheric transport

Landscape structure also plays an important role in shaping aeroecological dynamics. Urban environments are typically characterized by concentrated plantings of ornamental species, whereas agricultural landscapes often consist of cultivated fields interspersed with open habitats that support herbaceous vegetation (Cariñanos et al. 2014; Rojo et al. 2016). These structural differences can influence both the composition and temporal distribution of airborne pollen.

Atmospheric transport processes further contribute to these patterns. Back-trajectory analyses indicate that pollen peaks may originate from both local vegetation and regional air masses. Similar mechanisms have been documented in other aerobiological studies, where long-distance transport can introduce pollen from surrounding regions and modify local pollen spectra. In semiarid environments, these processes may also interact with mineral dust transport events, which are common in Mediterranean and Middle Eastern atmospheric circulation systems (Karanasiou et al. 2012).

Together, these findings suggest that aeroecological dynamics in semiarid ecotones emerge from the combined influence of climatic variability, landscape structure, and atmospheric transport processes. Understanding these interactions is essential for interpreting spatial and temporal variability in airborne pollen exposure.

Ecological implications

The aeroecological patterns observed in this comparative study indicate that different landscape structures may be associated with distinct pollen exposure regimes within the same semiarid ecotone. In particular, the agricultural landscape displayed a longer and more taxonomically heterogeneous pollen season compared with the urban site. These results suggest that monitoring strategies based solely on peak pollen days may not fully capture the complexity of pollen exposure in such environments. Several recent studies have emphasized the importance of incorporating additional parameters, including season duration, taxonomic diversity, and atmospheric processes, into aerobiological assessments (Beggs 2015; Ziello et al. 2012; Clot et al. 2024).

The comparison also highlights the presence of multiple phenological structures within the regional pollen calendar. Rather than following a single seasonal pattern, the semiarid ecotone appears to exhibit a mosaic of pollen dynamics associated with different landscape types. Urban environments are often characterized by concentrated spring peaks dominated by ornamental or planted tree taxa such as *Platanus* and Cupressaceae. In contrast, agricultural landscapes may be influenced by cultivated species such as *Olea europaea* and by herbaceous taxa including Gramineae, Chenopodiaceae/Amaranthaceae, and Urticaceae, which may contribute to extended seasonal pollen activity. Similar overlapping phenological patterns have been described in other Mediterranean aerobiological studies (Cariñanos et al. 2014; García-Mozo et al. 2016).

From an ecological perspective, such structural differences in pollen seasons may also have implications for pollen exposure patterns. Short and intense pollen peaks may generate episodic exposure events, whereas extended pollen seasons involving multiple taxa may lead to longer periods of lower but persistent exposure (Beggs 2015; D'Amato et al. 2020). Although clinical data were not included in the present study, this observation suggests a hypothesis for future interdisciplinary research linking aerobiological monitoring with medical data.

In addition, previous research has suggested that atmospheric conditions in semiarid regions may facilitate interactions between biological particles and mineral dust. Desert dust transport events have been proposed as a factor potentially influencing the atmospheric behaviour and physical properties of pollen grains (Karanasiou et al. 2012; D'Amato et al. 2020). While these processes were not directly investigated in this study, future work combining aerobiological observations with satellite and atmospheric monitoring systems may help clarify these possible biotic–abiotic interactions.

Methodological framework, limitations, and future perspectives

The analytical design of this study follows a space-for-time substitution approach. This framework is widely used in ecological research when long-term monitoring data are limited or unavailable (Pickett 1989; Blois et al. 2013). In the present study, the aim was not to reconstruct temporal changes in pollen dynamics but to compare the aeroecological characteristics of two landscapes with contrasting land-use structures located within the same semiarid ecotone.

To ensure methodological consistency, both monitoring sites used identical volumetric pollen samplers (Lanzoni VPPS 2000) and standardized aerobiological protocols recommended by the International Association for Aerobiology (Galán et al. 2014, 2017). These standardized methods allow comparisons between datasets collected in different locations and periods, although they do not eliminate all sources of variability.

One limitation of the present analysis is the relatively short duration of the available datasets. Pollen production and seasonal dynamics can vary substantially among years depending on climatic conditions and ecological factors (Ziello et al. 2012). In addition, the absence of detailed vegetation and land-use maps represents a constraint for

precisely linking airborne pollen spectra to local vegetation sources. Similar data limitations have been noted in aerobiological studies from other parts of the Eastern Mediterranean region (Cariñanos et al. 2014).

Another limitation concerns the temporal separation between the two monitoring periods. Because the datasets correspond to different years, the results should not be interpreted as direct evidence of temporal land-use change. Instead, they provide a comparative perspective on how different landscape structures may generate distinct aeroecological signatures under broadly similar regional climatic conditions.

Despite these limitations, the conceptual framework introduced in this study—the Aeroecological Paradox—offers a useful basis for future investigations. Expanding aerobiological monitoring networks, particularly through multi-site observations and automated pollen monitoring systems, could significantly improve the spatial resolution of pollen exposure assessments (Katz et al. 2014). The integration of aerobiological data with atmospheric transport modelling and satellite-based aerosol observations may also help clarify the complex interactions between pollen dynamics, land use, and atmospheric processes in semiarid regions.

Conclusion

This study highlights how contrasting landscape structures may be associated with distinct aeroecological patterns within the same semiarid ecotone. The comparison between the two study areas suggests that urban and agricultural landscapes can generate different atmospheric pollen regimes characterized by differences in pollen intensity, taxonomic composition, and seasonal structure.

These findings support the conceptual framework referred to here as the Aeroecological Paradox, which describes the coexistence of two contrasting pollen exposure regimes within similar climatic settings: a short and intense pollen season dominated by a limited number of taxa, and a longer season involving more heterogeneous pollen assemblages. This perspective emphasizes that aeroecological dynamics cannot be fully understood through peak pollen intensity alone but require the consideration of additional parameters such as phenological duration and taxonomic diversity.

From a practical perspective, the results underline the importance of considering vegetation structure and planting strategies when interpreting pollen exposure patterns in urban environments. Urban tree selection and green-space planning may strongly influence airborne pollen spectra and allergenic exposure (Cariñanos and Casares-Porcel 2011; Cariñanos et al. 2019). Therefore, urban and regional planning must account not only for the spatial distribution of vegetation but also for the inherent floral abundance and high pollen production potential of the selected taxa. Decision-support tools such as the Urban Green Zone Allergenicity Index (IUGZA) have been proposed as useful instruments for incorporating aerobiological knowledge into urban vegetation management (Schram-Bijkerk et al. 2018; Cariñanos and Marinangeli 2021).

Overall, this study provides a conceptual framework for interpreting how landscape structure and atmospheric processes interact to shape airborne pollen dynamics in semiarid environments. Expanding aerobiological monitoring networks and integrating pollen observations with land-use and atmospheric data may help improve the understanding and management of pollen exposure patterns in similar ecotonal regions.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11252-026-02001-8.

Acknowledgements This study was supported by the Scientific and Technological Research Council of Türkiye (TÜBİTAK) under project numbers 109S086 (Gaziantep) and 117Z252 (Kilis). We would like to express our sincere gratitude to Dr. Demet Yilmazkaya and Yusuf Keloglu for their valuable contributions to the project, particularly for their dedicated efforts in fieldwork and operational support.

Author contributions Adem Bicakci: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Project administration; Semih Bekil: Data curation, Formal analysis; Hasan Akgul: Resources, Investigation; Aycan Tosunoglu: Investigation, Data curation, Formal analysis.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). This study was supported by two separate projects funded by the Scientific and Technological Research Council of Türkiye (TÜBİTAK). Atmospheric data for Gaziantep were collected under project number 109S086, and data for Kilis under project number 117Z252.

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

Declarations

Competing interests The authors declare no competing interests.

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