



The duration and severity of the allergenic pollen season in Istanbul, and the role of meteorological factors

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Abstract Information on the allergenic pollen season provides insight on the state of the environment of a region and facilitates allergy symptom management. We present a retrospective analysis of the duration and severity of the allergenic pollen season and the role of meteorological factors in Istanbul, Turkey. Aerobiological sampling from January 2013 to June 2016, pollen identification and counting followed current standard methodology. Pollen seasons were defined according to 95% of the Annual Pollen Integral (API_n) and the season start date was compared with the first day of 5 day consecutive non-zero records. Generalized additive models (GAMs) were created to study the effect of meteorological factors on flowering. The main pollen contributors were taxa of temperate and Mediterranean climates, and neophytic *Ambrosia*. Cupressaceae, Poaceae, Pinaceae, *Quercus* and *Ambrosia* had the greatest relative abundance. The pollen season defined on 95% of the API_n was adequate for our location with total API_ns around

10.000 pollen*day*m⁻³. Woody taxa had generally shorter seasons than herbaceous taxa. In trees, we see precipitation as the main limiting factor for assimilate production prior to anthesis. A severe tree pollen season in 2016 suggests intense synchronous flowering across taxa and populations triggered by favourable water supply in the preceding year. GAM models can explain the effect of weather on pollen concentrations during anthesis. Under the climatic conditions over the study period, temperature had a negative effect on spring flowering trees, and a positive one on summer flowering weeds. Humidity, atmospheric pressure and precipitation had a negative effect on weeds. Our findings contribute to environmental and allergological knowledge in southern Europe and Turkey with relevancy in the assessment of impacts of climate change and the management of allergic disease.

Keywords Allergenic pollen seasons · Pollen severity · Allergy management · Generalized additive models · Meteorological factors · Masting

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1 Introduction

Information on the allergenic pollen season and its severity provides insight on the state of the environment of a region and facilitates allergy symptom management (Karatzas et al., 2019; Gehrig et al., 2018). Both aspects are closely connected in aerobiological research. Climate change gives rise to increased

respiratory allergy, due to its impact on the start and duration of the pollen season, the flowering intensity, and the presence of allergen content (D'Amato et al., 2020; Eguiluz-Gracia et al., 2020; Damialis et al., 2019; Katelaris & Beggs, 2018; Jenerowicz et al., 2012). The megacity Istanbul with a population of close to 18 million has now an allergy and asthma incidence of 20% in adolescents and adults (Turkish Statistical Institute, 2020). Furthermore, it supports health practitioners in the choice of allergen extracts to test (Zemmer et al., 2021; Ansotegui et al., 2020; Heinzerling et al., 2013), in the timing for implementation of clinical trials (Bastl et al., 2019; Pfaar et al., 2017) and in the sound interpretation of clinical results (Werchan et al., 2018). Pollen types detected in aerobiological sampling differ in their clinical relevance between regions (Karatzas et al., 2019; D'Amato et al., 2007). Within a region, relevance may also change over time. In Milan, for example, Cupressaceae only recently have become important with regard to allergy (Asero et al., 2020). Regular updates on local pollen information are, thus, essential (Ansotegui et al., 2020). In the interpretation of pollen information cross-reactivity patterns of taxa have to be considered (Ansotegui et al., 2020). Some of the major proteins causing allergy are panallergens, common to many flowering plants (McKenna et al., 2016). The major birch allergen Bet v 1, for example, belonging to the protein family PR10, has homologues in hazel (Cor a 1) and alder (Aln g 1) within the families Betulaceae and Fagaceae as in beech (Fag s 1) in the order Fagales (Matricardi et al., 2016; Weber, 2008) and also in non-related taxa, such as apple (Mal d 1) (McKenna et al., 2016). Therefore, when presenting pollen information, you can address clinical needs by grouping taxa above species, genus, and even family level (Hoffmann et al., 2020).

In environmental terms, the local pollen spectrum depends on the natural vegetation, land use, ornamental flora in green urban spaces, and the ruderal urban flora (Werchan et al., 2018; Monroy-Colín et al., 2018; McInnes et al., 2017; Tosunoglu et al., 2015; Carinanos et al., 2014; Fernández-Rodríguez et al., 2014; Çeter et al., 2012), as well as on prevailing air currents (Alan et al., 2019; Rojo et al., 2015; Damialis et al., 2005). It can reveal the arrival of invasive plants, such as ragweed, when the presence of local sources is not yet known (Zemmer et al., 2012). Meteorological factors influence the flowering

phenology, and thus, the duration and intensity of the pollen flow in anemophilous species (Dahl et al., 2013). So can accumulated temperature during the period when male catkins are initiated and formed, affect the amount of pollen released during flowering (Bogdziewicz et al., 2017; Dahl & Strandhede, 1996). Air humidity impacts pollen release. Dry air favours anther dehiscence in many anemophilous species (Dahl et al., 2013; Martin et al., 2010; Pacini, 2000; Bianchi et al., 1959). When air is humid, pollen grains absorb water and get heavier; some types like grass pollen will even burst as they cannot adjust to humidity (Dahl et al., 2013; Pacini, 2000). In dryer climates, water availability is a limiting factor affecting plant biomass accumulation (Szymczak et al., 2020) and flowering intensity (Velasco-Jiménez et al., 2020; Galán et al., 2016; García-Mozo et al., 2010; Peñuelas et al., 2004). The Mediterranean region, including southern Europe, will face increased arid conditions due to climate change (Hoegh-Guldberg et al., 2018). In Istanbul this trend has become evident in the shift from a moist-subhumid towards dry subhumid climate during the last twenty years (Turoğlu, 2014). The result may be spatial and temporal shifts of allergenic pollen sources (Damialis et al., 2019). Reports on phenology and flowering intensity of wind pollinated taxa of a region provide, therefore, important information on environmental changes over time (Velasco-Jiménez et al., 2020; Galán et al., 2016).

In this paper, we analyse atmospheric pollen monitored in Istanbul from the environmental perspective. The aims are to (1) define pollen seasons (2) report on the intensity of pollen concentrations (3) and on the effect of meteorological factors on the main taxa.

2 Materials and methods

2.1 Study area

The monitoring was performed in Büyükçekmece at the western fringes of Greater Istanbul. The climate of Istanbul corresponds to the Köppen Geiger Csa-type (Turoğlu, 2014) that is somewhat between temperate and Mediterranean (Climate-Data.org, 1999). The Bosphorus and the south of the city are influenced by the Marmara Sea, while the climate in the northern and western hinterland is more continental, as it is influenced by the Black Sea and the Balkans. The

study area is, thus, characterized by a transitional climate from cool and wet conditions northwards into the Istranca mountain range, to a dry and warm situation in the south and around Bosphorus (Baser, 2011; Fig. 1). The topography is hilly and the highest elevation is about 300 m above sea level. North-easterly winds prevail. The vegetation changes according to the climatic north–south gradient. In plant geographical terms, two floristic regions blend here into one another: the South-Euroasian and the Mediterranean (Schroeder, 1998). Most of the wood cover is situated upwind the trap in the Belgrad Forest, and features the following wind-pollinated deciduous thermophilus trees: *Quercus frainetto*, *Q. petraea*, *Q. robur*, *Q. cerris*, *Fagus orientalis*, *Castanea sativa*, *Corylus avellana*, *Carpinus betulus*, *C. orientalis*, *Alnus glutinosa*, *Fraxinus angustifolia*, *F. ornus*, *Populus tremula*, *Erica arborea*, *E. manipuliflora*, *Ulmus minor*, *Salix caprea* and *S. cinerea* (Çoban et al., 2016; Baser, 2011; Kavgaci et al., 2010). There are also areas of *Pinus nigra* plantations. Amidst patches of pseudomachus with *Quercus coccifera*, *Juniperus communis*, *Paliurus spina-christi* and *Pistacia terebinthus*, grasslands turning dry in summer, and agricultural lands, villages emerge. The agricultural land is used for the growth of annual crops (sunflower, canola, cereals). The area has four watersheds, some of them functioning as fresh water reserves of the city with restrictions on urban development.

Anemophilous urban flora on walls, wastelands and coasts feature herbaceous plants pertaining to Poaceae (i.e. *Digitaria sanguinalis*, *Setaria* ssp., *Echinochloa* ssp., *Sorghum halepense*), Asteraceae (i.e. *Artemisia vulgaris*, *A. annua*, *A. absinthium*, *Xanthium spinosum*, *X. strumarium*), Urticaceae (i.e. *Urtica dioica*, *U. membranacea*, *U. pilulifera*, *U. urens*, *Parietaria judaica*), Amaranthaceae (i.e. *Amaranthus* ssp., *Chenopodium* ssp., *Atriplex* ssp., *Salicornia* ssp.), Polygonaceae (*Rumex* ssp.), Plantaginaceae (i.e. *Plantago lanceolata*, *P. major*, *P. coronopus*, *P. afra*) (Bakis et al., 2020; Altay et al., 2010). Common anemophilous ornamental trees are *Cupressus sempervirens*, *Cedrus libani*, *Plantanus x acerifolia*, *P. orientalis*, *Thuja orientalis*, *Morus* ssp., *Salix babylonica*, *Fraxinus angustifolia*, *Ulmus* ssp., *Celtis australis*, *Ailanthus altissima*, *Acer negundo*, *Pinus* ssp. (Baser, 2011) and *Olea europaea*.

2.2 Pollen monitoring

Pollen data include a 3½ year period from 28th January 2013 to 26th June 2016 sampled according to the current standard methodology with a 7 day volumetric Hirst-type pollen sampler (Hirst, 1952). Pollen monitoring, identification and counting followed the minimum requirements of the European Society of Aerobiology (EAS) (Galán et al., 2014) and

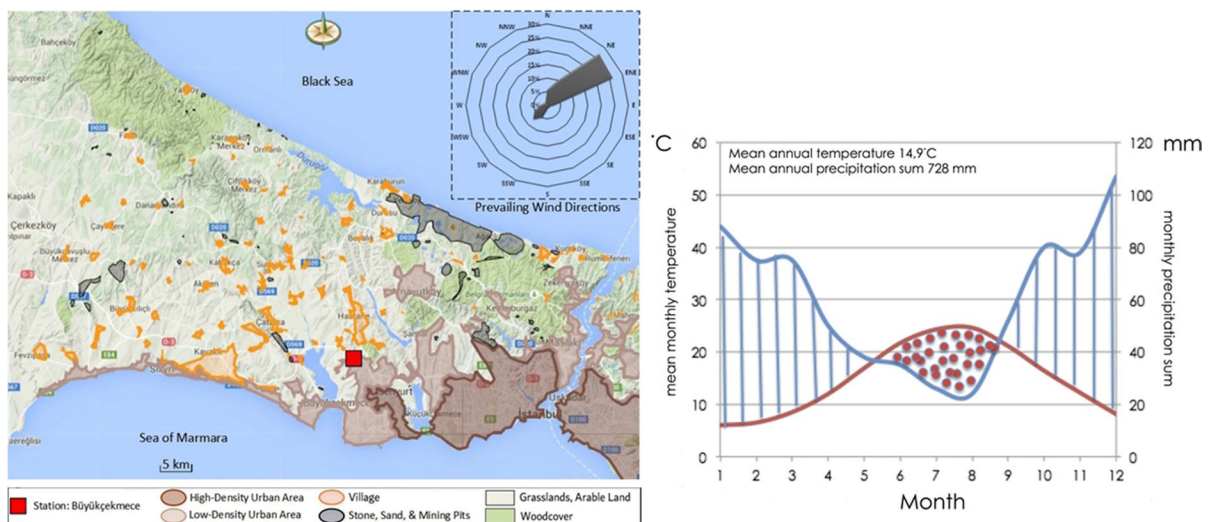


Fig. 1 Study area (left) and climate diagram of Istanbul (right). The striped areas in the climate diagram denote humid conditions, and the dotted areas show when the conditions are arid (constructed according to Walter & Lieth, 1960)

are normed by EN 16868 (2019). Daily mean pollen concentrations are expressed in pollen (p)*m⁻³ air.

On 21st April 2014 the position of the trap had to be moved from three to 10 m height (ca. 200 m ENE from the original position) due to a construction project. We did not alter the master data set for the period prior to the change, based on findings that the height of the trap does not influence the time series significantly (Rojo et al., 2019a; Fernández-Rodríguez et al., 2014; Galán et al., 1995). We verified this assumption following the theory that most pollen is shed in the vicinity of the trap (Adams-Groom et al., 2017). To do so, we studied the distribution of pollen concentrations of Poaceae and *Plantago*, growing in the immediate surrounding of the trap, and of *Olea* and Pinaceae growing at about 40 m distance during their peak flowering period (pre-peak in case of *Plantago*); all of them flowering during May (Fig. 2).

2.3 Meteorological data

Meteorological data on temperature, humidity and pressure were obtained from the open source www.weatherunderground.com, recorded at 41.14° N, 28.46° E Istanbul Hezarfen Airfield Station located 6 km northwest of the trap location. Precipitation data were purchased from the State Meteorological

Service (www.mgm.gov.tr). We tested the effect of maximum (T_{max}) and minimum daily temperature (T_{min}), mean daily humidity (HumMean), mean daily pressure (PressMean) and precipitation (Prec) on the main pollen taxa. Precipitation of the year 2012 was included to study the effect of this factor on trees a year ahead of anthesis when flowers are initiated (Dahl and Strandhede, 1996).

2.4 Data analysis

The dataset was homogenised to obtain equally 31 taxa for all years by removing pollen taxa with negligible Annual Pollen Integral (API_n), for example, *Arecaceae*, *Mercurialis*, *Typha*, *Iva*. Single pollen out of season attributed to resuspension or flowering out of season (for example, *Ulmus*) were removed. Next, a quality check was performed to identify missing data. In 2013 and 2015 sampling was discontinued during January for technical reasons. We interpolated the missing data with the moving mean function because it adapted better to our data than linear regression did in preliminary tests. We confirm that for aerobiological data, the moving mean interpolation performs better as compared to other methods as suggested by Picornell et al. (2021).

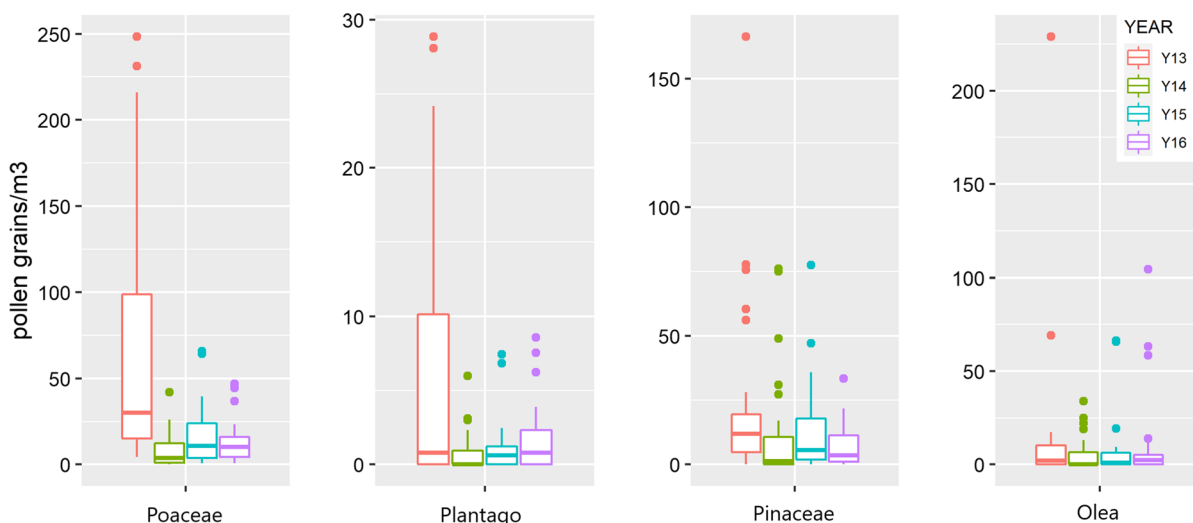


Fig. 2 Pollen concentrations of taxa growing in the surrounding of the trap during May in a four-year comparison. The boxes include 50% of the data, the interquartile range (IQR) between the first quartile (Q1), and the third quartile (Q3); the

line in the box is the median, the whiskers show the data range (Q1 – 1.5 * IQR, Q3 + 1.5 * IQR); dots are outliers and indicate peak concentrations

We present the weekly pollen concentration average of our studied years, not considering this presentation a pollen calendar for which at least five years of data are required (Galán et al., 2017). For this figure, we chose a scale of 10 colour gradients from light to dark: light colour standing for low and dark for higher pollen concentrations.

We used descriptive statistics for the analysis of phenology, represented by the timing of the pollen season, and the flowering intensity, represented by the Seasonal Pollen Integral (SPIn) and APIn. For the retrospective analysis of our aerobiological data the percent method was deemed appropriate (Bastl et al., 2018). The pollen seasons were, thus, defined according to the 95% method (Andersen, 1991): the season starts when 2.5% of the APIn is reached and ends on the day with 97.5% of the APIn. The result thereof can be used to calculate the SPIn. To assess the validity of this method for the season start date, the 1st day of 5 non-zero concentrations was determined. Aerobiological data were mainly analysed with the AeRobiology package (Rojo et al., 2019b) in RStudio version 3.6.3.

To analyse the effect of meteorological factors on pollen seasons, we run generalized additive models (GAMs) based on the assumption of a nonlinear relationship between meteorological factors and pollen concentrations. These models estimate the effect on the change of pollen concentrations with each added unit of independent variable (Ravindra et al., 2019). The model can automatically fit nonlinear dependencies and is adequate for short term and long-term time series (Ravindra et al., 2019). For the model we used the quasi-Poisson function and a spline function on time. GAMs were created with the nlme package (Pinheiro et al., 2021) in R.

3 Results

3.1 Trap position change

Herbaceous Poaceae and *Plantago* displayed pronouncedly higher pollen concentrations in May 2013 compared to the other years and peak concentrations were over three times higher. In woody *Olea* and Pinaceae, the bulk of the data was similar over the studied years. Peak concentrations, however, were twice higher in 2013 than in the other years. Effects

on pollen intensities of other taxa were negligible (compare SPIn and peak values in Tables 1, 2). When reading diagrams this bias should be considered.

3.2 Flowering phenology

We calculated numerical details on seasonal parameters of 31 woody and herbaceous taxa (Tables 1, 2).

The start (2.5%) and end date (97.5%) of the APIn of the pollen seasons reflecting the flowering phase of anemophilous plants varied between years (Fig. 3, Tables 1, 2). The longest seasons were generally observed in herbaceous plants, for example, Urticaceae (> 60 days difference between years), Amaranthaceae and Poaceae, but also in *Carpinus* (about 50 days difference between years). Variations for the end date of the seasons was pronounced in herbaceous *Plantago*, Amaranthaceae and Urticaceae, and for some trees, especially in Pinaceae (over 100 days difference between years), *Carpinus*, and to a lesser extent in *Fraxinus*.

We compared the 95% method to define the season start with the date of the 1st day of 5 non-zero concentrations for the main pollen contributing taxa to assess the feasibility of this method at our location. Cupressaceae, *Fraxinus*, Pinaceae, *Platanus*, Poaceae, and *Plantago* had a standard deviation < 5 in the dates of the season start during the study period. The differences in the season start dates were low also for *Olea* (except in 2016) and *Betula* (except in 2013).

3.3 Pollen intensity

The relative abundance of the 15 main pollen types is reported in Fig. 4. The summarization of Betulaceae and Fagaceae in the analysis is made to follow the rationale of cross-reactions in the Fagales order (Matricardi et al., 2016). *Alnus* and *Carpinus* were the main pollen contributors within Betulaceae and *Quercus* in the Fagaceae.

The details on the phenology and relative abundances of all taxa pertaining to the Fagales including *Corylus*, *Fagus* and *Castanea sativa*, all three with < 0.5% of the APIn, are presented as violin plots in Fig. 5. Violin plots can show the entire distribution of the data emphasising peak periods. Wider parts in the plot contain observations with higher density than in thinner parts (Hintze & Nelson, 1998). *Corylus*,

Table 1 Annual pollen seasons (PS), start and end date, duration, peak value and day, and the Seasonal Pollen Integral (SPIn) of woody taxa. For the main pollen contributing taxa the 1st day of 5 consecutive non-zero records, the standard deviation (Sd), and the days difference between the methods to define the season start date is reported. Empty cells imply not applicable calculations or data deficiency

Taxon	Year	PS start	PS end	Duration (days)	SPIn	Peak Value	Peak Date	1st day of 5 non-zero record date	Sd	Days difference
Alnus	2013	25/02/2013	03/04/2013	38	76	13	09/03/2013	09/03/2013	6.6	12
	2014	28/01/2014	29/03/2014	61	223	76	12/03/2014	24/01/2014		-4
	2015	24/02/2015	23/03/2015	28	60	7	25/02/2015	01/03/2015		5
	2016	11/02/2016	16/03/2016	35	75	12	20/02/2016	23/02/2016		12
Betula	2013	01/04/2013	09/05/2013	39	75	11	01/05/2013	29/04/2013	9.9	28
	2014	27/03/2014	18/05/2014	53	37	6	09/04/2014	01/04/2014		5
	2015	09/04/2015	06/05/2015	28	19	4	14/04/2015	13/04/2015		4
	2016	20/03/2016	13/05/2016	55	109	20	28/03/2016	27/03/2016		7
Carpinus	2013	21/03/2013	27/05/2013	68	40	6	10/04/2013		9.5	
	2014	25/01/2014	29/06/2014	156	57	8	08/04/2014	24/01/2014		-1
	2015	24/03/2015	03/06/2015	72	234	66	14/05/2015	13/04/2015		20
	2016	11/02/2016	27/04/2016	77	429	126	27/03/2016	29/02/2016		18
Celtis	2013	18/03/2013	27/04/2013	41	20	6	03/04/2013			
	2014									
Corylus	2015	21/02/2015	21/03/2015	29	2	1	21/03/2015			
	2016	14/03/2016	17/03/2016	4	7	4	16/03/2016			
	2013	02/02/2013	21/03/2013	48	30	8	13/02/2013			
	2014	16/01/2014	01/04/2014	76	67	9	16/02/2014	22/01/2014		6
	2015	12/02/2015	26/03/2015	43	33	5	05/03/2015			
	2016	24/01/2016	07/03/2016	44	20	4	11/02/2016			
Cupressaceae	2013	03/02/2013	19/06/2013	137	2274	309	13/03/2013	31/01/2013	0.8	-3
	2014	17/01/2014	16/05/2014	120	2180	183	19/01/2014	12/01/2014		-5
	2015	23/02/2015	22/05/2015	89	1760	422	26/02/2015			
	2016	27/01/2016	14/05/2016	109	3471	729	19/02/2016	23/01/2016		-4
Ericaceae	2013	10/03/2013	05/11/2013	241	26	4	10/03/2013			
	2014	15/03/2014	03/10/2014	203	24	5	24/03/2014			
	2015	05/03/2015	14/09/2015	194	31	4	25/03/2015			
	2016	23/02/2016				6	17/03/2016			

Table 1 (continued)

Taxon	Year	PS start	PS end	Duration (days)	SPI _n	Peak Value	Peak Date	1st day of 5 non-zero record date	Sd	Days difference
Fraxinus	2013	02/02/2013	23/03/2013	50	228	19	21/03/2013	06/02/2013	2.5	0
	2014	19/01/2014	04/05/2014	106	206	16	23/04/2014	22/01/2014		3
Moraceae	2015	09/02/2015	12/05/2015	93	89	7	10/02/2015			
	2016	10/02/2016	15/04/2016	66	528	70	01/03/2016	08/02/2016		-2
	2013	12/04/2013	11/05/2013	30	119	24	06/05/2013	01/05/2013	6.2	19
	2014	24/03/2014	05/05/2014	43	44	7	24/03/2014			
	2015	15/04/2015	22/05/2015	38	165	17	29/04/2015	20/04/2015		5
	2016	03/04/2016	30/04/2016	28	169	29	04/04/2016	10/04/2016		7
Olea	2013	16/05/2013	19/06/2013	35	431	229	22/05/2013	13/05/2013	12.2	-3
	2014	12/05/2014	01/06/2014	21	159	34	15/05/2014	12/05/2014		0
	2015	16/05/2015	08/06/2015	24	225	66	27/05/2015	13/05/2015		-3
	2016	08/04/2016	26/05/2016	49	392	105	09/05/2016	04/05/2016		26
Pinaceae	2013	10/04/2010	29/09/2013	173	963	166	22/05/2013	10/04/2013	2.7	0
	2014	27/03/2014	20/09/2014	178	581	76	14/05/2014	04/04/2014		8
	2015	17/04/2015	04/06/2015	49	836	99	24/04/2015	21/04/2015		4
	2016	06/03/2016	25/05/2016	81	1100	124	03/04/2016	13/03/2016		6
Platanus	2013	01/04/2013	30/04/2013	30	116	17	10/04/2013	01/04/2013	3.8	0
	2014	24/03/2014	20/04/2014	28	160	24	24/03/2014	01/04/2014		8
Populus	2015	14/04/2015	29/04/2015	16	342	80	26/04/2015	14/04/2015		0
	2016	16/03/2016	14/04/2016	30	773	108	05/04/2016	14/03/2016		-2
	2013	07/03/2013	23/04/2013	48	54	9	31/03/2013			
	2014	04/03/2014	11/04/2014	39	48	11	21/03/2014			
Quercus	2015	23/03/2015	14/04/2015	23	34	19	14/04/2015			
	2016	27/02/2016	30/03/2016	33	38	10	28/03/2016			
	2013	25/03/2013	28/05/2013	65	275	48	29/04/2013	05/05/2013	18.7	41
	2014	09/04/2014	01/06/2014	54	209	26	14/05/2014	15/04/2014		36
	2015	21/04/2015	30/05/2015	40	627	62	29/04/2015	16/04/2015		25
	2016	22/03/2016	19/05/2016	59	1516	232	04/04/2016	15/03/2016		-7

Table 1 (continued)

Taxon	Year	PS start	PS end	Duration (days)	SPI _n	Peak Value	Peak Date	1st day of 5 non-zero record date	Sd	Days difference
Salix	2013	11/03/2013	22/04/2013	43	208	56	13/04/2013	01/04/2013	7.6	21
	2014	17/03/2014	29/04/2014	44	321	41	24/03/2014	17/03/2014		0
Ulmaceae	2015	01/04/2015	11/05/2015	41	92	11	30/04/2015	14/04/2015		13
	2016	28/02/2016	15/04/2016	48	104	21	28/03/2016	14/03/2016		15
	2013	08/03/2013	31/03/2013	24	34	11	19/03/2013			
	2014	19/01/2014	28/03/2014	69	94	11	12/02/2014			
	2015	24/02/2015	08/04/2015	44	9	2	26/02/2015			
	2016	04/02/2016	17/03/2016	43	25	4	11/02/2016			

Quercus and *Castanea* had a shorter pre-peak period than *Alnus*, which can be inferred from the positive skewness of the distribution. *Alnus* displayed a short and intense flowering period. *Fagus* and *Betula* showed a more uniform distribution without a pronounced peak.

Variation in the interannual flowering intensity was pronounced for most species. We observed remarkable differences in the SPI_n of single years (Tables 1, 2 and Fig. 4). In 2013, the SPI_n of Poaceae was about four times (2426 pollen*day*m⁻³) and of *Plantago* (666 pollen*day*m⁻³), two times higher than the mean concentrations of the other three years observed. *Olea* had the highest SPI_n and peak value in 2013. Comparably higher SPI_ns and peak concentrations were observed also in *Salix* both in 2013 and 2014. In 2014 the SPI_n of *Corylus* (67 pollen*day*m⁻³) and *Alnus* (223 pollen*day*m⁻³) was over two times higher than the mean. The SPI_n of *Carpinus* was five times higher in 2015 (234 pollen*day*m⁻³) and nine times higher in 2016 (429 pollen*day*m⁻³) than the mean SPI_n of the two preceding years 2013 and 2014 (48 pollen*day*m⁻³). All in all, seven woody taxa (Pinaceae, *Platanus*, *Fraxinus*, Cupressaceae, *Betula*, *Quercus* and *Castanea*) out of 20 showed an obvious increase in the SPI_n in 2016. The SPI_n of *Ambrosia* increased steadily from 476 pollen*day*m⁻³ in 2013, to 539 pollen*day*m⁻³ in 2014 and 600 pollen*day*m⁻³ in 2015.

Weekly mean pollen concentrations of the 15 main pollen contributing taxa recorded in Büyükçekmece are shown in Fig. 6. The highest pollen concentrations were found in the months April and May. Table 3 provides an overview of taxa with concentrations >=100 pollen*m⁻³. Over the entire study period the highest pollen loads were recorded in April 2016. The API_n in 2013 was 9591 pollen*day*m⁻³; in 2014: 6695 pollen*day*m⁻³; in 2015: 7458 pollen*day*m⁻³. Interestingly, till the 26th June 2016 already more pollen (10790 pollen*day*m⁻³) was shed than in all the other years monitored.

Fraxinus and Pinaceae displayed pronounced bimodal flowering periods (Fig. 6). Low pollen concentrations of Cupressaceae were recorded irregularly in autumn, mostly in October and November and in the last week of December. *Urtica* and *Plantago* pollen were not continuously recorded during the season.

Table 2 Annual pollen seasons (PS), start and end date, duration, peak value and day, and the Seasonal Pollen Integral (SPI_n) of herbaceous taxa. For the main pollen contributing taxa the 1st day of 5 consecutive non-zero records, the standard deviation (Sd), and the days difference between the methods to define the season start date is reported. Empty cells imply not applicable calculations or data deficiency

Taxon	Year	PS start	PS end	Duration	SPI _n	Peak Value	Peak Date	1st day of 5 non-zero record date	Sd	Days difference
Amaranthaceae	2013	26/05/2013	15/09/2013	113	202	28	09/08/2013			
	2014	17/05/2014	22/10/2014	159	93	6	05/09/2014			
	2015	28/05/2015	20/09/2015	116	247	31	27/08/2015	24/07/2015		57
	2016									
Ambrosia	2013	03/07/2013	15/09/2013	75	471	51	19/08/2013	06/08/2013	14.9	35
	2014	28/07/2014	20/09/2014	55	539	89	05/09/2014	09/08/2014		12
	2015	07/08/2015	27/09/2015	52	600	138	31/08/2015	06/08/2015		– 1
	2016									
Apiaceae	2013	09/05/2013	08/09/2013	123	27	6	23/05/2013			
	2014	12/05/2014	14/08/2014	95	28	2	26/05/2014			
	2015	19/05/2015	31/08/2015	105	81	10	09/07/2015			
	2016	28/04/2016	25/06/2016	59	86	11	20/05/2016			
Atremisia	2013	31/07/2013	28/09/2013	60	107	12	01/08/2013			
	2014	13/07/2014	08/11/2014	119	45	3	10/08/2014			
	2015	15/07/2015	03/10/2015	81	78	7	27/08/2015			
	2016									
Brassicaceae	2013	25/09/2013	25/09/2013	1	1	1	25/09/2013			
	2014	05/04/2014	19/09/2014	168	44	7	13/05/2014			
	2015	03/04/2015	18/07/2015	107	25	4	27/04/2015			
	2016	04/04/2016			95	21	15/04/2016			
Cannabaceae	2013	01/08/2013	15/09/2013	46	68	9	02/08/2013			
	2014	23/07/2014	10/09/2014	50	32	4	03/09/2014			
	2015	17/07/2015	04/09/2015	50	27	3	15/08/2015			
	2016									
Plantago	2013	20/05/2013	04/08/2013	77	209	29	23/05/2013	20/05/2013	0.5	0
	2014	20/04/2014	14/09/2014	148	97	7	20/06/2014			
	2015	23/04/2015	12/08/2015	112	108	8	06/06/2015	22/04/2015		– 1
	2016									
Poaceae	2013	04/05/2013	14/09/2013	134	2426	248	21/05/2013	01/05/2013	2.3	1
	2014	06/04/2014	24/09/2014	172	482	42	12/05/2014	06/04/2014		0
	2015	26/04/2015	19/09/2015	147	869	66	22/05/2015	21/04/2015		– 5
	2016	27/03/2016				47	09/05/2016	25/03/2016		– 2
Rumex	2013	16/04/2013	25/05/2013	40	14	4	07/05/2013			
	2014	09/04/2014	13/07/2014	96	35	6	31/05/2014			
	2015	17/04/2015	21/07/2015	96	45	7	17/05/2015			
	2016									
Urticaceae	2013	27/04/2013	15/11/2013	203	179	22	13/08/2013	31/07/2013	49.9	95
	2014	03/02/2014	08/11/2014	279	281	12	23/07/2014	06/06/2014		123
	2015	05/04/2015	27/08/2015	145	280	18	31/05/2015	17/05/2015		42
	2016	06/02/2016			247	16	19/06/2016	30/01/2016		– 7

Table 2 (continued)

Taxon	Year	PS start	PS end	Duration	SPI _n	Peak Value	Peak Date	1st day of 5 non-zero record date	Sd	Days difference
Xanthium	2013	01/08/2013	22/09/2013	53	43	7	01/09/2013			
	2014	05/08/2014	23/09/2014	50	34	7	02/09/2014			
	2015	10/08/2015	13/09/2015	35	28	4	23/08/2015			
	2016									

Fig. 3 Variability in the pollen season start and end dates of the 15 main pollen taxa monitored in Büyükçekmece between January 2013 and June 2016

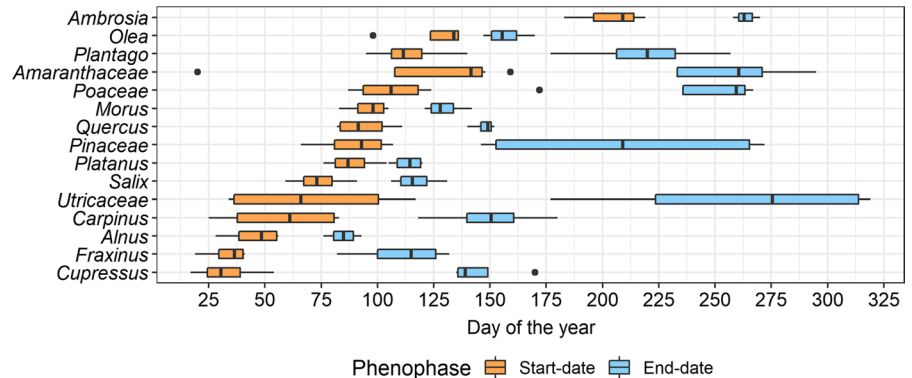
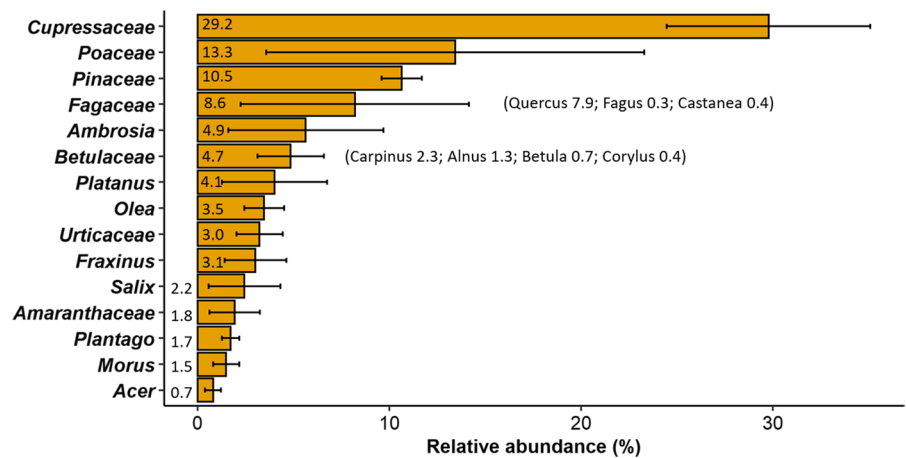


Fig. 4 Relative abundance of the 15 main pollen taxa during the study period based on API_ns. The error bars reflect the annual variability. *Alnus*, *Corylus*, *Carpinus* and *Betula* are grouped into Betulaceae; *Quercus*, *Fagus* and *Castanea* into Fagaceae



3.4 The effect of meteorological factors

We observed an increased flowering intensity in spring flowering trees in 2015 and even more so in 2016. This was most likely elicited by abundant and evenly distributed rains throughout spring 2014 and the second half of 2014 including the winter months, which continued into spring 2015 (Table 4). As a

result, the API_n in 2015 was higher than in 2014. In Istanbul’s winters, humidity is higher than it is in summer (Table 4) with pronounced daily fluctuations due to frequent precipitation events during this season. Water was sufficiently available during the vegetative growth period in winter and early spring during the years studied. The dry period in Istanbul lasts from May to September (Fig. 1). We investigated the effect of meteorological factors on the 15 main woody

Fig. 5 The phenology and relative intensity of Fagales pollen taxa (January 2013–June 2016) calculated on the base of the density of daily mean pollen concentration records of each taxon without scales and units

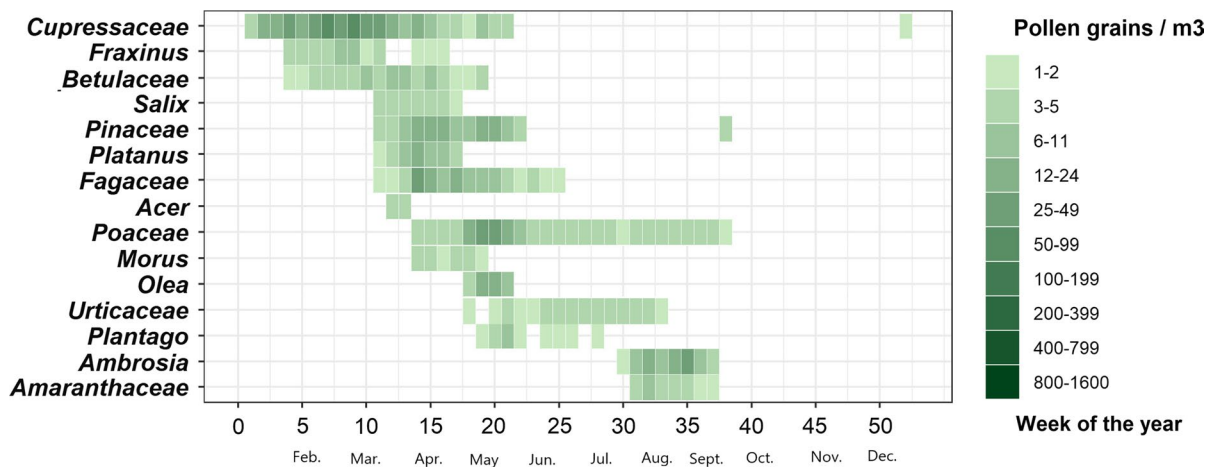
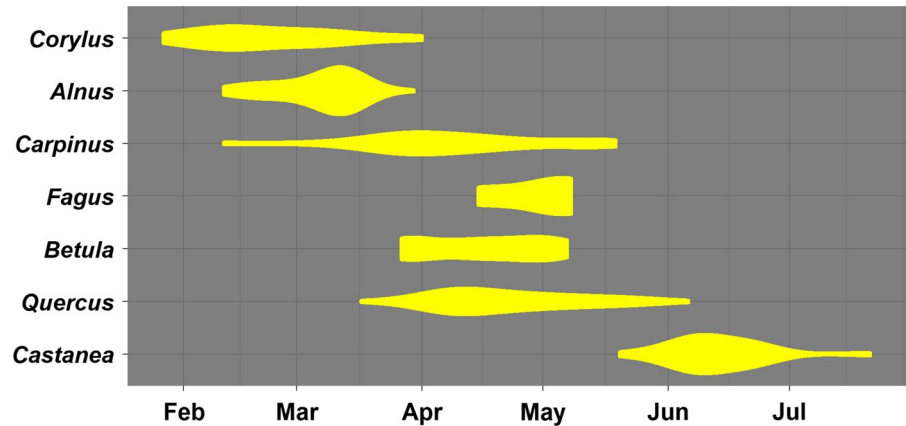


Fig. 6 Phenology and intensity of pollen based on mean weekly airborne pollen concentrations on a 10 scaled-colour gradient of the main pollen taxa monitored in Büyükçekmece.

Weekly means < 1 are not considered in the plot, so that staggered occurrence is eliminated

and herbaceous taxa with generalized additive models (GAMs) (Table 5).

In GAMs including the entire study period, we observed the following patterns (Table 5): The effect of temperature on pollen concentrations was significantly negative for tree taxa mainly flowering in winter and spring within April (Table 1 and Fig. 6). On Poaceae and *Olea*, with peak flowering in May, the effect faded. For the weeds with flowering phenophase in summer (*Plantago*, Amaranthaceae and *Ambrosia*), the effect of temperature turned to be the opposite. This applies also to Urticaceae, which have their peak in summer (Table 2, Fig. 6). Relative humidity had a positive effect on winter and spring flowering Cupressaceae, *Fraxinus*, Betulaceae and *Salix*, and in Fagaceae. Significances

for relative humidity, pressure, and precipitation were mostly negative for taxa with a pollen season in summer.

4 Discussion

4.1 Flowering phenology

Airborne pollen can be used to infer the timing of flowering of taxa that are relevant in allergological terms. The intensity of the pollen season depends on the magnitude of the flowering, as well as on weather and climate (Dahl et al., 2013). The duration of the season, however, is bound to how it is defined. The

Table 3 The frequency of daily pollen concentrations $\geq 100 \text{ p}^* \text{m}^{-3}$, $\geq 200 \text{ p}^* \text{m}^{-3}$, $\geq 400 \text{ p}^* \text{m}^{-3}$ recorded over the study period

Year	Taxon	Concentration ($\text{p}^* \text{m}^{-3}$)		
		≥ 100	≥ 200	≥ 400
2013	Cupressaceae	7	3	0
	Olea	1	1	0
	Pinaceae	1	0	0
	Poaceae	8	3	0
2014	Cupressaceae	3	0	0
2015	Ambrosia	1	0	0
	Cupressaceae	4	2	1
2016	Carpinus	1	0	0
	Cupressaceae	10	3	2
	Pinaceae	1	0	0
	Platanus	1	0	0
	Quercus	3	1	0

95% method based on the APIn (Andersen, 1991), can be suitable for low pollen concentrations (Bastl et al., 2018), as it is the case at the trap location in Büyükcemece/Istanbul with APIns $< 10.000 \text{ pollen}^* \text{day}^* \text{m}^{-3}$ during 2013–2015. To compare, Kastamonu, located in the mountainous Turkish Black Sea Region with dense forest cover, has APIns $> 100.000 \text{ pollen}^* \text{day}^* \text{m}^{-3}$ (Çeter et al., 2012); Antalya, on the Mediterranean coast on the foot of the Taurus mountains has $> 20.000 \text{ pollen}^* \text{day}^* \text{m}^{-3}$ (Tosunoglu et al., 2015). The disadvantage of the percentual method is that the delineation of seasons depends on the flowering intensity, on missing data in the database, and can only be done retrospectively (Bastl et al., 2018; Grundström et al., 2019). The inherent bias for an earlier start of the season for years with lower intensities was seen, for example, in Poaceae and *Ambrosia*. Alternatively, with the 1st day of 5 non-zero concentrations, the start date of the season was generally delayed, except for taxa with high pollen production, such as Cupressaceae or Poaceae. For *Fraxinus* and *Platanus*, but also Pinaceae, Poaceae, and *Plantago* the season start date using both methods were very similar. In South Spain the pollen season start for *Fraxinus* and *Populus* was defined with 1 pollen grain $^* \text{m}^{-3}$ plus 5 non-zero concentrations (Velasco-Jiménez et al., 2020) suggesting that this method could possibly work also in Istanbul for some taxa. The five consecutive non-zero

concentrations are not suitable for all taxa at our location because the start date would fall far into the main flowering phase of the taxon and even trespass the first peak. Grundström et al (2019), who analysed several methods to calculate the oak pollen season across Europe found that the cumulative sum method of three consecutive days with $5 \text{ p}^* \text{m}^{-3}$ delayed the start 10–12 days into the oak season as compared to the cumulative sum of 50 pollen grains. Further investigation targeted to individual taxa would be needed to delineate the most suitable method to define the pollen season in Istanbul. Other factors determine the duration of the pollen season. First, the taxonomic level of identification of a taxon under the light microscope, whether it consists of a species (i.e. *Olea europaea*), genus (i.e. *Quercus*) or family (i.e. Cupressaceae, Poaceae). Second, if conspecific plants flower at the same time (synchronously) or continuously staggered (asynchronously) and how many flowers are open per day (the flowering rate). The third important factor is weather conditions (Dahl et al., 2013). The pollen season start and end of herbaceous plants, for example, Urticaceae, showed considerable variations over three pollen seasons and a long flowering duration. In Urticaceae we can observe asynchronous flowering with the contribution of *Parietaria judaica* to the pollen spectrum of this family. *Parietaria judaica*, a perennial herb, grows and flowers all year long in shaded, ruderal urban (wall) communities of the city (Altay et al., 2010). Continuous growth ensures reproduction when availability of resources is unpredictable (Fotiou et al., 2011). The course of the Urticaceae season in Istanbul was comparable to the Urticaceae season in Thessaloniki (Fotiou et al., 2011), with continuous records from May to August and irregular ones stretching into November. In contrast, in Krakow, in an analysis of pollen season dynamics on a 17 year long data series, pollen seasons of herbaceous plants were reported to have generally low variability with regard to the season start and end date (Myszkowska et al., 2011). We explain this difference with summer drought in Mediterranean regions forcing herbaceous plants to an opportunistic flowering behaviour (Dahl et al., 2013). In Krakow, a typical city with warm temperate cfb climates of Europe, June, July and August are the wettest months (Climate-Data.org, 1999), while they are the driest in Istanbul. The pollen season start and end dates were less variable for grasses. The onset

of the grass pollen season in Istanbul is preceded by regular equinoctial (winter) rains facilitating growth during the developmental phase (Dahl et al., 2013). This leads to rather short and intense flowering peaks. When abundant rains occur during anthesis, the grass pollen season can be prolonged (Dahl et al., 2013). We observed this phenomenon during 2014, when grass flowering coincided with persistent rainfalls in spring.

Woody taxa had generally shorter pollen seasons than herbaceous ones, which was also observed by Werchan et al. (2018) and Myszkowska et al. (2011). The season end of Pinaceae, however, was prolonged due to the bi-modal flowering of this taxon. Tosunoglu et al. (2015) identified a distinct pollen season for *Cedrus* in Antalya, from the end of September to mid-December, with highest concentrations in October. It could be envisioned to record *Cedrus*-pollen separately from the rest of the Pinaceae family also in Istanbul to better delineate the pollen season of this taxon. Cupressaceae, *Carpinus* and *Fraxinus* had long seasons, too. In the case of ash, for example, *Fraxinus angustifolia* flowers in early spring, but *Fraxinus ornus* in April. While *Fraxinus angustifolia* is a common ornamental tree, *F. ornus* grows in the submediterranean woods in the hinterland of the city. The consequence is an ash season that can possibly stretch from the last week of January into the beginning of May. We observed pollen of *Carpinus* rather irregularly, with two months difference in the start and the end date of pollen seasons in four years of observations. The *Carpinus/Ostrya* type in Split (Croatia) varied also six weeks in the season start (Puljak et al., 2016). Eurosiberian vegetation is found mostly about 80 km upwind and at ca. 15 km downwind of our trap location. Temporal shifts in the beginning of flowering due to temperature differences at the different growth locations, and atmospheric transport can explain the long season of this taxon.

4.2 Flowering intensity

Relative abundances and the SPIn of pollen are measures of flowering intensity. Differences in the magnitudes have to be discussed in the light of annual variations and the bias of the trap height for some taxa in 2013 and early 2014. Annual variation depends on meteorological conditions and species inherent physiological flowering dynamics in

woody perennial plants. The weather determines the amount of resources (i.e. assimilates in form of carbohydrates, the resorption of nutrients) that a plant can accumulate (Bogdziewicz et al., 2017; Dahl et al., 2013; Dahl & Strandhede, 1996). In 2016, conspicuously high intensities of Cupressaceae, *Quercus*, *Fraxinus*, Pinaceae, *Platanus* and *Carpinus* seem to be the result of favourable environmental conditions for the accumulation of resources acting across families. We suspect a masting phenomenon across taxa and populations. Masting, in fact, does not occur independently of environmental factors (Bogdziewicz et al., 2017). At time intervals plant populations in a wider area spend these resources in highly synchronous mass reproduction (Koenig et al., 2015). Masting is typical for many wind-pollinated woody species (Pearse et al., 2016) including *Betula*, *Quercus*, and *Fraxinus* (Bogdziewicz et al., 2020; Dahl et al., 2013; Dahl & Strandhede, 1996; Tapper, 1992). The correlation of weather with synchronous fluctuations in pollination success of isolated populations (known as pollination Moran effect) acts on individuals of the same taxon but also across taxa and ecosystems (Hansen et al., 2020; Pearse et al., 2016). Interestingly, in 2016 the highest birch pollen concentrations since the start of the records were reported for Poland and connected to long distance transport from Southeast Europe early in the birch pollen season in April (Myszkowska et al., 2021).

An increased magnitude of pollen with pronouncedly higher daily peak values of Poaceae and *Plantago* growing within 10 m of the trap location was detected when the trap was positioned at three m height, than when it was positioned at 10 m height. Also, higher peak values of *Olea*, *Salix* and possibly Pinaceae in 2013 could result from stands in the vicinity. Conversely, several *Platanus* trees grow about 250 m (N)NE of the original trap location but pollen concentrations were not increased in comparison to other years. Pollen concentration, in fact, is highest in the immediate vicinity of the source (Adams-Groom et al., 2017). All in all, the change of the trap height did not constitute an apparent effect on most pollen type concentrations monitored, which is consistent with Rojo et al. (2019a).

The main contributing pollen taxa in Istanbul observed during the study period are very similar to the taxa reported for Thessaloniki (in order of magnitude: Cupressaceae, *Quercus*, Urticaceae, Oleaceae,

Pinaceae, Poaceae, *Platanus*, *Corylus*, Amaranthaceae, Asteraceae, *Populus* and Plantaginaceae) (Gioulekas et al., 2004). The city is located at a similar geographical latitude as Istanbul and has warm-temperate cfa climate with more precipitation in summer (Climate-Data.org, 1999). Cupressaceae typically dominates the pollen spectrum of Mediterranean cities in the winter and spring (Puljak et al., 2016; Tosunoglu et al., 2015; Martínez-Bracero et al., 2015; Gioulekas et al., 2004). Cupressaceae pollen can be responsible for pollinosis early in the year (Asero et al., 2020; Charpin et al., 2019; Sposato & Scalsese, 2013). However, sensitization to Cupressaceae allergen in western Istanbul seems low (3%) (Zemmer et al., 2021). Comparing data from our trap location in the western suburbs with data from Central Istanbul obtained between 2005 and 2006 (Celenk et al., 2010), relative abundances for Cupressaceae (34%), *Fraxinus* (3%), and Moraceae (2%) were similar. Abundances of Poaceae, Pinaceae, *Quercus*, *Olea* and *Salix* pollen, in contrast, were considerably higher at our site, while *Platanus* (24%) and Urticaceae pollen (13%) appeared to be more important in the city centre. In highly urbanised Central Istanbul ornamentals like *Platanus* and *Fraxinus* are frequent. In the historic peninsula there are still many *Platanus* trees originating from the Ottoman Empire (Baser, 2011) which are very large in size. Besides, *Parietaria judaica* is the most common species on the ancient stone walls of the city (Altay et al., 2010). In contrast, the hinterland of Istanbul features grass- and woodlands. Pollen from taxa of the Fagales order reached considerable concentrations at our study site, due to northeasterly air currents. Considering Fagales as a group facilitates the practitioner as well as self-empowered patients to identify periods of increased incidence of this allergenic pollen. Highly allergenic *Ambrosia* has become the main weed pollen contributor in western Istanbul with proven clinical relevance (Zemmer et al., 2021). A clinical pollen season (Pfaar et al., 2017) of ragweed identified on the base of pollen data from 2018 (Hoffmann et al., 2020), endorses this finding.

4.3 Meteorological factors

An important limiting factor for flowering intensity in the Mediterranean is precipitation (Galán et al., 2016; Dahl et al., 2013). Prior to anthesis, in the example of

Betula, catkin initiation depends on the availability of assimilates during the vegetation period previous to flowering (Dahl & Strandhede, 1996). In summer-dry Istanbul, water availability plays an important role in this process (Table 4).

The flowering intensity of herbaceous plants such as grasses and weeds is influenced by meteorological conditions during vegetative growth (Dahl et al., 2013). The peak flowering period of grasses in Istanbul is May. Water was sufficiently available during the vegetative growth period in winter and early spring during the years studied, necessary for the induction of flowering shoots (Dahl et al., 2013). Drought, as a limiting growth factor in the study area, might have affected the intensity of the Urticaceae pollen season in 2013. This taxon has the peak period in summer, but flowers all year so that water deprivation might have reduced the vigour of the plants and the ability to produce flowers.

To assess the effect of meteorological factors during anthesis we ran GAMs. In aerobiological studies, the relationship between meteorological factors and pollen concentrations is often discussed on the base of correlations (Kluska et al., 2020; Bruffaerts et al., 2018) and regressions (Gioulekas et al., 2004) assuming a linear dependency (Le, 2003). The effects of meteorological factors studied in a GAM provide insight on flowering behaviour and can be part of predictive models (Cordero et al., 2021). Significances in the GAMs reflected direct impacts of meteorological factors on the pollen curve during peak flowering periods. If the factor units follow the pollen curve, the effect will be positive, otherwise negative. Temperature models were significantly positive when pollen concentrations rose with rising temperatures, as in the case of weeds. Summer rains – often torrential – reduce temperatures. As temperatures rise again and humidity decreases when skies clear, dehiscence occurs (Dahl et al., 2013). The effect turns negative when the pollen curve falls as temperatures are still on the rise as seen in spring flowering trees. Grasses and *Olea* flower at the onset of summer when temperatures increase and precipitation becomes less frequent. This may explain why the GAM model did not show a significant effect in temperature.

Humidity models were positive for early spring (winter) flowering trees, as Cupressaceae and *Fraxinus*. In Istanbul's winters humidity is higher than in summer with high daily fluctuations due to frequent

Table 4 Meteorological factors recorded during the study period. Precipitation data of 2012 were included for the interpretation of the effects on the flowering of woody taxa

Parameter/ MONTH	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual precipita- tion
2012 Precipitation (mm)	41	111	40	115	54	27	2	46	18	33	40	131	658
2013 Max. mean tem- perature (°C)	10	12	14	18	25	27	30	31	26	19	14	10	
Min. mean tem- perature (°C)	4	6	7	10	16	20	22	23	18	6	11	4	
Mean rel. humidity (%)	76	74	68	66	63	60	54	59	54	73	73	72	
Mean pressure (hPa)	1021	1012	1009	1012	1009	1009	1010	1010	1011	1012	1016	1025	
Precipitation (mm)	94	68	66	32	21	22	7	11	8	52	62	50	494
2014 Max. mean tem- perature (°C)	12	12	15	19	22	26	30	30	25	20	15	13	
Min. mean tem- perature (°C)	6	6	7	11	15	19	22	23	19	14	10	8	
Mean rel. humidity (%)	80	78	71	71	70	68	63	65	68	78	75	81	
Mean pressure (hPa)	1015	1016	1012	1010	1009	1010	1008	1008	1010	1014	1017	1115	
Precipitation (mm)	41	24	73	44	77	64	12	72	122	40	71	97	736
2015 Max. mean tem- perature (°C)	10	10	12	15	23	26	30	31	27	20	17	11	
Min. mean tem- perature (°C)	5	5	7	8	15	19	22	24	21	15	12	6	
Mean rel. humidity (%)	72	76	71	66	64	66	59	60	68	72	72	72	
Mean pressure (hPa)	1015	1028	1016	1014	1010	1010	1003	1010	1011	1016	1016	1026	
Precipitation (mm)	108	153	41	82	5	25	1	3	56	61	51	12	596
2016 Max. mean tem- perature (°C)	9	13	14	20	22	28							
Min. mean tem- perature (°C)	4	8	8	12	15	21							
Mean rel. humidity (%)	74	74	68	59	65	60							
Mean pressure (hPa)	1013	1016	1011	1010	1009	1009							
Precipitation (mm)	158	78	86	29	42	24							417 (first half of the year)

precipitation events during this season. Rising pollen curves must have coincided with rising mean humidity levels, when dehiscence can still occur at sunny spells during a day. In 2015, mean humidity was higher in February than in January and may have had an effect on the global model. Negative humidity

signals for summer flowering weeds could be either linked to both short term precipitation effects as in *Amaranthaceae* or *Ambrosia* or to a seasonal decrease in humidity after the peak period in the course the pollen seasons as in *Plantago*.

Table 5 The results of generalized additive models, where meteorological factors are used as independent variables, and pollen concentrations of the main pollen taxa are used as the dependent ones

Pollen taxon	T_{\max}	T_{\min}	Hum mean	Press mean	Prec
Cupressaceae	*** (-)	***(-)	**		.(-)
Fraxinus	***(-)	***(-)	*	**(-)	
Betulaceae	***(-)	***(-)	***		
Salix	***(-)	***(-)	**		
Pinaceae	*(-)	***(-)			
Acer	***(-)	***(-)			
Platanus	***(-)	***(-)			.(-)
Fagaceae	***(-)	***(-)	**		
Morus	***(-)	***(-)			
Olea				**(-)	
Poaceae		.(-)		***(-)	**(-)
Urticaceae	***	***	*** (-)	*** (-)	*(-)
Amaranthaceae	***	***	*** (-)	*** (-)	*** (-)
Ambrosia	***	***	*** (-)	*(-)	

Signif. codes <0.001 '***' <0.01 '**' <0.05 '*' <0.1 '.'

Negative estimate (-)

In weeds, the signals of atmospheric pressure were the same as in the humidity models. The moist parameters humidity, pressure and precipitation had a similar negative effect, as they are interconnected (Brenner, 2004). This was not evident in spring flowering trees due to daily weather fluctuations.

Precipitation generally lowers pollen concentrations (Paschalidou et al., 2020). This phenomenon occurs due to wash out (Tormo-Molina et al., 2010), whereby $5 \text{ mm} \cdot \text{h}^{-1}$ are necessary for a pronounced effect (Kluska et al., 2020) and is seen also in correlation analysis (Bruffaerts et al., 2018). In Poaceae, for example, an extended period of rain during the last week of April and first decade of May in 2014 may have caused a decrease in airborne pollen concentrations and explain the negative effect in the GAM.

GAMs run over a time series of several years provide a more general picture on the effect of the factors studied on the pollen seasons, than seasonal or annual GAMs. A higher resolution of the effects on the pollen curve can be obtained with short term GAMs and used in forecasts (Cordero et al., 2021; Ravindra et al., 2019).

5 Conclusion

The main pollen contributing taxa were Cupressaceae, Poaceae, Pinaceae, *Quercus*, *Carpinus*, *Olea*, *Fraxinus*, Urticaceae, *Salix*, Amaranthaceae, *Plantago*, *Morus*, *Acer*, *Platanus* and neophytic ragweed. The definition of the pollen season, referring to the period when 95% of the APIn is dispersed, seems adequate due to low concentrations of airborne pollen. For Pinaceae, *Platanus*, *Fraxinus*, *Cupressaceae*, as well as for Poaceae and *Plantago*, the method of consecutive 5 non-zero daily concentrations could be an alternative to the percent-method. Further investigations on single taxa are needed to define a pollen season start detached from the percentual method. High pollen concentrations observed in 2016 indicate that weather cues prior to anthesis can trigger intense flowering across tree populations. We possibly witnessed a masting phenomenon. Further research on pollen seasons of neighbouring regions in 2016 would provide insight on the truth of this hypothesis. A change in how high the pollen trap was positioned mainly affected pollen concentrations of taxa growing

in the immediate surrounding. Differences in the importance of pollen contributing taxa between the city centre and the suburbs suggest that one trap in the city centre and one each at the western and eastern outskirts of the city would assure representable pollen information for Istanbul. GAMs provide causative explanations on the effect of weather on pollen concentrations during anthesis. Meteorological factors showed contrasting effects on spring and summer flowering taxa.

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Data availability Data spreadsheets used for analysis are provided upon request.

Declarations

Conflict of interest The authors declare that they have no known conflict of interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Adams-Groom, B., Skjøth, C. A., Baker, M., & Welch, T. E. (2017). Modelled and observed surface soil pollen deposition distance curves for isolated trees of *Carpinus betulus*, *Cedrus atlantica* *Juglans Nigra* and *Platanus Acerifolia*. *Aerobiologia*, 33(3), 407–416. <https://doi.org/10.1007/s10453-017-9479-1>
- Alan, Ş, Sarışahin, T., Acar Şahin, A., Kaplan, A., & Pinar, N. M. (2019). An assessment of ragweed pollen and allergen loads in an uninvaded area in the western black sea region of Turkey. *Aerobiologia*. <https://doi.org/10.1007/s10453-019-09620-z>
- Altay, V., Özyiğit, I. I., & Yarci, C. (2010). Urban ecological characteristics and vascular wall flora on the Anatolian side of Istanbul, Turkey. *Maejo International Journal of Science and Technology*, 4(03), 483–495.
- Andersen, T. B. (1991). A model to predict the beginning of the pollen season. *Grana*, 30(1), 269–275. <https://doi.org/10.1080/00173139109427810>
- Ansotegui, I. J., Melioli, G., Canonica, G. W., Caraballo, L., Villa, E., Ebisawa, M., Passalacqua, G., Savi, E., Ebo, D., Gómez, R. M., Luengo Sánchez, O., Oppenheimer, J. J., Jensen-Jarolim, E., Fischer, D. A., Haahtela, T., Antila, M., Bousquet, J. J., Cardona, V., Chiang, W. C., & Zuberbier, T. (2020). IgE allergy diagnostics and other relevant tests in allergy, a World Allergy Organization position paper. *World Allergy Organization Journal*, 13(2), 100080. <https://doi.org/10.1016/j.waojou.2019.100080>
- Asero, R., Ceriotti, V., & Bonini, M. (2020). Cypress pollen allergy in milan: The story of an ongoing growth. *European Annals of Allergy and Clinical Immunology*. <https://doi.org/10.23822/EurAnnACI.1764-1489.155>
- Bakis, Y., Babac, M., & Uslu, E. (2020). Turkish Plants Data Service (TÜBİVES). <http://www.tubives.com/>
- Baser, B. (2011). Natural and cultural traces of the flora of Istanbul. *Turkish Academy of Sciences Journal of Cultural Inventory*, 9, 155–170.
- Bastl, K., Bastl, M., Bergmann, K.-C., & Berger, U. (2019). How to do a clinical trial? Recommendations from the aerobiological point of view. *World Allergy Organization Journal*, 12(4), 100020. <https://doi.org/10.1016/j.waojou.2019.100020>
- Bastl, K., Kmenta, M., & Berger, U. E. (2018). Defining pollen seasons: Background and recommendations. *Current Allergy and Asthma Reports*, 18(12), 73. <https://doi.org/10.1007/s11882-018-0829-z>
- Bianchi, D. E., Schwemmin, D. J., & Wagner, W. H. (1959). Pollen release in the common ragweed (*ambrosia artemisiifolia*). *Botanical Gazette*, 120(4), 235–243.
- Bogdziewicz, M., Fernández-Martínez, M., Bonal, R., Belmonte, J., & Espelta, J. M. (2017). The moran effect and environmental vetoes: Phenological synchrony and drought drive seed production in a mediterranean oak. *Proceedings of the Royal Society B: Biological Sciences*, 284(1866), 20171784. <https://doi.org/10.1098/rspb.2017.1784>

- Bogdziewicz, M., Pesendorfer, M., Crone, E. E., Pérez-Izquierdo, C., & Bonal, R. (2020). Flowering synchrony drives reproductive success in a wind-pollinated tree. *Ecology Letters*, 23(12), 1820–1826. <https://doi.org/10.1111/ele.13609>
- Brenner, I. S. (2004). The relationship between meteorological parameters and daily summer rainfall amount and coverage in west-central Florida. *Weather and Forecasting*, 19(2), 286–300. [https://doi.org/10.1175/1520-0434\(2004\)019%3c0286:TRBMPA%3e2.0.CO;2](https://doi.org/10.1175/1520-0434(2004)019%3c0286:TRBMPA%3e2.0.CO;2)
- Bruffaerts, N., De Smedt, T., Delcloo, A., Simons, K., Hoebeke, L., Verstraeten, C., Van Nieuwenhuysse, A., Packedu, A., & Hendrickx, M. (2018). Comparative long-term trend analysis of daily weather conditions with daily pollen concentrations in Brussels Belgium. *International Journal of Biometeorology*, 62(3), 483–491. <https://doi.org/10.1007/s00484-017-1457-3>
- Cariñanos, P., Casares-Porcel, M., & Quesada-Rubio, J.-M. (2014). Estimating the allergenic potential of urban green spaces: A case-study in Granada, Spain. *Landscape and Urban Planning*, 123, 134–144. <https://doi.org/10.1016/j.landurbplan.2013.12.009>
- Celenk, S., Bicakci, A., Tamay, Z., Guler, N., Altunoglu, M. K., Canitez, Y., Malyer, H., Sapan, N., & Ones, U. (2010). Airborne pollen in European and Asian parts of Istanbul. *Environmental Monitoring and Assessment*, 164(1–4), 391–402. <https://doi.org/10.1007/s10661-009-0901-1>
- EN 16868. (2019). Ambient air—Sampling and analysis of airborne pollen grains and fungal spores for networks related to allergy—Volumetric hirst method.
- Çeter, T., Pinar, N. M., Güney, K., Yildiz, A., Aşçı, B., & Smith, M. (2012). A 2 year aeropalynological survey of allergenic pollen in the atmosphere of Kastamonu Turkey. *Aerobiologia*, 28(3), 355–366. <https://doi.org/10.1007/s10453-011-9240-0>
- Charpin, D., Pichot, C., Belmonte, J., Sutra, J.-P., Zidkova, J., Chanez, P., Shahali, Y., Sénéchal, H., & Poncet, P. (2019). Cypress pollinosis: From tree to clinic. *Clinical Reviews in Allergy & Immunology*, 56(2), 174–195. <https://doi.org/10.1007/s12016-017-8602-y>
- Climate-Data.org. (1999). Climate data for cities worldwide. <https://en.climate-data.org/>
- Çoban, S., Bayraktar, S., & Akgül, M. (2016). Forest vegetation maps and its development in turkey: A case study from istanbul-belgrade forest. *Forest Review*, 47(7), 7–16.
- Cordero, J. M., Rojo, J., Gutiérrez-Bustillo, A. M., Narros, A., & Borge, R. (2021). Predicting the *Olea* pollen concentration with a machine learning algorithm ensemble. *International Journal of Biometeorology*, 65(4), 541–554. <https://doi.org/10.1007/s00484-020-02047-z>
- D'Amato, G., Cecchi, L., Bonini, S., Nunes, C., Annesi-Maesano, I., Behrendt, H., Liccardi, G., Popov, T., & van Cauwenberge, P. (2007). Allergenic pollen and pollen allergy in Europe. *Allergy*, 62(9), 976–990. <https://doi.org/10.1111/j.1398-9995.2007.01393.x>
- D'Amato, G., Chong-Neto, H. J., Monge Ortega, O. P., Vitale, C., Ansotegui, I., Rosario, N., Haahtela, T., Galán, C., Pawankar, R., Murrieta-Aguttes, M., Cecchi, L., Bergmann, C., Ridolo, E., Ramon, G., Gonzalez Diaz, S., D'Amato, M., & Annesi-Maesano, I. (2020). The effects of climate change on respiratory allergy and asthma induced by pollen and mold allergens. *Allergy*, 75(9), 2219–2228. <https://doi.org/10.1111/all.14476>
- Dahl, Å., Galán, C., Hajkova, L., & Pauling, A. (2013). The onset, course and intensity of the pollen season. In M. Sofiev & B. C. Bergmann (Eds.), *Allergenic pollen: A review of the production, release, distribution and health impacts* (pp. 29–70). Springer.
- Dahl, Å., & Strandhede, S.-O. (1996). Predicting the intensity of the birch pollen season. *Aerobiologia*, 12(2), 97–106. <https://doi.org/10.1007/BF02446601>
- Damialis, A., Gioulekas, D., Lazopoulou, C., Balafoutis, C., & Vokou, D. (2005). Transport of airborne pollen into the city of Thessaloniki: The effects of wind direction, speed and persistence. *International Journal of Biometeorology*, 49(3), 139–145. <https://doi.org/10.1007/s00484-004-0229-z>
- Damialis, A., Traidl-Hoffmann, C., & Treudler, R. (2019). Climate change and pollen allergies. In M. R. Marselle, J. Stadler, H. Korn, K. N. Irvine, & A. Bonn (Eds.), *Biodiversity and health in the face of climate change* (pp. 47–66). Springer.
- Eguiluz-Gracia, I., Mathioudakis, A. G., Bartel, S., Vijverberg, S. J. H., Fuertes, E., Comberiat, P., Cai, Y. S., Tomazic, P. V., Diamant, Z., Vestbo, J., Galán, C., & Hoffmann, B. (2020). The need for clean air: The way air pollution and climate change affect allergic rhinitis and asthma. *Allergy*, 75(9), 2170–2184. <https://doi.org/10.1111/all.14177>
- Fernández-Rodríguez, S., Skjøth, C. A., Tormo-Molina, R., Brandao, R., Caeiro, E., Silva-Palacios, I., Gonzalo-Garijo, Á., & Smith, M. (2014). Identification of potential sources of airborne *Olea* pollen in the south-west Iberian Peninsula. *International Journal of Biometeorology*, 58(3), 337–348. <https://doi.org/10.1007/s00484-012-0629-4>
- Fotiou, C., Damialis, A., Krigas, N., Halley, J. M., & Vokou, D. (2011). *Parietaria judaica* flowering phenology, pollen production, viability and atmospheric circulation, and expansive ability in the urban environment: Impacts of environmental factors. *International Journal of Biometeorology*, 55(1), 35–50. <https://doi.org/10.1007/s00484-010-0307-3>
- Galán, C., Alcázar, P., Oteros, J., García-Mozo, H., Aira, M. J., Belmonte, J., Diaz de la Guardia, C., Fernández-González, D., Gutiérrez-Bustillo, M., Moreno-Grau, S., Pérez-Badía, R., Rodríguez-Rajo, J., Ruiz-Valenzuela, L., Tormo, R., Trigo, M. M., & Domínguez-Vilches, E. (2016). Airborne pollen trends in the Iberian Peninsula. *Science of the Total Environment*, 550, 53–59. <https://doi.org/10.1016/j.scitotenv.2016.01.069>
- Galán, C., Alcázar-Teno, P., Domínguez-Vilches, E., Villamandos de la Torre, F., & Garcia-Pantaleon, F. I. (1995). Airborne pollen grain concentrations at two different heights. *Aerobiologia*, 11(2), 105–109. <https://doi.org/10.1007/BF02738275>
- Galán, C., Ariatti, A., Bonini, M., Clot, B., Crouzy, B., Dahl, A., Fernandez-González, D., Frenguelli, G., Gehrig, R., Isard, S., Levetin, E., Li, D. W., Mandrioli, P., Rogers, C. A., Thibaudon, M., Sauliene, I., Skjøth, C., Smith, M., & Sofiev, M. (2017). Recommended terminology for aerobiological studies. *Aerobiologia*, 33(3), 293–295. <https://doi.org/10.1007/s10453-017-9496-0>

- Galán, C., Smith, M., Thibaudon, M., Frenguelli, G., Oteros, J., Gehrig, R., Berger, U., Clot, B., & Brandao, R. (2014). Pollen monitoring: Minimum requirements and reproducibility of analysis. *Aerobiologia*, *30*(4), 385–395. <https://doi.org/10.1007/s10453-014-9335-5>
- García-Mozo, H., Mestre, A., & Galán, C. (2010). Phenological trends in southern Spain: A response to climate change. *Agricultural and Forest Meteorology*, *150*(4), 575–580. <https://doi.org/10.1016/j.agrformet.2010.01.023>
- Gehrig, R., Maurer, F., & Schwierz, C. (2018). Designing new automatically generated pollen calendars for the public in Switzerland. *Aerobiologia*, *34*(3), 349–362. <https://doi.org/10.1007/s10453-018-9518-6>
- Gioulekas, D., Balafoutis, C., Damialis, A., Papakosta, D., Gioulekas, G., & Patakas, D. (2004). Fifteen years' record of airborne allergenic pollen and meteorological parameters in Thessaloniki Greece. *International Journal of Biometeorology*, *48*(3), 128–136. <https://doi.org/10.1007/s00484-003-0190-2>
- Grundström, M., Adams-Groom, B., Pashley, C. H., Dahl, Å., Rasmussen, K., de Weger, L. A., Thibaudon, M., Fernández-Rodríguez, S., Silva-Palacios, I., & Skjøth, C. A. (2019). Oak pollen seasonality and severity across Europe and modelling the season start using a generalized phenological model. *Science of the Total Environment*, *663*, 527–536. <https://doi.org/10.1016/j.scitotenv.2019.01.212>
- Hansen, B. B., Grøtan, V., Herfindal, I., & Lee, A. M. (2020). The moran effect revisited: Spatial population synchrony under global warming. *Ecography*, *43*(11), 1591–1602. <https://doi.org/10.1111/ecog.04962>
- Heinzerling, L., Mari, A., Bergmann, K.-C., Bresciani, M., Burbach, G., Darsow, U., Durham, S., Fokkens, W., Gjomarkaj, M., Haahtela, T., Bom, A. T., Wöhrl, S., Mai-bach, H., & Lockey, R. (2013). The skin prick test – European standards. *Clinical and Translational Allergy*, *3*, 1. <https://doi.org/10.1186/2045-7022-3-3>
- Hintze, J. L., & Nelson, R. D. (1998). Violin plots: A box plot-density trace synergism. *The American Statistician*, *52*(2), 181–184. <https://doi.org/10.1080/00031305.1998.10480559>
- Hirst, J. M. (1952). An automatic volumetric spore trap. *Annals of Applied Biology*, *39*(2), 257–265. <https://doi.org/10.1111/j.1744-7348.1952.tb00904.x>
- Hoegh-Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, A., Diedhiou, A., Daljante, R., Ebi, K. L., Engelbrecht, F., & et al. (2018). Impacts of 1.5°C global warming on natural and human systems. In *Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.
- Hoffmann, T. M., Acar Şahin, A., Aggelidis, X., Arasi, S., Barbalace, A., Bourgoïn, A., Bregu, B., Brighetti, M. A., Caeiro, E., Caglayan Sozmen, S., Caminiti, L., Charpin, D., Couto, M., Delgado, L., Di Rienzo Businco, A., Dimier, C., Dimou, M. V., Fonseca, J. A., Goksel, O., & Dramburg, S. (2020). Whole versus fragmented approach to EAACI pollen season definitions: A multicenter study in six Southern European cities. *Allergy*, *75*(7), 1659–1671. <https://doi.org/10.1111/all.14153>
- Jato, V., Rodríguez-Rajo, F. J., Fernández-González, M., & Aira, M. J. (2015). Assessment of *Quercus* flowering trends in NW Spain. *International Journal of Biometeorology*, *59*(5), 517–531. <https://doi.org/10.1007/s00484-014-0865-x>
- Jenerowicz, D., Wojciech, S., Dańczak-Pazdrowska, A., & Polańska, A. (2012). Environmental factors and allergic diseases. *Annals of Agricultural and Environmental Medicine*, *19*(3), 475–481.
- Karatzas, K., Tsiamis, A., Charalampopoulos, A., Damialis, A., & Vokou, D. (2019). Pollen season identification for three pollen taxa in Thessaloniki, Greece: A 30 year retrospective analysis. *Aerobiologia*, *35*(4), 659–669. <https://doi.org/10.1007/s10453-019-09605-y>
- Katellaris, C. H., & Beggs, P. J. (2018). Climate change: Allergens and allergic diseases. *Internal Medicine Journal*, *48*(2), 129–134. <https://doi.org/10.1111/imj.13699>
- Kavgacı, A., Carni, A., Tecimeni, B., & Özalp, G. (2010). Diversity and ecological differentiation of oak forests in NW Thrace (Turkey). *Archives of Biological Sciences*, *62*(3), 705–718. <https://doi.org/10.2298/ABS1003705K>
- Kluska, K., Piotrowicz, K., & Kasprzyk, I. (2020). The impact of rainfall on the diurnal patterns of atmospheric pollen concentrations. *Agricultural and Forest Meteorology*, *291*, 108042. <https://doi.org/10.1016/j.agrformet.2020.108042>
- Koenig, W. D., Knops, J. M. H., Carmen, W. J., & Pearse, I. S. (2015). What drives masting? The phenological synchrony hypothesis. *Ecology*, *96*(1), 184–192. <https://doi.org/10.1890/14-0819.1>
- Le, C. T. (2003). *Introductory biostatistics*. Wiley-Interscience.
- Martin, M. D., Chamecki, M., & Brush, G. S. (2010). Anthesis synchronization and floral morphology determine diurnal patterns of ragweed pollen dispersal. *Agricultural and Forest Meteorology*, *150*(9), 1307–1317. <https://doi.org/10.1016/j.agrformet.2010.06.001>
- Martínez-Bracero, M., Alcázar, P., Díaz de la Guardia, C., González-Minero, F. J., Ruiz, L., Trigo Pérez, M. M., & Galán, C. (2015). Pollen calendars: A guide to common airborne pollen in Andalusia. *Aerobiologia*, *31*(4), 549–557. <https://doi.org/10.1007/s10453-015-9385-3>
- Matricardi, P. M., Kleine-Tebbe, J., Hoffmann, H. J., Valenta, R., Hilger, C., Hofmaier, S., Aalberse, R. C., Agache, I., Asero, R., Ballmer-Weber, B., Barber, D., Beyer, K., Biedermann, T., Bilò, M. B., Blank, S., Bohle, B., Bosshard, P. P., Breiteneder, H., Brough, H. A., & Ollert, M. (2016). EAACI Molecular allergology user's guide. *Pediatric Allergy and Immunology*, *27*, 1–250. <https://doi.org/10.1111/pai.12563>
- McInnes, R. N., Hemming, D., Burgess, P., Lyndsay, D., Osborne, N. J., Skjøth, C. A., Thomas, S., & Vardoulakis, S. (2017). Mapping allergenic pollen vegetation in UK to study environmental exposure and human health. *Science of the Total Environment*, *599–600*, 483–499. <https://doi.org/10.1016/j.scitotenv.2017.04.136>
- McKenna, O. E., Asam, C., Araujo, G. R., Roulias, A., Goullart, L. R., & Ferreira, F. (2016). How relevant is panallergen sensitization in the development of allergies? *Pediatric Allergy and Immunology*, *27*(6), 560–568. <https://doi.org/10.1111/pai.12589>

- Monroy-Colín, A., Silva-Palacios, I., Tormo-Molina, R., Maya-Manzano, J. M., Rodríguez, S. F., & Gonzalo-Garijo, Á. (2018). Environmental analysis of airborne pollen occurrence, pollen source distribution and phenology of *Fraxinus angustifolia*. *Aerobiologia*, *34*(3), 269–283. <https://doi.org/10.1007/s10453-018-9512-z>
- Myszkowska, D., Piotrowicz, K., Ziemianin, M., Bastl, M., Berger, U., Dahl, Å., Dąbrowska-Zapart, K., Górecki, A., Laffersová, J., Majkowska-Wojciechowska, B., Malkiewicz, M., Nowak, M., Puc, M., Rybnicek, O., Saarto, A., Šaulienė, I., Ščevková, J., Kofol Seliger, A., Šikoparija, B., & Czarnobilska, E. (2021). Unusually high birch (*Betula* spp.) pollen concentrations in Poland in 2016 related to long-range transport (LRT) and the regional pollen occurrence. *Aerobiologia*, *37*(3), 543–559. <https://doi.org/10.1007/s10453-021-09703-w>
- Myszkowska, D., Jenner, B., Stepalska, D., & Czarnobilska, E. (2011). The pollen season dynamics and the relationship among some season parameters (start, end, annual total, season phases) in Kraków, Poland, 1991–2008. *Aerobiologia*, *27*(3), 229–238. <https://doi.org/10.1007/s10453-010-9192-9>
- Pacini, E. (2000). From anther and pollen ripening to pollen presentation. *Plant Systematics and Evolution*, *222*(1/4), 19–43.
- Paschalidou, A. K., Pistaki, K., Charalampopoulos, A., Vokou, D., Kassomenos, P., & Damialis, A. (2020). Identifying patterns of airborne pollen distribution using a synoptic climatology approach. *Science of the Total Environment*, *714*, 136625. <https://doi.org/10.1016/j.scitotenv.2020.136625>
- Pearse, I. S., Koenig, W. D., & Kelly, D. (2016). Mechanisms of mast seeding: Resources, weather, cues, and selection. *New Phytologist*, *212*(3), 546–562. <https://doi.org/10.1111/nph.14114>
- Peñuelas, J., Filella, I., Zhang, X., Llorens, L., Ogaya, R., Lloret, F., Comas, P., Estiarte, M., & Terradas, J. (2004). Complex spatiotemporal phenological shifts as a response to rainfall changes. *New Phytologist*, *161*(3), 837–846. <https://doi.org/10.1111/j.1469-8137.2004.01003.x>
- Pfaar, O., Bastl, K., Berger, U., Buters, J., Calderon, M. A., Clot, B., Darsow, U., Demoly, P., Durham, S. R., Galán, C., Gehrig, R., Gerth van Wijk, R., Jacobsen, L., Klimek, L., Sofiev, M., Thibaudon, M., & Bergmann, K. C. (2017). Defining pollen exposure times for clinical trials of allergen immunotherapy for pollen-induced rhinoconjunctivitis—An EAACI position paper. *Allergy*, *72*(5), 713–722. <https://doi.org/10.1111/all.13092>
- Picornell, A., Oteros, J., Ruiz-Mata, R., Recio, M., Trigo, M. M., Martínez-Bracero, M., Lara, B., Serrano-García, A., Galán, C., García-Mozo, H., Alcázar, P., Pérez-Badía, R., Cabezudo, B., Romero-Morte, J., & Rojo, J. (2021). Methods for interpolating missing data in aerobiological databases. *Environmental Research*, *200*, 111391. <https://doi.org/10.1016/j.envres.2021.111391>
- Pinheiro, J., Bates, D., DebRoy, S., Sarkar, D., & R Core Team. (2021). nlme: Linear and nonlinear mixed effects models (R package version 3.1–152).
- Puljak, T., Mamić, M., Mitić, B., Hrga, I., & Hruševar, D. (2016). First aerobiological study in mediterranean part of Croatia Dalmatia: Pollen spectrum and seasonal dynamics in the air of split. *Aerobiologia*, *32*(4), 709–723. <https://doi.org/10.1007/s10453-016-9444-4>
- Ravindra, K., Rattan, P., Mor, S., & Aggarwal, A. N. (2019). Generalized additive models: Building evidence of air pollution, climate change and human health. *Environment International*, *132*, 104987. <https://doi.org/10.1016/j.envint.2019.104987>
- Rojo, J., Oteros, J., Pérez-Badía, R., Cervigón, P., Ferencova, Z., Gutiérrez-Bustillo, A. M., Bergmann, K.-C., Oliver, G., Thibaudon, M., Albertini, R., Rodríguez-De la Cruz, D., Sánchez-Reyes, E., Sánchez-Sánchez, J., Pessi, A.-M., Reinharju, J., Saarto, A., Calderón, M. C., Guerrero, C., Berra, D., & Buters, J. (2019a). Near-ground effect of height on pollen exposure. *Environmental Research*, *174*, 160–169. <https://doi.org/10.1016/j.envres.2019.04.027>
- Rojo, J., Picornell, A., & Oteros, J. (2019b). Aerobiology: The computational tool for biological data in the air. *Methods in Ecology and Evolution*, *10*(8), 1371–1376. <https://doi.org/10.1111/2041-210X.13203>
- Rojo, J., Rapp, A., Lara, B., Fernández-González, F., & Pérez-Badía, R. (2015). Effect of land uses and wind direction on the contribution of local sources to airborne pollen. *Science of the Total Environment*, *538*, 672–682. <https://doi.org/10.1016/j.scitotenv.2015.08.074>
- Schroeder, F.-G. (1998). *Lehrbuch der Pflanzengeographie*. Quelle u. Meyer.
- Sposato, B., & Scalese, M. (2013). Prevalence and real clinical impact of *Cupressus sempervirens* and *Juniperus communis* sensitisations in Tuscan Maremma Italy. *Allergologia Et Immunopathologia*, *41*(1), 17–24. <https://doi.org/10.1016/j.aller.2011.08.001>
- Szymczak, S., Häusser, M., Garel, E., Santoni, S., Huneau, F., Knerr, I., Trachte, K., Bendix, J., & Bräuning, A. (2020). How do mediterranean pine trees respond to drought and precipitation events along an elevation gradient? *Forests*, *11*(7), 758. <https://doi.org/10.3390/f11070758>
- Tapper, P.-G. (1992). Irregular fruiting in fraxinus excelsior. *Journal of Vegetation Science*, *3*(1), 41–46. <https://doi.org/10.2307/3235996>
- Tormo-Molina, R., Gonzalo-Garijo, M., Silva-Palacios, I., & Muñoz-Rodríguez, A. (2010). General trends in airborne pollen production and pollination periods at a mediterranean site (Badajoz, Southwest Spain). *Journal of Investigational Allergology and Clinical Immunology*, *20*(7), 567–574.
- Tosunoglu, A., Altunoglu, M. K., Bicakci, A., Kilic, O., Gonca, T., Yilmazer, I., Saatcioglu, G., Akkaya, A., Celenk, S., Canitez, Y., Malyer, H., & Sapan, N. (2015). Atmospheric pollen concentrations in Antalya South Turkey. *Aerobiologia*, *31*(1), 99–109. <https://doi.org/10.1007/s10453-014-9350-6>
- Turkish Statistical Institute (TUIK). (2020). Statistics by topic. Turkey health survey - period: 2019. www.tuik.gov.tr
- Turoğlu, H. (2014). Detection of changes on temperature and precipitation features in Istanbul (Turkey). *Atmospheric and Climate Sciences*, *4*, 549–562.
- Velasco-Jiménez, M. J., Alcázar, P., Díaz de la Guardia, C., Trigo, M. D. M., de Linares, C., Recio, M., & Galán, C. (2020). Pollen season trends in winter flowering trees in South Spain. *Aerobiologia*, *36*(2), 213–224. <https://doi.org/10.1007/s10453-019-09622-x>

- Walter, H., & Lieth, H. (1960). *Klimadiagramm-Weltatlas climate diagram world atlas*. Fischer.
- Weber, R. W. (2008). Guidelines for using pollen cross-reactivity in formulating allergen immunotherapy. *Journal of Allergy and Clinical Immunology*, 122(1), 219–221. <https://doi.org/10.1016/j.jaci.2008.05.034>
- Werchan, M., Werchan, B., & Bergmann, K.-C. (2018). German pollen calendar 4.0 – update based on 2011–2016 pollen data. *Allergo Journal International*, 27(3), 69–71. <https://doi.org/10.1007/s40629-018-0055-1>
- Zemmer, F., Cenk, E., Dahl, A., Galán, C., & Ozkaragoz, F. (2021). A multidisciplinary approach of outdoor aeroallergen selection for skin prick testing in the geographical area of greater Istanbul. *European Annals of Allergy and Clinical Immunology*. <https://doi.org/10.23822/EurAnnACI.1764-1489.188>
- Zemmer, F., Karaca, F., & Ozkaragoz, F. (2012). Ragweed pollen observed in Turkey: Detection of sources using back trajectory models. *Science of the Total Environment*, 430, 101–108. <https://doi.org/10.1016/j.scitotenv.2012.04.067>