

Prediction of wind-carried Gramineae and Urticaceae pollen occurrence in the Friuli Venezia Giulia region (Italy)

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Abstract Wind-carried pollen is universal outdoor and indoor components and is recognized as sources of respiratory allergies. Pollen information is important for determining clinical strategies in allergic patients, and several studies aim to forecast the presence of pollen in the atmosphere in order to reduce the risk of exposure for allergic patients. Forecasting models described in the literature are based on meteorological parameters requiring long historical series of coupled meteorological and pollen monitoring data as well as needing local calibration to produce reliable results. For this study, three different forecasting methods have been developed: two of them have shown to be suitable for foreseeing onset, abundance and duration of pollen presence in the atmosphere for the Gramineae and the Urticaceae families of allergenic plants being monitored in the Friuli Venezia Giulia region (north-eastern Italy).

Keywords Pollen · Forecast · Time series · Autoregressive model · Urticaceae · Gramineae

1 Introduction

Wind-carried pollen is universal outdoor and indoor atmospheric components and is generally recognized

as sources of respiratory allergies (D'Amato et al. 1981).

Pollen information can aid clinical strategies in patients with suspected allergies (Astray et al. 2010; Candau et al. 1994; Frenguelli et al. 1989, 1991).

A literature review carried out for this study indicates that several studies have focused on the prediction of the atmospheric pollen content, besides examining the relationship between airborne pollen levels and prevailing meteorological parameters (Astray et al. 2010; Galàn et al. 1998).

Forecasting of aeroallergens has been a scientific goal for many researchers in order to reduce the risk of exposure for allergic patients. However, when functional relationships between the presence of airborne pollen in the atmosphere and meteorological factors have been analysed, temporary weather conditions seemed to be less important for the overall pollen load than the average meteorological characteristics for a whole season, or at least less important than prevailing conditions just prior to the flowering season (Dąbrowska 2008; Fuertes-Rodríguez 2007).

Regardless of the approach employed for model development, forecasting tools require local calibration to produce reliable results (Arca et al. 2004; Galàn et al. 1998; Ranzi et al. 2003).

In this paper, the authors describe the development of three different forecasting methods for allergenic pollen being monitored in the Friuli Venezia Giulia region (north-eastern Italy). These methods were tested on the

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Gramineae and Urticaceae families, since their pollen types are recognized as aetiological agents of high prevalence among the allergic population (D'Amato et al. 1998).

2 Materials and methods

2.1 Geographical and climatic features of the Friuli Venezia Giulia region

In spite of its relatively small surface area (7,844 km²), the Friuli Venezia Giulia region (north-eastern Italy) is characterized by high meteorological and climatic variability due to the presence of mountainous terrain (40 % of the total surface area), hills (20 %), lowlands (40 %) and a coastal area extending for 120 km along the Adriatic Sea (REGIONE FVG 2010); vegetation composition reflects this variability. Almost all taxa of allergological interest related to the five vegetational areas as identified by D'Amato et al. (2007) were described by Pignatti (1982), specifically: (1) Arctic: birch; (2) Central: deciduous forest, birch and grasses; (3) Eastern: grasses, mugwort and ragweed; (4) Mountains: grasses; (5) Mediterranean: pellitory and nettle, olive trees, grasses and cypress.

2.2 Pollen regional monitoring network

The Regional Environmental Protection Agency of Friuli Venezia Giulia (ARPA FVG) currently manages

five pollen sampling stations, whose data are weekly published on the internet sites of ARPA FVG (<http://www.arpaweb.fvg.it/cp/gmapscsp.asp>) and of POLLnet, the Italian Environmental Protection Agencies System aerobiological monitoring network (<http://www.pollnet.it>). The aerobiological survey described in this study was carried out for three of these monitoring stations, respectively, named TS1, PN1 and UD3 (Fig. 1). The study covered a period of eight consecutive years (2005–2012) associated with station TS1 and PN1 and seven years (2006–2012) associated with station UD3.

Station TS1 is located about 20 m above ground level within the Bastione Fiorito of San Giusto Castle borough in the city centre of Trieste. Monitoring activities undertaken by the Regional Environmental Protection Agency commenced in 2005, and it had been previously managed by the University of Trieste's Department of Biology (Rizzi-Longo and Cristofolini 1987; Rizzi-Longo et al. 2009). Station TS1 is located in an area representative of the physiographical landscape characterizing the city itself as well as Karst features situated within its geographical district (Rizzi-Longo and Cristofolini 1987).

Station PN1 is positioned 18 m above ground level, on top of the building where the local Departmental Office of the Environmental Protection Agency is located in the city of Pordenone; this site is representative of the surrounding lowland. Monitoring activities at this site commenced in 2005.

Fig. 1 Map of Friuli Venezia Giulia region, with the position of the aerobiological monitoring stations used in this study



In operation, since 2006, station UD3 is positioned about 17 m above ground level, on top of a building in the town centre of Tolmezzo which is located at the confluence of the main regional valleys; this site is representative of the mid-altitude mountainous terrain.

2.3 Target pollen

Airborne pollen is collected each day by means of Hirst-type 7-day volumetric traps (VPSS 2000 Lanzoni) set up at each monitoring station. Sampling methodology, slide preparation and data interpretation are performed according to the standard technique adopted by POLLnet (Frenguelli 2000; UNI 11108 2004). Pollen grain counts are expressed as the daily number of particles per cubic metre of air ($\text{pt}/\text{m}^3 \text{ day}$), and the daily mean values are employed for the elaboration of tables, graphs, and annual calendars showing the mean.

The annual (January–December) regional atmospheric concentrations of pollen grains for 13 families and 13 genera of allergological interest (D'Amato et al. 2007) are constantly monitored by the regional pollen monitoring network. The taxa having a more extensive distribution were the Urticaceae, Gramineae, Cupressaceae, Plantaginaceae, *Alnus*, *Betula*, *Ambrosia*, *Corylus* and *Olea*. For this study, different forecasting approaches were tested on the Gramineae and Urticaceae taxa.

2.4 Meteorological parameters

A weather station was associated with each pollen monitoring station on the basis of geo-climatic contiguity and altitude criteria. Weather stations belong to the regional weather network managed by OSMER-ARPA FVG (the regional weather observatory, <http://www.meteo.fvg.it/~www/IT/STAZIONI/StrutturaStazioni.php>). The following meteorological parameters were detected: daily precipitation (mm/day ; accuracy 1 mm/day); daily minimum, average, maximum temperature 2 m above ground level ($^{\circ}\text{C}$; accuracy 0.5 $^{\circ}\text{C}$); average daily humidity (%; accuracy 1 %); 2 m above ground level; daily time of each octant wind 10 m above ground level (minutes; accuracy 1 min); daily average and maximum wind speed 10 m above ground level (m/s ; accuracy 3 m/s); daily global radiation (kJ/m^2 ; accuracy 50 kJ/m^2); daily solar radiation time (min; accuracy 5 min).

2.5 Forecasting approaches

For this study, three different forecasting approaches were tested as described below.

1. Concentration forecasting based on meteorological parameters

For the first approach, a forecasting method was selected to find a relationship between a given range of pollen concentration (i.e. abundance class) and a combination of meteorological conditions. The abundance classes of the Gramineae and Urticaceae families adopted by POLLnet are shown in Fig. 2. It was assumed that the relationships were both pollen taxon (family) and monitoring site specific. Daily pollen concentrations measured at each station from year 2005 (or 2006 for UD3 station) to 2010 were coupled to meteorological parameters associated with the same station for the same day. Meteorological parameters were averaged on the basis of associated pollen abundance class.

Meteorological parameters were selected on the basis of significance for pollen concentration for each station and pollen family, established as follows; comparing the null and the whole of non-null classes, significant parameters differed more than 10 % as mean values and had a relative standard deviation <67 %. These criteria were established on experience.

A meteorological profile was designed as a set of mean values of significant parameters for each pollen abundance class in the time series.

For each pollen abundance class, all mean values of significant meteorological parameters were calculated and normalized with respect to the mean values of corresponding parameters of the null class and then expressed as percentages of their sum. These percentages represented the weight W of each parameter on the meteorological influence on the considered class.

To forecast the pollen abundance class, the corresponding weight of the I -th class was accounted; specifically when a significant meteorological parameter fell into the range between the pollen abundance class I (with $0 \leq I \leq 4$) mean values and the previous abundance class $I - 1$ mean values, the corresponding weight of the I -th class was accounted. The sum of the W weights of meteorological parameters, according to class, yielded the probability of the pollen abundance class, and the most probable abundance class was then considered for forecasting estimates.

abundance class	NULL	MIN	MED	MAX
	absent/very low	low	medium	high
	<=	>	>	>
POLLEN				
Gramineae		0.5	9.9	29.9
Urticaceae		1.9	19.9	69.9

Fig. 2 Abundance classes of Gramineae and Urticaceae pollen, as indicated by POLLnet (http://www.pollnet.it/valori_di_riferimento_it.asp)

The meteorological approach was tested, as further described, for 2011. The forecasted daily pollen abundance classes were compared with the actual pollen measurements taken during 2011 by means of Pearson's nonlinear regression and a calculation of reliability percentage (described below).

2. Daily MEan-based Forecast (DAMEF): mean calendar elaboration

A second forecasting approach provided a daily estimate based on the same day-of-the-year pollen concentration historical means (e.g. 2 March 2011 forecast was given by the mean of all March 2nds of the period 2005–2010). Forecasting “calendars” were obtained by averaging the day-of-the-year pollen concentrations based on previous 3- to 7-year range (3- to 6-year range in the case of station UD3). The length of the averaged historical period was tested in order to determine the best forecasting reliability.

3. Modelling with the ARMA process based on meteorological or concentration data

For this approach, a model for time series was used; in a first intensive computational screening, models were tested both for daily values and averaged weekly values on historical pollen data. When the concentration was zero or data were missing, the substitution with the method detection limit value, estimated as 0.05 particles/m³ day, was performed. Daily values were not suitable for the excessive variability and lack of autocorrelation; as a result, the choice was to consider the weekly means.

The linear models that were applied include: autoregressive (AR), moving average (MA), autoregressive moving average (ARMA), autoregressive integrated moving average (ARIMA), the corresponding multivariate extension to meteorological parameters (VARMA, VARIMA) with or without a backshift or delay operator

D , and with or without variance stabilization by logarithmic transformation. In addition, some nonlinear models such as the autoregressive conditional heteroskedasticity models (ARCH, GARCH) were also applied in combinations with a backshift operator.

In all cases, the fitting was performed computationally by minimizing the sum of the squared errors (ε_t) which are the differences between the observed value X_t and the computed value $X_{t,c}$. The goodness of fit was then estimated by the determination coefficient R^2 ; the higher the coefficient, the better the model.

The best model was found to be ARMA (p , q) by having $p = q$, and ARMA (p , p) working on the weekly mean concentrations (conventionally taken from Sunday to Saturday). No benefit was found using a multivariate regression with meteorological parameters or by way of an integrated process. In addition, a backshift operator or delay D was found to be an important enhancement, as was also operating on the log-transformed data $\ln X_t$ (in fact, data showed a high degree of heteroskedasticity) to stabilize the variance. The linear model used can be written as follows:

$$\ln X_{t,c} = \sum_{i=1}^p \varphi_i \cdot \ln X_{t-D-i} + \theta_i \cdot \varepsilon_{t-D-i}$$

where φ_i and θ_i are the p autoregressive and p moving-average coefficients, respectively, D the delay and ε_i the errors.

The estimated D and p values for each time series were obtained from the correlogram, which typically showed alternatively positive and negative autocorrelation terms. In the correlogram, the first positive term after the first negative set of terms was adopted as delay factor D ; then, the number of the set of positive terms after D was adopted as number of regressors p .

In a typical application, D ranged from 44 to 49 weeks; the p number was limited to a maximum of 20 terms, and typically, 8–20 terms were found.

Since the ARMA model was applied with a delay D , the first D week value was needed only for starting the model; normally, this value corresponded to about the first year of the series (Figs. 3, 4, 5, 6, 7, 8). For the second year, the forecasting measurement was not very good, but the R^2 value increased from year to year as shown in Figs. 3, 4, 5, 6, 7 and 8. The enhancing of the forecast based on the length of the time series is the best feature of this model. In fact, after 5–7 years, the R^2 was about 70 %. Another appreciable characteristic of the model is that D weeks forward values can be forecasted.

3 Results

3.1 Evaluation of correlation

between meteorological parameters and daily pollen concentration

Spearman's correlations between meteorological parameters and Gramineae and Urticaceae pollen concentrations measured at each station were calculated using PAST (Hammer et al. 2009) as shown in Tables 1, 2, 3, 4, 5 and 6.

For each station and year, Tables 1, 2, 3, 4, 5 and 6 show a significant correlation between temperature and the considered pollen concentrations, as well as negative correlation with relative humidity, even

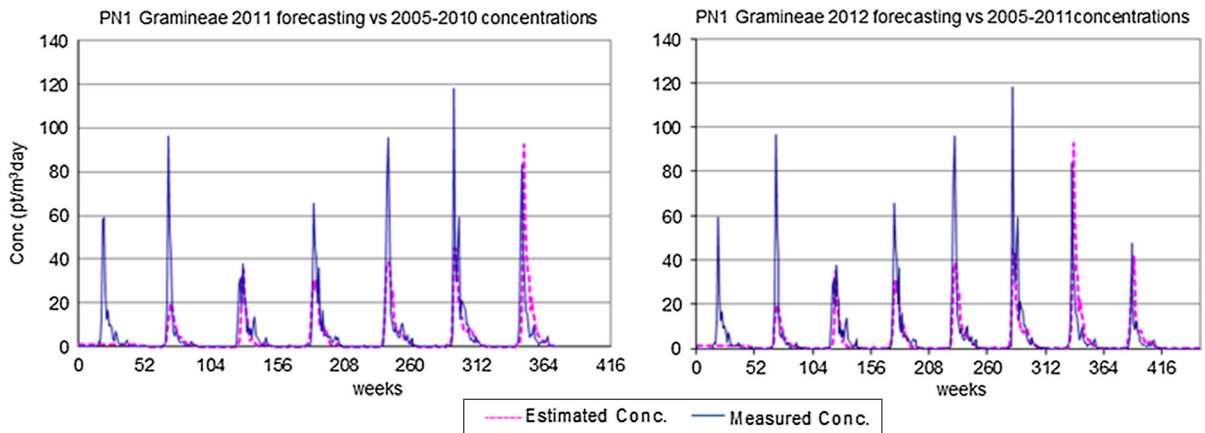


Fig. 3 Overlapping of weekly Gramineae concentration levels and estimated concentrations through ARMA process at PN1 station. Weeks time of pollen monitoring from the beginning.

The latest peaks on the *right* of each graph correspond to 2011 concentrations on the *left* graph and to 2012 concentrations on the *right* graph, respectively

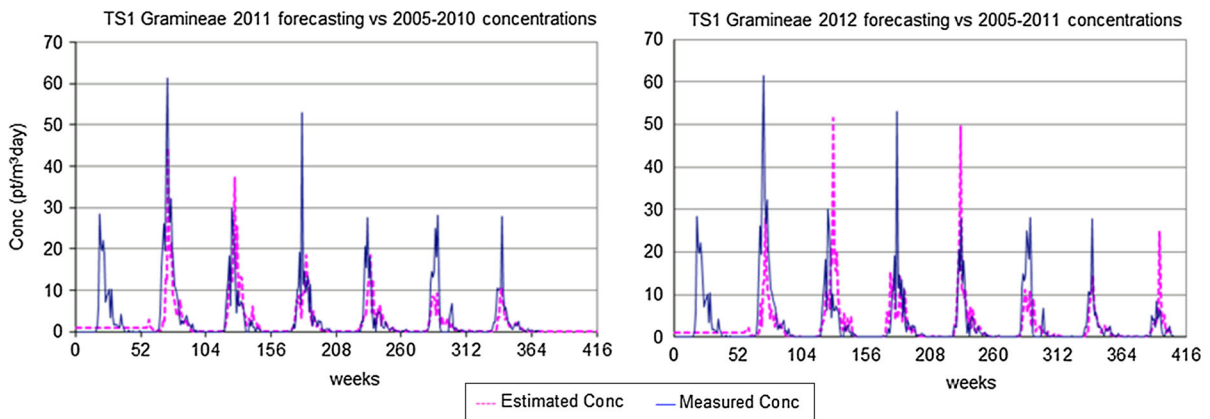


Fig. 4 Overlapping of weekly Gramineae concentration levels and estimated concentrations through ARMA process at TS1 station. Weeks time of pollen monitoring from the beginning.

The latest peaks on the *right* of each graph correspond to 2011 concentrations on the *left* graph and to 2012 concentrations on the *right* graph, respectively

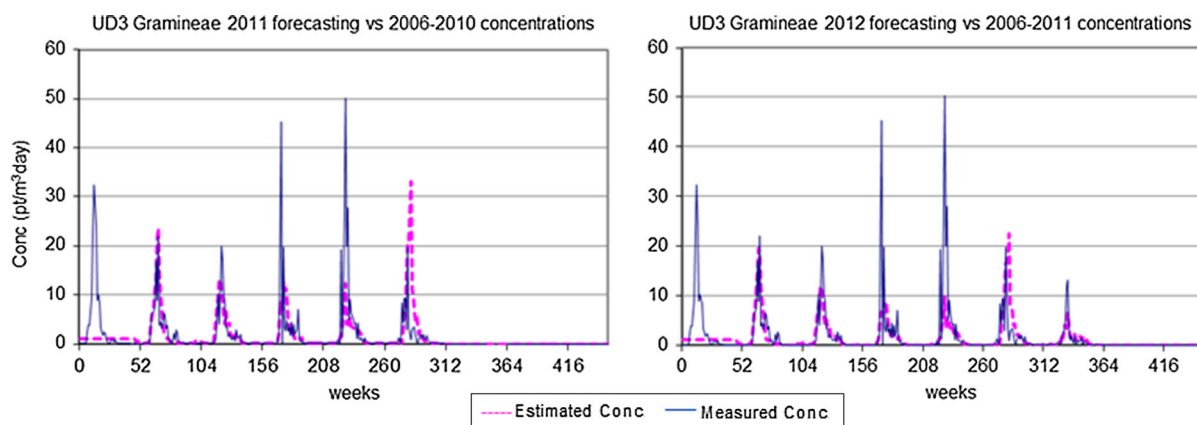


Fig. 5 Overlapping of weekly Gramineae concentration levels and estimated concentrations through ARMA process at UD3 station. *Weeks* time of pollen monitoring from the beginning.

The latest peaks on the *right* of each graph correspond to 2011 concentrations on the *left graph* and to 2012 concentrations on the *right graph*, respectively

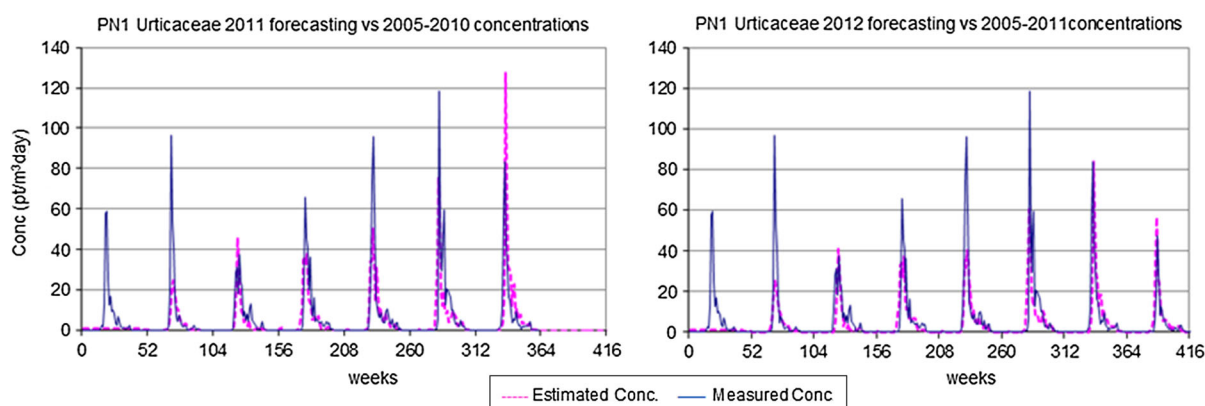


Fig. 6 Overlapping of weekly Urticaceae concentration levels and estimated concentrations through ARMA process at PN1 station. *Weeks* time of pollen monitoring from the beginning.

The latest peaks on the *right* of each graph correspond to 2011 concentrations on the *left graph* and to 2012 concentrations on the *right graph*, respectively

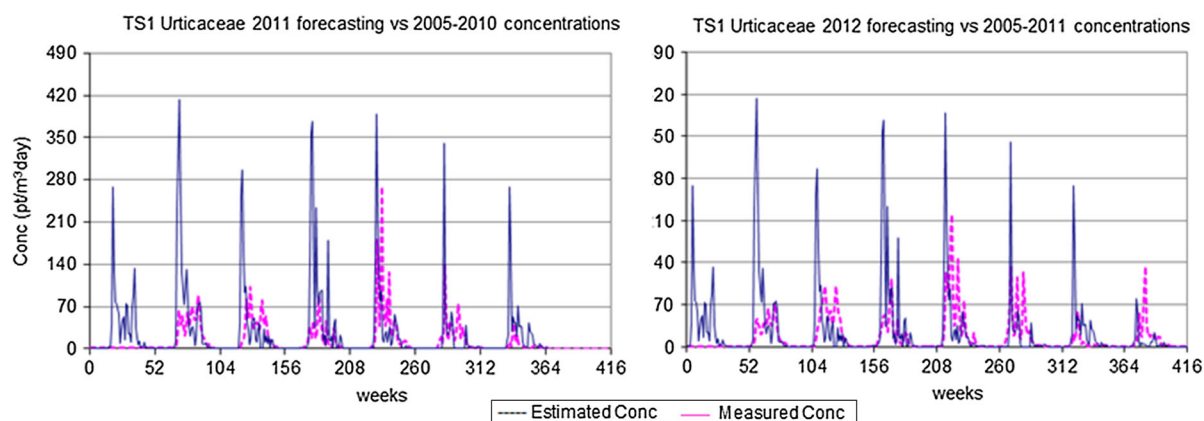


Fig. 7 Overlapping of weekly Urticaceae concentration levels and estimated concentrations through ARMA process at TS1 station. *Weeks* time of pollen monitoring from the beginning.

The latest peaks on the *right* of each graph correspond to 2011 concentrations on the *left graph* and to 2012 concentrations on the *right graph*, respectively

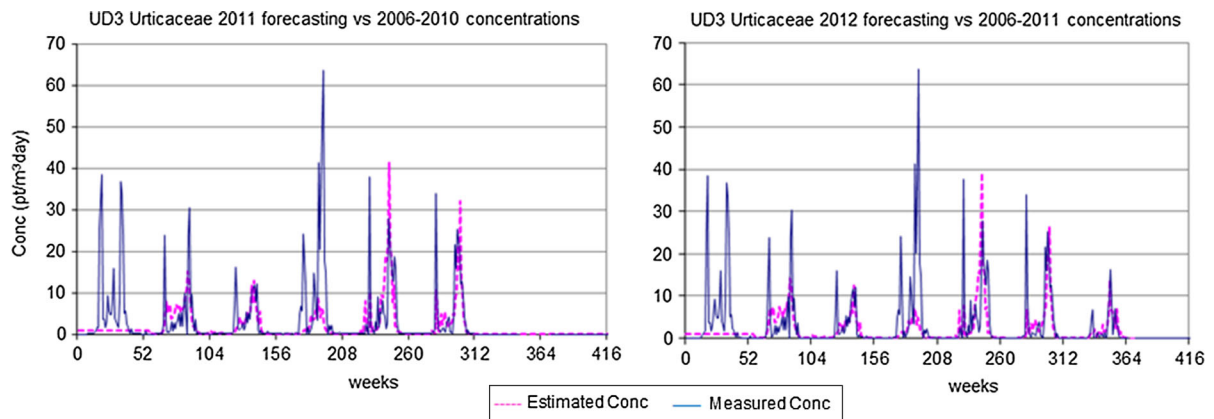


Fig. 8 Overlapping of weekly Urticaceae concentration levels and estimated concentrations through ARMA process at UD3 station. *Weeks* time of pollen monitoring from the beginning.

The latest peaks on the *right* of each graph correspond to 2011 concentrations on the *left* graph and to 2012 concentrations on the *right* graph, respectively

Table 1 Spearman's correlation coefficients for Gramineae levels and meteorological parameters measured during 2005–2010 period at PN1 station

PN1 Gramineae	2005–2010	2005	2006	2007	2008	2009	2010
FD	1969	339	335	309	343	296	339
Daily precip	−0.075***	−0.027	−0.108*	−0.111	−0.009	−0.097	−0.187***
Min daily T	0.712***	0.229***	0.648***	0.706***	0.728***	0.659***	0.785***
Aver daily T	0.755***	0.257***	0.710***	0.755***	0.755***	0.703***	0.824***
Max daily T	0.749***	0.266***	0.712***	0.752***	0.740***	0.707***	0.810***
Aver daily H	−0.388***	−0.184**	−0.439***	−0.481***	−0.371***	−0.346***	−0.451***
N wind	−0.203***	−0.063	−0.215***	−0.234***	−0.143**	−0.178**	−0.267***
NE wind	−0.068**	−0.067	0.014	0.037	−0.102	−0.095	−0.162**
E wind	0.095***	0.078	0.117*	0.112*	0.126*	0.090	−0.032
SE wind	0.403***	0.282***	0.389***	0.331***	0.405***	0.436***	0.408***
S wind	0.380***	0.202***	0.283***	0.357***	0.426***	0.362***	0.486***
SW wind	0.130***	0.005	0.139*	0.059	0.160**	0.148*	0.204***
W wind	0.123***	−0.014	0.061	0.069	0.205***	0.074	0.197***
NW wind	−0.095***	−0.117*	−0.139*	−0.191***	0.020	−0.048	−0.007
Daily strong precip	0.209	0.090	0.293***	0.280***	0.164*	0.137*	0.173**
Daily max wind speed	0.306	0.184***	0.319***	0.358***	0.259***	0.250***	0.295***
Daily glob rad	0.717	0.361***	0.711***	0.751***	0.717***	0.715***	0.725***
Daily solar rad time	0.700	0.331***	0.718***	0.729***	0.674***	0.703***	0.703***

FD degrees of freedom

* $p(\text{uncorrel.}) < 0.05$, ** $p(\text{uncorrel.}) < 0.01$, *** $p(\text{uncorrel.}) < 0.001$

though correlation with this last parameter was not always significant and as it yielded low values for the correlation coefficient. Data reported in the tables confirm what was previously observed for fungal spores at station TS1 by Rizzi-Longo et al. (2009) both for the Gramineae and Urticaceae pollen. Other meteorological factors strongly correlating with

concentration data were found to be the daily global radiation and its duration; these parameters showed a highly positive and significant correlation with both pollen families collected from all stations, with the exception of Urticaceae concentrations registered at station PN1 in 2007 and the lack of correlation between Gramineae concentration and daily global

Table 2 Spearman's correlation coefficients for Gramineae levels and meteorological parameters measured during 2005–2010 period at TS1 station

TS1 Gramineae FD	2005–2010 1910	2005 363	2006 236	2007 297	2008 346	2009 360	2010 298
Daily precip	−0.106***	−0.158*	−0.048	−0.121*	−0.096	−0.139**	−0.068
Min daily T	0.674***	0.525***	0.638***	0.730***	0.732***	0.666***	0.468***
Aver daily T	0.685***	0.544***	0.651***	0.748***	0.737***	0.667***	0.475***
Max daily T	0.691***	0.576***	0.667***	0.760***	0.740***	0.663***	0.462***
Aver daily H	−0.135***	−0.126	−0.052	−0.324	−0.144**	−0.029	−0.082
N wind	0.211***	0.389***	0.337***	0.075	0.145**	0.168**	0.173**
NE wind	−0.020	0.066	0.028	−0.056	−0.042	−0.030	−0.185**
E wind	−0.187***	−0.217***	−0.193***	−0.095	−0.169*	−0.184***	−0.251***
SE wind	−0.101***	−0.337***	−0.235***	0.006	−0.005	−0.043	0.018
S wind	−0.021	−0.018	−0.035	−0.068	−0.008	−0.031	0.058
SW wind	0.185***	0.242***	0.195***	0.111	0.237***	0.169**	0.129*
W wind	0.273***	0.284***	0.260***	0.246***	0.321***	0.200***	0.291***
NW wind	0.264***	0.338***	0.347***	0.171*	0.206***	0.264***	0.348***
Daily aver wind speed	−0.049*	−0.102	−0.079	0.045	−0.038	−0.076	−0.162**
Daily max wind speed	−0.091***	−0.110	−0.113*	−0.027	−0.045	−0.119*	−0.173**
Daily glob rad	0.191***	0.218***	0.182***	0.149*	0.213***	0.179***	0.181**
Daily solar rad time	0.640***	0.629***	0.662***	0.733***	0.654***	0.579***	0.429***

FD degrees of freedom

* $p(\text{uncorrel.}) < 0.05$, ** $p(\text{uncorrel.}) < 0.01$, *** $p(\text{uncorrel.}) < 0.001$ **Table 3** Spearman's correlation coefficients for Gramineae levels and meteorological parameters measured during 2006–2010 period at UD3 station

UD3 Gramineae FD	2006–2010 1476	2006 285	2007 263	2008 336	2009 257	2010 327
Daily precip	0.028	−0.020	0.087	0.140*	−0.023	−0.017
Min daily T	0.648***	0.372***	0.731***	0.716***	0.663***	0.712***
Aver daily T	0.704***	0.477***	0.764***	0.745***	0.690***	0.785***
Max daily T	0.695***	0.487***	0.749***	0.715***	0.681**	0.785***
Aver daily H	−0.253***	−0.318***	−0.215***	−0.132*	−0.198**	−0.319***
N wind	0.180***	0.144*		0.319***	0.194***	0.243***
NE wind	0.299***	0.362***	0.132***	0.368***	0.278***	0.307***
E wind	0.415***	0.392***	0.509***	0.410***	0.325***	0.507***
SE wind	0.385***	0.263***	0.470***	0.345***	0.386***	0.460***
S wind	0.312***	0.230***	0.294***	0.368***	0.357***	0.357***
SW wind	−0.131***	−0.060	−0.249***	−0.109*	−0.123*	−0.095
W wind	−0.387***	−0.330***	−0.366***	−0.469***	−0.402***	−0.436***
NW wind	−0.309***	−0.182**	−0.277***	−0.328***	−0.305***	−0.424***
Daily aver wind speed	0.128***	0.083	0.126*	0.025	0.137*	0.204***
Daily max wind speed	0.320***	0.256***	0.319***	0.187**	0.342***	0.435***
Daily glob rad	0.659***	0.578***	0.700***	0.625***	0.648***	0.706***
Daily solar rad time	0.636***	0.577***	0.645***	0.597***	0.638***	0.682***

FD degrees of freedom

* $p(\text{uncorrel.}) < 0.05$, ** $p(\text{uncorrel.}) < 0.01$, *** $p(\text{uncorrel.}) < 0.001$

Table 4 Spearman's correlation coefficients for Urticaceae levels and meteorological parameters measured during 2005–2010 period at PN1 station

PN1 Urticaceae FD	2005–2010 1969	2005 337	2006 309	2007 297	2008 343	2009 296	2010 339
Daily precip	−0.079***	0.070***	−0.068	−0.121*	0.002	−0.135*	−0.115*
Min daily T	0.758***	0.817***	0.736***	0.730***	−0.081	0.727***	0.811***
Aver daily T	0.789***	0.827***	0.785***	0.748***	−0.167**	0.757***	0.850***
Max daily T	0.779***	0.813***	0.781***	0.760***	0.390***	0.755***	0.844***
Aver daily H	−0.308***	−0.073	−0.360***	−0.324	0.009	−0.266***	−0.442***
N wind	−0.196***	−0.165	−0.230***	0.075	0.170**	−0.129*	−0.237***
NE wind	−0.088***	−0.039	−0.078	−0.056	−0.018	−0.170**	−0.171**
E wind	0.073**	0.090	0.121*	−0.095	−0.021	0.085	0.017
SE wind	0.305***	0.320***	0.302***	0.006	−0.051	0.259***	0.340***
S wind	0.316***	0.242***	0.330***	−0.068	−0.173**	0.269***	0.450***
SW wind	0.117***	0.062	0.074	0.111	−0.242***	0.101	0.184**
W wind	0.120***	0.036	0.136*	0.246***	−0.088	0.132*	0.204***
NW wind	−0.078***	−0.134*	−0.133*	0.171*	0.180**	0.060	0.016
Daily aver wind speed	0.088***	0.083	0.118*	0.045	0.125*	−0.086	0.072
Daily max wind speed	0.179***	0.192***	0.267***	−0.027	−0.266***	0.055	0.171**
Daily glob rad	0.637***	0.563***	0.676***	0.149*	−0.285***	0.598***	0.690***
Daily solar rad time	0.621***	0.561***	0.634***	0.733***	0.654***	0.584***	0.658***

FD degrees of freedom

* $p(\text{uncorrel.}) < 0.05$, ** $p(\text{uncorrel.}) < 0.01$, *** $p(\text{uncorrel.}) < 0.001$ **Table 5** Spearman's correlation coefficients for Urticaceae levels and meteorological parameters measured during 2005–2010 period at TS1 station

TS1 Urticaceae FD	2005–2010 1897	2005 242	2006 357	2007 291	2008 346	2009 360	2010 291
Daily precip	0.007***	−0.074	−0.027*	0.046	−0.055	0.109*	0.131*
Min daily T	0.742***	0.654***	0.740***	0.766***	0.721***	0.700***	0.787***
Aver daily T	0.749***	0.668***	0.756***	0.774***	0.721***	0.704***	0.790***
Max daily T	0.748***	0.675***	0.763***	0.776***	0.717***	0.697***	0.772***
Aver daily H	−0.082***	−0.003	−0.011	−0.291***	−0.070	0.049	−0.027
N wind	0.240***	0.366***	0.260***	0.131*	0.215***	0.262***	0.191**
NE wind	−0.071***	−0.017	−0.053	−0.086	−0.106	−0.108*	−0.192***
E wind	−0.227***	−0.185**	−0.186***	−0.109	−0.259***	−0.309***	−0.242***
SE wind	−0.052*	−0.301***	−0.123*	0.027	0.049	−0.035	0.160***
S wind	−0.003	−0.049	−0.023***	−0.121*	0.057	0.083	0.096
SW wind	0.212***	0.248***	0.211***	0.068	0.282***	0.270***	0.130*
W wind	0.348***	0.416***	0.307***	0.294***	0.389***	0.376***	0.246***
NW wind	0.334***	0.412***	0.363***	0.243***	0.301***	0.399***	0.296***
Daily aver wind speed	−0.151***	−0.207**	−0.128*	−0.057	−0.173**	−0.265***	−0.112***
Daily max wind speed	−0.186***	−0.233***	−0.158**	−0.139*	−0.178***	−0.264***	−0.147*
Daily glob rad	0.676***	0.677***	0.653***	0.775***	0.693***	0.645***	0.484***
Daily solar rad time	0.653***	0.640***	0.634***	0.754***	0.666***	0.633***	0.456***

FD degrees of freedom

* $p(\text{uncorrel.}) < 0.05$, ** $p(\text{uncorrel.}) < 0.01$, *** $p(\text{uncorrel.}) < 0.001$

Table 6 Spearman's correlation coefficients for Urticaceae levels and meteorological parameters measured during 2005–2010 period at UD3 station

UD3 Urticaceae FD	2006–2010 1476	2005	2006 285	2007 263	2008 336	2009 257	2010 327
Daily precip	0.009		0.015	0.087	0.086	−0.068	−0.017
Min daily T	0.722***		0.648***	0.697***	0.689***	0.750***	0.754***
Aver daily T	0.763***		0.723***	0.722***	0.716***	0.778***	0.801***
Max daily T	0.753***		0.715***	0.711***	0.700***	0.766***	0.795***
Aver daily H	−0.243***		−0.209***	−0.230***	−0.165**	−0.218**	−0.267***
N wind	0.229***		0.206***	0.138*	0.322***	0.178***	0.274***
NE wind	0.269***		0.241***	0.134*	0.260***	0.212***	0.315***
E wind	0.356***		0.328***	0.358***	0.314***	0.315***	0.451***
SE wind	0.340***		0.201***	0.361***	0.284***	0.488***	0.425***
S wind	0.326***		0.268***	0.262***	0.336***	0.495***	0.322***
SW wind	−0.127***		−0.041	−0.237***	−0.128*	−0.063	−0.127*
W wind	−0.413***		−0.290***	−0.410***	−0.414***	−0.457***	−0.459***
NW wind	−0.203***		−0.047	−0.105	−0.232***	−0.370***	−0.297***
Daily aver wind speed	0.081**		0.012	0.045	0.080	0.037	0.173***
Daily max wind speed	0.236***		0.119*	0.207***	0.169**	0.296***	0.359***
Daily glob rad	0.631***		0.622***	0.605***	0.602***	0.636***	0.649***
Daily solar rad time	0.607***		0.605***	0.577***	0.544***	0.640***	0.618***

FD degrees of freedom

* $p(\text{uncorrel.}) < 0.05$, ** $p(\text{uncorrel.}) < 0.01$, *** $p(\text{uncorrel.}) < 0.001$

radiation at station TS1. Considering the parameter daily duration of wind in each octant, the positive or negative correlation reflects the prevalence of transport or knocking-down effects of wind, due to both wind strength and the relative position of pollen “sources” versus pollen traps, so that this correlation is typical for each station. Both Urticaceae and Gramineae pollen levels mainly show low or no significant correlation with east and north-east wind at station TS1, noting that the area frequently experiences strong gusts (REGIONE FVG 2010) and having effects on pollution (ARPA FVG 2012). West wind shows a negative correlation for station UD3, but it is still more significant than that for the east and north-east wind on station TS1.

3.2 Evaluation of DAily MEan-based Forecast (DAMEF): daily mean pollen concentration correlation with daily pollen concentration

Daily mean Gramineae and Urticaceae pollen concentrations of 3-, 4-, 5-, 6- and (in the case of PN1 and TS1 stations) 7-year series lengths were calculated,

and Spearman's correlations between daily means and the daily concentrations of the successive year were evaluated, as shown in Tables 7, 8 and 9.

For each mean comparison, a reliability index was quantified as follows; both over-years daily means and daily concentration were referred to abundance classes, as indicated by POLLnet (refer to Fig. 2).

For each day of the year taken into consideration, the value 1 was attributed as exact match and 0 as mismatch. An extended reliability index was calculated attributing also 0.5 to one class, −0.5 to two classes and −1 to three classes mismatches, respectively, in order to evaluate the entity of mismatches. Reliability indices are given as percentages of scores sum based on the total number of comparisons.

Tables 7 and 8 generally show similar, high and significant Spearman's correlation coefficients and reliability percentages between forecasted and measured pollen levels for each station, pollen family and year combination, independent of time series length. These similarities are demonstrated by applying Huber's test at a 99 % significance level (Huber 2011) to apparently lower or higher values.

Table 7 Spearman's correlation, reliability coefficients, as well as difference between forecast and observed pollination start (as appearance of the lower abundance class) for Gramineae (left) and Urticaceae (right) levels and DAMEF (calculated from 3- to 7-year series during 2005–2011 period)/ARMA forecasts at PN1 station

PN1	Time series/forecast (years)	Gramineae				Urticaceae					
		Rel. (%) ^a	Ext. Rel. (%) ^b	Pollination start, forecast–observed, difference (days)	FD ^c	Spearman's rs	Rel. (%) ^a	Ext. Rel. (%) ^b	Pollination start, forecast –observed, difference (days)	FD ^c	Spearman's rs
DAMEF	2005–2007/2008				347	0.892***					
DAMEF	2005–2008/2009				300	0.867***					
	2006–2008/2009				300	0.869***					
DAMEF	2005–2009/2010				345	0.901***					
	2006–2009/2010				345	0.899***					
	2007–2009/2010				345	0.900***					
ARMA	2005–2010/2011	73.9	82.6	–14	45	0.932***	75.6	87.8	–14	45	0.946***
		79.5	89.5	–15	361	0.903***	73.0	83.8	–3	362	0.757***
DAMEF	2006–2010/2011	79.2	89.3	–14	361	0.906***	72.2	84.3	4	362	0.768***
	2007–2010/2011	76.5	87.8	–15	361	0.907***	73.0	84.7	–3	362	0.765***
	2008–2010/2011	76.2	87.8	–15	361	0.889***	69.4	82.6	1	362	0.730***
ARMA	2005–2011/2012	82.6	91.3	0	45	0.903***	77.8	88.9	7	45	0.927***
		79.8	88.5	–14	359	0.868***	70.4	82.7	–6	359	0.812***
DAMEF	2006–2011/2012	80.1	88.1	–8	359	0.868***	69.6	83.0	–6	359	0.808***
	2007–2011/2012	78.7	86.6	–9	359	0.867***	70.7	83.5	–6	359	0.796***
	2008–2011/2012	78.9	87.0	–8	359	0.874***	70.7	83.5	–5	359	0.784***
	2009–2011/2012	75.3	84.9	–7	359	0.869***	71.2	83.5	–4	359	0.781***

^a Reliability, ^b Extended reliability, ^c Degrees of freedom, *** $p(\text{uncorrel.}) < 0.001$

Table 8 Spearman's correlation, reliability coefficients, as well as difference between forecast and observed pollination start (as appearance of the lower abundance class) for Gramineae (left) or Urticaceae (right) levels and DAMEF (calculated from 3- to 7-year series during 2005–2011 period)/ARMA forecasts at TS1 station

TS1	Time series/forecast (years)	Gramineae				Urticaceae					
		Rel. (%) ^a	Ext. Rel. (%) ^b	Pollination start, forecast–observed, difference (days)	FD ^c	Spearman's rs	Rel. (%) ^a	Ext. Rel. (%) ^b	Pollination start, forecast–observed, difference (days)	FD ^c	Spearman's rs
DAMEF	2005–2007/2008				345	0.814***				345	0.806***
DAMEF	2005–2008/2009				363	0.791***				363	0.833***
	2006–2008/2009				363	0.781***				363	0.839***
DAMEF	2005–2009/2010				300	0.708***				293	0.737***
	2006–2009/2010				300	0.704***				293	0.722***
	2007–2009/2010				300	0.703***				293	0.683***
ARMA	2005–2010/2011	81.4	89.2	–21	42	0.889***	58.3	70.8	–7	48	0.867***
		75.9	85.5	–11	361	0.876***	61.9	76.3	1	363	0.858***
DAMEF	2006–2010/2011	75.1	85.3	–11	361	0.876***	62.7	77.6	1	363	0.867***
	2007–2010/2011	77.0	85.2	–11	361	0.872***	67.4	79.9	1	363	0.862***
	2008–2010/2011	74.2	85.1	–15	361	0.841***	66.8	80.2	–1	363	0.858***
ARMA	2005–2011/2012	62.2	81.1	1	42	0.803***	60.4	69.8	0	48	0.738***
		63.0	77.9	–11	363	0.690***	51.9	57.8	1	363	0.762***
DAMEF	2006–2011/2012	62.7	77.1	–10	363	0.690***	55.5	59.4	1	363	0.769***
	2007–2011/2012	65.8	80.7	1	363	0.690***	56.7	62.2	2	363	0.767***
	2008–2011/2012	63.0	78.5	–10	363	0.694***	56.7	63.6	3	363	0.751***
	2009–2011/2012	64.7	77.7	–9	363	0.677***	59.2	68.4	3	363	0.737***

^a Reliability, ^b Extended reliability, ^c Degrees of freedom, *** $p(\text{uncorrel.}) < 0.001$

Table 9 Spearman's correlation, reliability coefficients, as well as difference between forecast and observed pollination start (as appearance of the lower abundance class) for Gramineae (left) or Urticaceae (right) levels and DAMEF (calculated from 3- to 6-year series during 2006–2011 period)/ARMA forecasts at UD3 station

UD3	Time series/forecast (years)	Gramineae				Urticaceae					
		Rel. (%) ^a	Ext. Rel. (%) ^b	Pollination start, forecast–observed, difference (days)	FD ^c	Spearman's rs	Rel. (%) ^a	Ext. Rel. (%) ^b	Pollination start, forecast–observed, difference (days)	FD ^c	Spearman's rs
DAMEF	2006–2008/2009				258	0.774***					
DAMEF	2006–2009/2010				328	0.871***					
	2007–2009/2010				328	0.859***					
ARMA	2006–2010/2011	78.7	87.2	–7	46	0.826***	70.2	85.1	0		0.835***
		73.7	86.3	–14	360	0.720***	70.4	83.4	–2	360	0.708***
DAMEF	2007–2010/2011	73.7	86.3	–16	360	0.715***	72.3	84.6	–2	360	0.702***
	2008–2010/2011	75.1	85.6	–6	360	0.707***	71.8	83.1	2	360	0.655***
ARMA	2006–2011/2012	93.5	96.7	0	45	0.875***	87.5	93.8	–21		0.763***
		68.2	84.4	–9	363	0.628***	71.2	84.1	10	363	0.598***
DAMEF	2007–2011/2012	69.9	84.4	–6	363	0.630***	72.9	85.2	10	363	0.608***
	2008–2011/2012	70.1	84.2	–4	363	0.633***	73.4	85.5	7	363	0.603***
	2009–2011/2012	71.0	84.1	–4	363	0.636***	71.5	84.2	10	363	0.607***

^a Reliability, ^b Extended reliability, ^c Degrees of freedom, *** $p(\text{uncorrel.}) < 0.001$

For this study, the beginning of pollination season was assumed to be the first appearance of the lower abundance class having a duration of at least three consecutive days, whereas classical calculations for determining the start of season are based on the total annual pollen load (Galán et al. 1995; Jäger et al. 1996) or on daily concentration levels (Giorato et al. 2000; Sánchez-Mesa et al. 2003); this assumption was made since the work was based on abundance classes of concentrations. In terms of difference between forecast and observed pollen start, in most cases, the delay decreased and sometimes the timing associated with an early pollen start was improved with shorter time series calculated for means.

3.3 Evaluation of correlation between ARMA process from previous concentrations and weekly pollen concentration

For each station, by means of the ARMA process based on 2005–2010 and 2005–2011 time series, weekly mean Gramineae and Urticaceae pollen concentrations for 2011 and 2012 were estimated, respectively. For both forecasts, Spearman's correlations with observed weekly mean concentrations were evaluated, as shown in Tables 7, 8 and 9. The overlap of estimated and measured weekly concentrations is represented by the peaks on the right (from week 312 for 2011 and from week 364 for 2012, respectively) of each graph as shown in Figs. 3, 4, 5, 6, 7 and 8. Tables 7, 8 and 9 show a high and significant correlation as well as good reliability indices; this trend is confirmed by the overlap between each forecast-detected yearly peak, starting from the third forecasting year, as illustrated by Figs. 3, 4, 5, 6, 7 and 8.

4 Discussion

4.1 Suitability of weather parameter-based pollen forecasting approach

This study found a lower reliability by employing a weather parameter-based pollen forecasting approach, when compared to local pollen concentration data, since the uncertainty of forecasted meteorological parameters has to be addressed in addition to the uncertainty of the pollen forecasting process itself. This could be due to a number of factors such as the availability of short

temporal data series. Station TS1 had been active from 1993 to 2004 and was managed by Rizzi-Longo et al. (1987, 2004, 2009); however, data from this location were not available for this study. Unavailability of meteorological stations just next to pollen samplers poses another problem, especially if we consider the high climatic and meteorological variability characterizing this region. Weather stations are not representative of the “source” conditions, as the pollen-producing plants are distributed almost all over the regional area and beyond the regional and national borders. This aspect could explain the apparent low correlation that was observed between air pollen concentration and parameters, such as relative humidity and rain, which are recognized to influence the onset and duration of the pollen season (García-Mozo et al. 2006; Escuredo et al. 2010). On the other hand, the distribution of pollen is the final step of the flowering process, which is influenced by a complex interplay of meteorological and physiological conditions, often set several months before the pollination event itself. (Dąbrowska et al. 2008; Fuertes-Rodríguez et al. 2007; Galán et al. 1998; Yli-Panula et al. 2009). In addition, meteorological parameters provide only a short-term forecast, thus limiting pollen prediction timeliness. Poor forecasting and the effort of calculation make this approach not suitable for this purpose.

4.2 Choice of pollen concentration-based forecasting approaches

This study identified parameters that better represent meteorological–climatological and physiological factors, besides geophysical and soil use characteristics, and pollen concentrations themselves, as recorded at each monitoring station.

To establish the minimal time series of data, the correlation between daily means 3- to 6-year or 3- to 7-year series and the daily observed values of each temporal sequence's successive year was determined. The DAMEF approach did not show differences in correlation strength or reliability among time series; apparently, lower values corresponding to shorter (2009–2011) time series were not anomalous when evaluated using a Huber's test, except for the 2009–2011 series as 2011 forecast. Comparisons between DAMEF and ARMA approaches also generally show similar reliability indices, even if ARMA often

yielded significantly higher correlation coefficients, as demonstrated whenever a Huber's test is applied. On the other hand, target-year specificity seems to influence forecast accuracy more than time series width, regardless of whether the ARMA or DAMEF approach is employed, also taking into account the 2008–2010 DAMEF forecasts. This could explain the apparent loss of reliability and correlation observed in both methods when comparing 2011 and 2012 forecasts.

Considering ARMA and DAMEF behaviour in predicting pollen initiation, the latter approach revealed to be more suitable, especially with shorter time series calculated for means; this aspect could be explained in terms of medium-period climatic and/or phenologic changes, so that shorter (3 years) time series would not be affected by these conditions.

5 Conclusions

For this study, three different pollen forecasting approaches have been developed. The approach based on meteorological parameters was deemed unsuitable because of the high uncertainty and short time forecast given by meteorological parameters. The other two pollen concentration-based approaches, named DAMEF and ARMA, respectively, were able to predict, on weekly and daily basis, respectively, the onset, the class of abundance and the duration of the flowering season for the Urticaceae and Gramineae taxa; both methods are based on previously recorded concentration data and are station specific. Of significance is the fact that both of these forecasting approaches have proved to be suitable for short-time databases (3 years minimum length), independent of the meteorological measures and also allowing for long-term forecasting (1 year for DAMEF and about 44–49 weeks for ARMA). The ARMA and DAMEF approaches can be implemented by integrating each other, as ARMA sometimes has shown to be more accurate and reliable, whereas DAMEF seems to be more suitable for predicting the start of the pollination period.

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Conflict of interest The Authors declare that there are no conflicts of interest.

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