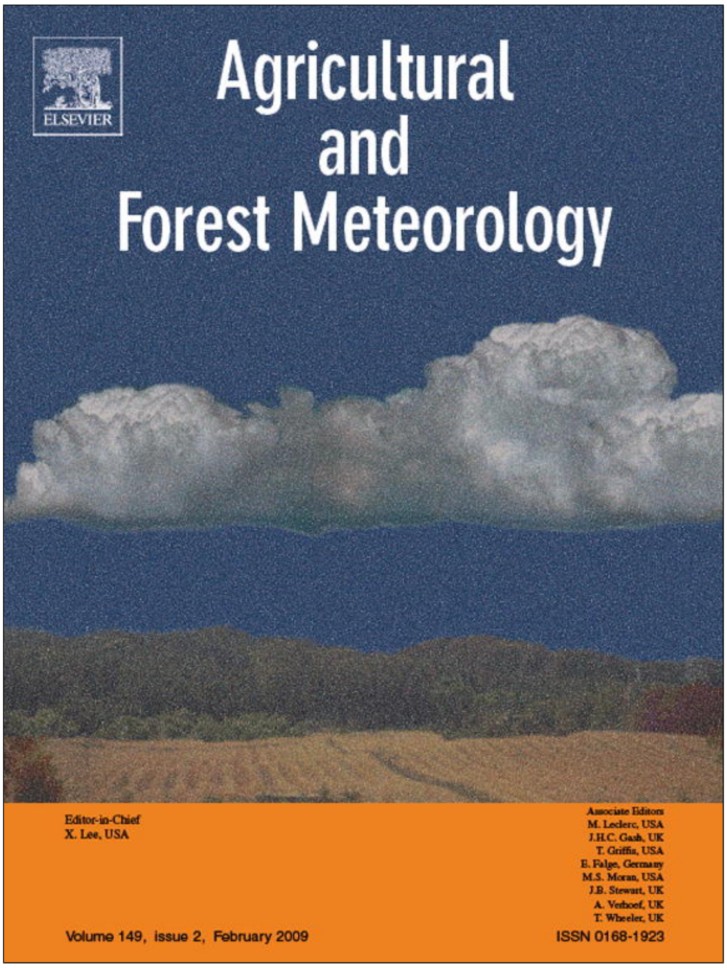
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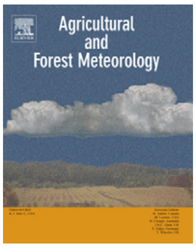

Predicting the start and peak dates of the Poaceae pollen season in Spain using process-based models

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ABSTRACT

The present study examines variations in the timing of flowering between populations of Iberian Poaceae species using pollen data from 12 sites in Spain. The spatial variation in pollen season start-date for any given year was around 1 month; year-on-year differences at any given site ranged around 1.5 months. The spatial variation in the pollen season peak-date was smaller, at around 15 days, while the year-on-year variation for the peak-date at a given site was never greater than 20 days.

Two process-based models were developed, one to predict the start-date and the other the peak-date of the grass pollen season. These models take into account the effects of temperature, photoperiod and water availability on the timing of grass flowering in Spain. Apart from predicting the pollen-season start and peak dates, the models provide information on (i) the Poaceae response to weather-related factors, (ii) the period during which these factors affect grass growth, and (iii) the relationship between photoperiod, temperature and water availability for flowering grasses.

Internal validation showed that the models accounted for 45% of the variance in start-date and 68% of the variance in peak-date. External validation was performed for 2006 and 2007 at all sites: the root mean square error for the actual and predicted dates was around 4 days for the start-date and 6 for the peak-date. Analysis of the model estimates showed that a single model parameter set for all Spain, taking into account different bioclimatic factors, could be sufficient to account for the variability of the Poaceae pollen season across space and time.

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1. Introduction

The Poaceae family is well represented in the Iberian Peninsula. The most abundant genera causing pollinosis are: *Phleum* spp., *Dactylis* spp., *Lolium* spp., *Trisetum* spp., *Festuca* spp., *Poa* spp., *Cynodon* spp. and *Anthoxanthum* spp. (Subiza, 2003). Other taxa have been shown to make an important contribution to the pollen spectrum in Southern Spain: *Holcus lanatus* L., *Trisetaria* spp., *Elymus repens* L., *Sorghum halepense* (L.) Pers., *Vulpia* spp. and *Piptatherum miliaceum* (L.) Coss. (Prieto-Baena et al., 2003; Prieto-Baena, 2004).

In Spain, 22% of the population suffers pollen allergies, and an average of 80% of pollen-allergy sufferers in Spain are affected by grass pollen (Subiza, 2003). The percentage of sensitized patients ranges from 97% in northern Spain to 48% in coastal south-eastern Spain; these figures match the reported prevalence of Poaceae pollen allergy throughout Europe (D'Amato et al., 2007).

Grasses are all anemophilous species, in which pollen release is favoured by a number of environmental factors. In Spain, daily airborne grass-pollen concentrations in spring can reach 800 grains/m^3 (Férnández-González et al., 1999). The development of grasses is positively influenced by water availability, especially in Mediterranean areas (Clary et al., 2004). High temperatures, a critical photoperiod and low relative humidity contribute to high atmospheric levels of airborne Poaceae pollen (Sánchez-Mesa et al., 2005). A number of studies report that reproduction patterns in this family vary according to latitude, ecology and climatology (Raju et al., 1985; Connor, 1986). In the species studied by Prieto-Baena et al. (2003), pollen production ranged from 14.5×10^4 to 22×10^6grains per inflorescence, and was greater in perennial species.

Grass pollen concentrations are greatly influenced by weather conditions. Prior to flowering, the primary factors – temperature, photoperiod and water availability – influence plant growth and development. During flowering, other, secondary weather-related factors, such as rainfall and relative humidity, influence pollen release (Laaidi, 2001). Several studies have highlighted the relationship between weather-related factors and airborne grass-pollen counts (Davies and Smith, 1973; Norris-Hill, 1995). Although various authors have developed models for predicting grass-pollen concentrations (e.g. Moseholm et al., 1987; Emberlin et al., 1999; Sánchez-Mesa et al., 2005), few papers have addressed the development of models to forecast the main pollen-season dates, i.e. start-date (Clot, 1998; Chuine and Belmonte, 2004; Laaidi, 2001) and peak-date (Stach et al., 2008). The main difficulty in developing forecasting models for this taxon is that grass pollen counts are an amalgam of pollen from many species, and pollen release dynamics prompt a large number of peaks (Férnández-González et al., 1999; Emberlin et al., 1999).

Férnández-González et al. (1999) made a preliminary study of differences in the length and timing of the grass-pollen season in various Spanish regions, using data from 14 sites representative of different bioclimatic provinces in the Iberian Peninsula. They found that pollen counts were higher in the centre and northwest of the Peninsula than in the south and west, and reported a Mediterranean-Atlantic gradient at the start of the pollen season. However, few studies have reported on models to forecast the main grass-pollen season dates.

The present study sought to examine the variation in the timing of flowering of grasses across Spain. Two models were developed to forecast the start-date and the peak-date, respectively; these process-based models took into account the effect of temperature, photoperiod and accumulated rainfall as an estimate of water availability. The models were used to forecast the grass-pollen season and to study: (i) the Poaceae response to weather-related factors; (ii) the period during which these factors affect grass growth; and (iii) the relationship between photoperiod, temperature and water availability for flowering grasses.

2. Materials and methods

2.1. Pollen data

12 sampling sites (Fig. 1, Table 1) were chosen for this study in view of their geographic distribution and different bio-climatic conditions. The sites were grouped for study purposes into Southern sites and Central-Northern sites, on the basis of similar climate conditions and species spectrum. Daily pollen data were collected using Hirst-type volumetric spore traps (Hirst, 1952), following the standard methodology laid down by the Spanish Aerobiology Network (REA) (Galán et al., 2007). The pollen-season start-date was defined as the first day on which 5 pollen grains/m^3 were recorded with the three following days recording 5 or more pollen grains/m^3. The peak-date was defined as the day on which maximum pollen counts were recorded, indicating that most plants in a given population were in full bloom.

2.2. Modelling

The models assume that flowering occurs when the state of development of flowers, described by the so-called state of forcing function (S_f), reaches a critical value (F^*). The state of forcing function is described by a daily sum of rate of forcing ($R_f(t)$), starting at day t_1 such that

$$S_f(t_f) = \sum_{t_1}^{t_f} R_f(t) = F*$$

where $R_f(t) = 1/(1 + e^{d(x(t)+e)})$ with $x(t)$, the daily temperature, t_f (the date of flowering) and d and e are parameters fitted for model calibration.

Day t_1 is defined as the day by which a critical amount of rainfall (R^*) has occurred within the last 7 days, such that

$$\sum_{t_1-7}^{t_{1f}} R(t) = R*, \quad \text{where } R(t) \text{ is daily rainfall.}$$

Effect of rainfall accumulation only occurs when a critical photoperiod (P^*) has been reached, i.e. $P(t_0) = P^*$ where $P(t)$ is the daily photoperiod, calculated as a function of latitude, and $t_0 \leq t_1 - 7$.

The model thus has five parameters (F^*, P^*, R^*, d and e). Two different sets of these parameters were fitted, one to the start dates and a second to the peak dates of the pollen season.

Fig. 1 – Location of the study sites in Spain.

2.3. *Model calibration*

Data sets for grass-pollen counts spanning the period from 1994 to 2005 were used to fit the model parameters. Calibrated models were then externally validated using data for 2006 and 2007. Adjustments were made by minimizing the least-square function in the parameter space using the simulated-annealing algorithm of Metropolis et al. (1953), (Chuine et al., 1998) and the Marsaglia random generator (Marsaglia et al., 1990). Several independent adjustments were made, and the best fit,

Table 1 – Biogeographical characteristics of the study sites

Region	Sites	Altitude	Coordinates	T°	R_f
South	Córdoba	123	37°50′N, 4°45′W	18.0	674
	Sevilla	18	37°25′N, 5°54′W	18.0	600
	Badajoz	186	38°53′N, 6°58W	16.8	497
	Granada	685	37°11′N, 3°35′W	15.5	462
	Málaga	5	36°47′N, 4°19′W	18.0	575
	Cartagena	10	37°36′N, 0°59′W	17.0	300
Central-North	Madrid	600	40°27′N, 3°45′W	14.0	440
	Zaragoza	200	41°39′N, 2°48′E	15.0	314
	León	830	42°34′N, 5°35′W	11.0	535
	Ourense	130	42°21′N, 7°51′W	13.8	802
	Santiago	270	42°53′N, 8°32′W	12.8	1545
	Barcelona	90	41°24′N, 2°9′E	16.4	593

Altitude expressed in meters above sea level; T°, annual mean temperature (°C); R_f, average annual rainfall (mm).

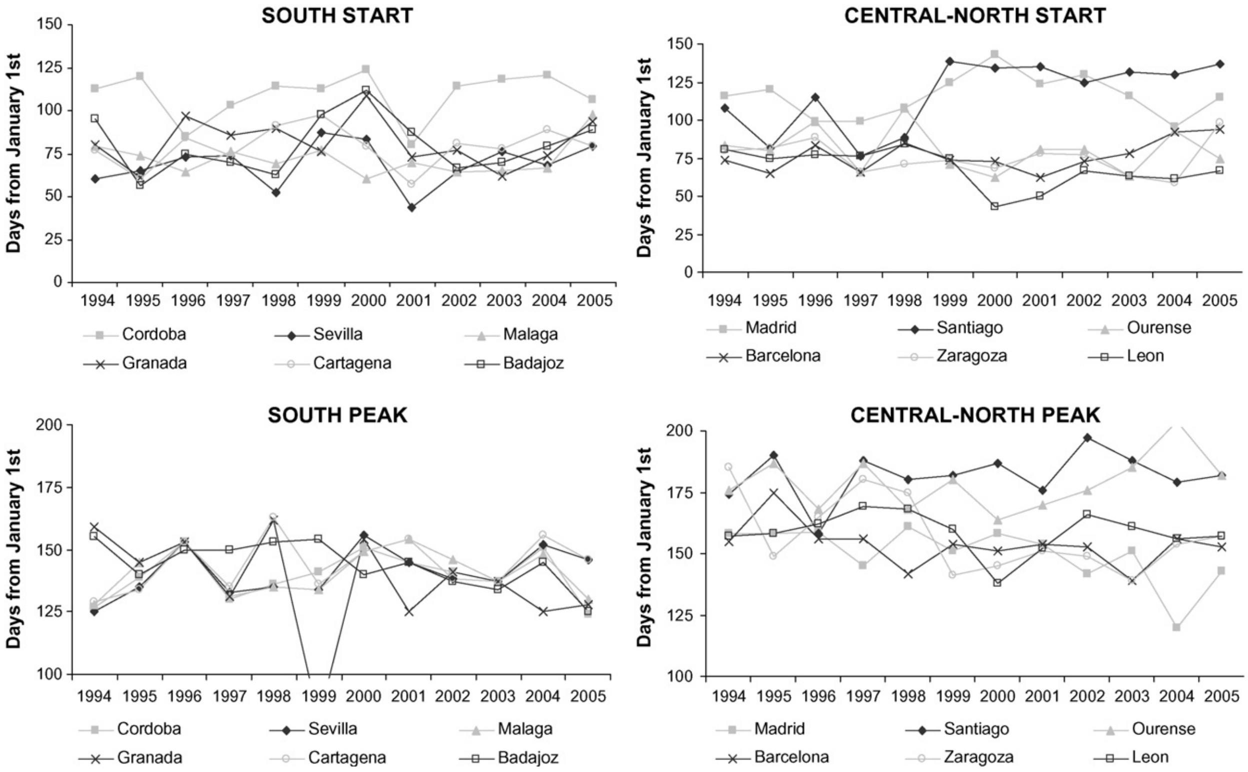

Fig. 2 – Variations of the start and peak dates among the years at the studied sites. Localities are grouped according to geographical placement in the South or Central and North Spain.

defined by the highest model efficiency (percentage of variance explained by the model), was chosen.

3. Results

Variations in start and peak dates are shown in Fig. 2. Inter-site variation in pollen-season start dates was greater than variation in peak dates. The average inter-site variation in start-date was, within any given year, around 1 month. Greater variation was found in the central-northern area, where inter-site differences of up to 3 months were observed, especially in the latter years of the study. Year-on-year variations in start-date at any given site were up to 1.5 months, with less variation in coastal cities such as Málaga, Cartagena (southern Spain) and Barcelona (north-western Spain).

In southern Spain, the peak-date was recorded around mid-May, while at northern sites peak pollen release was recorded in mid-June or even early July. Inter-site variation was less marked in southern areas, while in central-northern Spain it was always around 15 days. At any given site, year-on-year variations in the peak-date lay within a range of 20 days.

The critical photoperiod (P^*) was 9.6 h for the start-date and 10.72 h for the peak-date (Table 2). This photoperiod corresponded to different dates for each site, depending on their latitude. Critical 7-day accumulated rainfall (R^*) was 9.9 mm for the start and 2.26 mm for the peak (Table 2). Fig. 3 provides a graphical representation of the rate of forcing function ($R_f(t)$). The function of rate of forcing of the grass populations contributing to the start of the pollen season was different from that of the populations contributing to the peak of the pollen season. This difference is evident in the slope at the inflexion point of the function, which is lower for the ‘‘peak population’’. The mid-response temperature was 3.9 °C for the ‘‘start population’’ and 2.6 °C for the ‘‘peak population’’.

Goodness-of-fit tests showed that the models accounted for 45% of the variance in start-date and 68% of the variance in

Table 2 – Parameter estimates of the two models

Model	R^2	SSres	RMSE	d	e	F^* (°C)	P^*(h)	R^*(mm)
Start	0.45	99272	5.02	−1.92	−3.94	70.59	9.60	9.90
Peak	0.68	80233	4.76	−0.13	−2.59	74.02	10.72	2.26

SSres, residual sum of squares; RMSE, root mean square error; F^*, growing degree days; R^*, rainfall; P^*, photoperiod (h); d and e, model parameters.

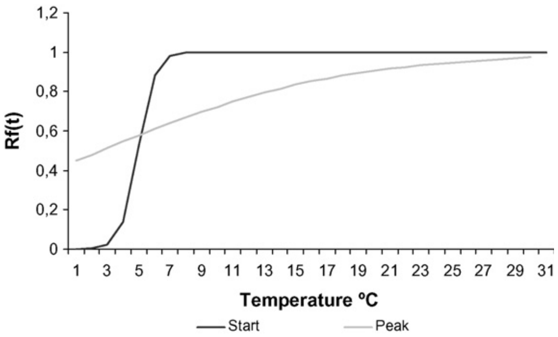

Fig. 3 – Graphical representation of the relationship between temperature and heat cumulation calculated with the process-based models for the start (black line) and peak (grey line).

peak-date; RMSE was 5.02 days for the start and 4.76 days for the peak (Table 2).

The results of external validation using data for 2006 and 2007 at all sites indicated that the RMSE for the differences between actual and predicted dates was 4.52 days for the start-date and 6.27 days for the peak-date (Table 3). For the start-date, the best forecast was obtained for the central area, i.e. Badajoz, Madrid, León, and in the southern coastal cities of Cartagena and Málaga. For the peak-date, the best forecast was obtained for Badajoz, central area, and for Barcelona, north-eastern coast; the maximum observed error was 11 days for the start-date of 2006 in Barcelona and the start-date of 2007 in Córdoba; and 12 days for the peak-date of 2006 in Santiago.

4. Discussion

Previous studies have shown that only a small number of Poaceae species are responsible for most airborne pollen (Emberlin et al., 1999; Subiza, 2003; Prieto-Baena et al., 2003). In the present study, the main pollen-contributing species were found at all 12 sites. This may explain, in part, why a single model for the whole taxon Poaceae and the whole of Spain can provide accurate predictions, as shown here.

From a medical point of view, information on grass pollen-season dates is useful for planning treatments and activities for allergy sufferers (Subiza, 2003). There was a marked seasonal variation in start and peak dates in Spain, with considerable differences between annual start and peak dates. It appears that the timing of the start and peak of the grass pollen seasons in Spain are controlled by different populations at each site. There are much greater year-on-year differences in start-date compared to peak-day, the latter having a much smaller range. One reason for that is that the early flowering grass species (i.e. *Dactylis glomerata* L., *Trisetum paniceum* (Lam.)

Table 3 – External validation of the model in the years 2006 and 2007

	Year	Start			Peak		
		Observed	Predicted	Difference*	Observed	Predicted	Difference*
Córdoba	2006	2/4	31/3	−2	19/5	23/5	4
	2007	1/4	12/4	11	11/6	1/6	−10
Madrid	2006	31/3	1/4	1	18/5	24/5	6
	2007	22/4	19/4	−3	19/5	28/5	9
Santiago	2006	1/5	3/5	2	21/5	2/6	12
	2007	21/4	21/4	0	12/5	21/5	9
Ourense	2006	25/4	24/4	−1	7/6	1/6	−6
	2007	22/4	19/4	−3	7/6	29/5	−9
León	2006	26/4	26/4	0	28/5	1/6	4
	2007	20/4	20/4	0	6/6	4/6	−2
Málaga	2006	27/3	27/3	0	20/5	20/5	0
	2007	13/4	10/4	−3	11/5	15/5	4
Sevilla	2006	26/3	19/3	−7	7/5	18/5	11
	2007	30/4	30/4	0	20/5	18/5	−2
Granada	2006	12/4	4/4	−8	8/5	16/5	8
	2007	17/4	13/4	−4	14/5	24/5	10
Cartagena	2006	4/4	4/4	0	29/5	26/5	−3
	2007	15/4	9/4	−6	28/5	24/5	−4
Barcelona	2006	24/4	13/4	−11	23/5	23/5	0
	2007	6/5	11/5	5	31/5	31/5	0
Badajoz	2006	21/3	21/3	0	23/5	23/5	0
	2007	8/3	12/3	4	19/5	19/5	0
Zaragoza	2006	28/4	30/4	2	2/6	29/5	−4
	2007	11/5	10/5	−1	14/6	16/6	2
Abs. Mean				3			5
RMSE				4.52			6.27

Observed and predicted dates are expressed in day/month. The Difference* between expected and actual dates was expressed in number of days. Minus signs indicate advance forecasts. Abs. Mean, absolute mean value; RMSE, root mean square error.

Pers.) are more responsive to meteorological factors such as temperature and so the start grass pollen varies more than the peak where other species flower (i.e. *Trisetaria* spp., *Festuca* spp., *Lolium* spp.). Given the year-on-year variations in start and peak-dates, annual forecasts of these events could be particularly valuable, especially since weekly pollen counts tend to be issued 9 days after being recorded (7 pollen-recording days followed by 2 days of analysis).

Previous studies comparing pollen counts in locations with different climates have shown that temperature was the main factor controlling the start of the grass pollen season and also the timing of peak pollen counts (Frenguelli et al., 1989; Galán et al., 1995). Therefore, most methods applied to the forecasting of grass pollen-season dynamics have used only temperature as the main independent variable. Accumulation of degree-days has been included in several statistical models as a forecasting tool for grass pollen, mainly using regression equations or neuronal networks (Clot, 1998; Laaidi, 2001; Sánchez-Mesa et al., 2005; Smith and Emberlin, 2006). In the present study, various attempts were made to develop temperature models to forecast the start and peak, with poorer results. Recent studies have also highlighted the influence of rainfall on grass pollen-season intensity (Smith and Emberlin, 2006; Sánchez-Mesa et al., 2005). The seasonal rhythm of photoperiod also influences the development of grass species (Laaidi, 2001). Our modelling results showed that inter-site variation was attributable to latitude (photoperiod) but also to climate conditions, and particularly to the reciprocal relationship between the specific climate, vegetation and geographical make-up of each bio-geographical area. Taking into account all these factors, we developed two similar process-based models combining the effect of temperature; photoperiod and rainfall with a view to obtaining accurate predictions of the Poaceae pollen season in the study area.

Most similar models reported in the literature aim to forecast the start of the grass-pollen season (Clot, 1998; Laaidi, 2001; Chuine and Belmonte, 2004). The present model provides more accurate results. Recently, Stach et al. (2008) have proposed models to forecast daily grass-pollen concentrations; the degree of significance was <0.5, and was therefore lower than those noted here.

The present results show that the RMSE for the external validation between actual and predicted dates was 4.52 days for the start-date and 6.27 days for the peak-date, i.e. similar to that recorded in other studies designed to forecast only the start-date (Clot, 1998; Laaidi, 2001). Differences between actual and predicted results are satisfactory; validation therefore revealed acceptable results. These models will have to be tested over the next few years, in order to improve their robustness, but they can already be used as forecasting tools. Moreover, they could be readily adapted to other phytoclimatic conditions, to enable their use in other areas of Spain or even elsewhere in Europe.

5. Conclusions

The results showed that a process-based model taking into account different bioclimatic factors could accurately predict the timing of the grass-pollen season in different areas of Spain. The traditional difficulties encountered in modelling and forecasting studies for Poaceae were minimized by including several variables affecting plant development. The models explain the varying influence of climate by taking into account latitude, cumulative rainfall and temperature. The models proposed accounted for a large amount of the variation in data sets, and proved effective using data for years not included in model development.

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