A comparative study of different temperature accumulation methods for predicting the start of the *Quercus* pollen season in Córdoba (South West Spain)

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Garcia-Mozo, H., Galan, C., Gomez-Casero, M. T. & Dominguez-Vilches, E. 2000. A comparative study of different temperature accumulation methods for predicting the start of the *Quercus* pollen season in Córdoba (South West Spain). – Grana 39: 194–199. ISSN 0017-3134.

The aim of the present paper is to study the influence of air temperature on the start of *Quercus* pollination in Córdoba (Andalusia, Spain). Sixteen years of pollen counts were used. The start date of the pollen season in this period varied between 26^{th} February and 7^{th} April. Chilling requirements and heat accumulation were taken into account although no significant correlation between chilling hours and the start date was observed. Five different predictive methods based on heat accumulation were compared in this paper: 1) Number of days over a threshold; 2) Heat Units (accumulated daily mean temperature after deducting a base temperature); 3) Growing Degrees Days (Snyder 1988), as a measure of physiological growing time; 4) Accumulated maximum temperatures; and 5) Mean maximum temperature.

Results indicated that the optimum base temperature for heat accumulation was 11°C. This threshold was used in the first three methods mentioned above. Good statistical results were obtained with the five methods, yielding high levels of explanation (p = 99%). Nevertheless, the most accurate method appeared to be the Growing Degree Days (GDD°) method, which indicated that a mean of 127.3 GDD° must be accumulated from the end of the chilling period up to the beginning of the *Quercus* pollen season in Córdoba (South West Spain). Results were tested for predicting start dates in 1999 and 2000. The predicted dates were only one day after the actual dates.

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(*Manuscript accepted 30 November 2000*)

The effect of meteorological parameters on flowering depends on the bioclimatic conditions in different areas. In areas with temperate climates, the factor with the greatest influence on flowering time in arboreal species that flower in early spring is temperature. Temperature plays a particularly decisive role in the maturation of reproductive organs. It has been shown that tree flowering requires a period of low temperature in order to break late summer and autumn bud dormancy, followed by a period of defined heat accumulation, depending on the species and site (Vegis 1964, Aron 1983, Faust 1989, Frenguelli et al. 1991).

In recent years, a number of forecasting studies have been carried out to predict the start of the pollen season of different taxa (Andersen 1991, Driessen et al. 1989, Spieksma et al. 1989, Frenguelli et al. 1991, Larsson 1993, Spieksma 1995, Frenguelli et al. 1998, Galán et al. 1998, Peeters 1998) although very few studies have focused on forecasting the start of the *Quercus* pollen season.

Although rainfall can affect the duration of the *Quercus* pollen season, pollen production and daily pollen variation it has been shown that, temperature is the main factor influencing the start of the pollen season. (Norris-Hill 1998, Recio et al. 1999, Corden & Millington 1999). The analysis presented in this work consisted in a variety of heat accumulation methods used in order to predict the start of *Quercus* pollination in Córdoba (South West Spain, Iberian Peninsula). Traditional aerobiological and other methods employed in agronomic phenology (Tabuenca & Herrero 1965, Alcalá & Barranco 1992) were used.

Quercus trees are common in the Spanish countryside, being one of the most important taxa in forest economy, particularly for wood production and livestock breeding. This pollen type is one of the most abundant in the atmosphere of the Iberian Peninsula (García-Mozo et al. 1999). Allergic sensitization in the population is not fully understood. Recent studies have reported an increase in hayfever in the UK and *Quercus* pollen has been highlighted as one of the main causes (Ross et al. 1996, Butland et al. 1997). Farnham (1990) reported a 29% positive skin prick test to *Quercus* pollen in USA. Subiza et al. (1987) in Spain and Negrini & Arobba (1992) in Italy reported up to 15% positive prick tests. In contrast, low results – around 4% – have been reported by Gergen et al. (1987) and Luscr et al. (1996) in the USA, and by Prados et al. (1995) in Spain. In Córdoba, the allergenic capacity of this taxon is currently being studied, and positive skin prick tests have been reported in individuals from the northern part of the Córdoba province by the Allergy Service of the University Hospital Reina Sofía (unpublished results). These differences in results may explain the small number of studies that have focused on the aerobiology of the *Quercus* taxon. Moreover, the irregular inter-annual biological behaviour of these trees makes the study of pollen data, despite its importance in agriculture and the huge pollen grain levels recorded in most European countries. (Corden & Millington 1999, Norris-Hill 1998, García-Mozo et al. 1999, Rodríguez et al. 1999). Very few studies on this kind of pollen forecasting were found in the literature.

The absence of predictive models in Córdoba for most anemophilous trees made it necessary to study their heat and chilling requirements. This work, based on 16 years of pollen recording, studied one of the most important taxa in the area around the city of Córdoba. In subsequent works, we will attempt to model predictive formulas for other allergenic taxa.

MATERIALS AND METHODS

The city of Cordoba is located at 37°26′20″N, 4°11′30″W in the South West of the Iberian Peninsula. In the northern area of Cordoba Province the dominant vegetation is the Mediterranean *Quercus* forest Airborne pollen was trapped using Hirst's volumetric method (1952). A seven-day recording spore trap (Burkard Manufacturing) was placed on the roof of the Faculty of Sciences, University of Córdoba, approximately 15m above ground level. The standard sampling procedures proposed by the Spanish Aerobiology Network (REA; Domínguez et al. 1991) were used to obtain pollen counts.

Data for 16 years (1982–1988, 1990–1998) of pollen monitoring and meteorological records were studied here. The year 1989 could not been included in this work due to technical problems with the trap. Meteorological data were supplied by the National Institute of Meteorology, based on readings taken at Córdoba Airport, which is located 5 km south of the sampling site.

The start of the *Quercus* pollen season was defined as the date on which 1.0 pollen grain/m^3 was recorded and when subsequent days also had 1 or more pollen grains/m^3 (García-Mozo et al. 1999).

In order to calculate the freezing requirement, the authors used the model proposed by Aron (1983); this model calculates the chilling hours between 0 and 7.2°C. The coldest months in Córdoba are normally December and January. Chilling hours were calculated from 1st December. The start of heat accumulation has been taken both from 1st January and from the final day of the chilling period in each year (Table I).

Only temperatures above or equal to 0° were taken into account in order to calculate cumulative sums; negative temperatures (frost) were considered as equal to 0°.

Five methods were used in this work:

1. Determination of the number of days with a higher mean temperature than the threshold temperature, starting both from 1st January and after the chilling requirement was fulfilled, until the pollination start date. This method, in addition to its predictive value, was used in order to determine base temperatures for the heat accumulation methods described below. This is based on the method used by Tabuenca & Herrero (1965) for fruit trees and Alcalá & Barranco (1992) to predict the flowering time of *Olea europaea* L. in Córdoba.
2. Accumulated Heat Units (H.U), starting on the first date of heat accumulation until blooming. Heat Units were calculated every day as the difference between the daily mean temperature and the threshold (Tabuenca & Hererro 1965, Alcalá & Barranco 1992).
3. Growing Degrees Days (GDD°) accumulated after chilling and up to the pollination start date. One GDD° is equal to one degree above the base temperature during 24 hours. GDD° were calculated using the Hand Calculating Degree Days method described by Snyder in 1988 (Figure 1).
4. Accumulated °C using the maximum temperatures ($\sum$°CMx) recorded after chilling and until the pollination start date.
5. Mean maximum temperature (MnMx) from the end of chilling up until the pollination start date; this was a modified method based on the original Mean maximum temperature method used by Tabuenca & Hererro (1965) and Alcalá & Barranco (1992). Accumulated $\sum$°CMx

Table I. *Beginning of the main pollination season of Quercus (day-month), number of days from 1 January and date of the end of the chilling period.*

	Date start	N° Days	Date end chilling	Chilling hours
1982	6–3	65	4–1	
1983	13–3	72	24–1	502
1984	3–4	94	20–1	336
1985	23–3	82	20–1	401
1986	7–4	97	14–2	506
1987	19–3	78	23–1	495
1988	10–3	70	24–1	338
1990	7–3	66	25–1	76
1991	5–4	95	21–2	909
1992	10–3	70	25–1	454
1993	21–3	80	29–1	471
1994	15–3	74	27–1	444
1995	24–3	74	24–1	428
1996	22–3	82	15–1	52
1997	26–2	57	8–1	75
1998	1–3	60	3–1	75
Mean value	12–3	71	23–1	348

$T_L > Tmax$	$GDD° = 0$
$TL < Tmin$	$GDD° = Tm - T_L$
$Tmax > T_L > Tmin$	$GDD° = 1/\pi\, [(Tm - T_L) (\pi/2 - \theta_1) + \alpha \cos(\vartheta_1)]$
	$\vartheta_1 = \sin^{-1} [(T_L - Tm)]/\alpha$ $\alpha = [(Tmax - Tmin)/2)]$

Fig. 1. Growing Degree Days° (GDD°) calculation for the three possible daily temperature cases. A sine wave is used to approximate the daily temperature curve Snyder (1988). The single sine method to determine degree days. $\theta_1$is the time (expressed in radians) when the sine wave intersects the threshold temperature and α is the daily temperature range. GDD° have been computed every day fom the day which cold period is over until pollen season start.

were divided by the number of days in the period. In this case and in the previous one, the threshold was not used.

Days over a base temperature, H.U., GDD° and Maximum temperature, calculated on a daily basis, were added until the pollen season start date was obtained. In the case of the last method (MnMx), the sum of maximum temperatures was divided by the number of days in the previous period until the start of the season. The average number of Days over a threshold, H.U., GDD°, ∑°CMx and MnMx from the sixteen study years was used as predictive value for consecutive years.

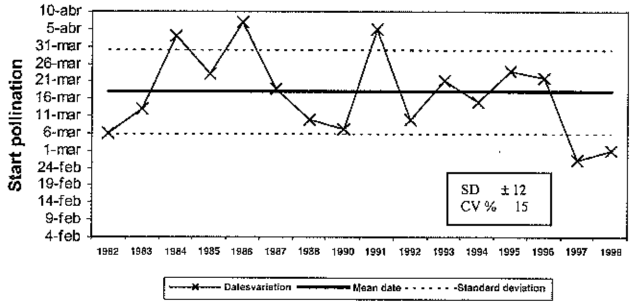

Fig. 2. Variation of the beginning of the *Quercus* pollen season over 16 years.

RESULTS

The dates corresponding to the start of the pollen season are shown in Table I. The most common period for the start of the *Quercus* pollen season is late March, the mean date being 18th March, although dates vary from year to year (Fig. 2). Pollination was very late in three years – 1984, 1986 and 1991 – but early in 1982, 1990, 1997 and 1998.

Table I shows the number of chilling hours calculated for every year, excluding 1982 due to a lack of meteorological data for 1981. These data showed that in Córdoba the chilling requirement may be achieved from mid December to the end of January. The mean value is 348 hours although there are four years in which lower values were recorded (1990, 1996, 1997 and 1998).

The number of days with mean temperatures higher than various threshold temperatures, Range, Standard Deviation (S.D.) and the Coefficient of Variation in percentage terms (CV%) were calculated. Table II shows the results obtained when taking 10, 11, 11.5 and 12°C as the possible thresholds and 1st January and the chilling date as the starting points of the heat accumulation period. The best fit results, showing a relatively low Range and low Standard Deviation and Coefficient of Variation, were obtained with a 11°C base temperature using the end of chilling as a reference day.

Table III shows the results obtained with the Heat Units and Growing Degree Days methods. The 11° threshold was taken, based on conclusions from the results of the previous method, and checking this with other base temperatures where the Standard Deviation and Coefficient of Variation were higher. The heat units required to induce flowering ranged from 31.3°C in 1992 to 125°C in 1987, the mean being 76°C. Heat accumulation, expressed as GDD°C, was also calculated over a base temperature of 11°. Results varied between 95°C in 1988 and 160°C in 1987, the mean being 127.3. A comparison of the two accumulative methods

Table II. *Number of days with a mean temperature higher than 10, 11, 11.5 and 12°C from 1 January and from end of the chilling period.*

	10°		11°		11.5°		12°	
	1 Jan	End chil	1 Jan	End chil	1 Jan	End chil	1 Jan	End chil
1982	50	48	34	34	27	27	25	25
1983	33	33	25	25	24	24	23	23
1984	42	41	29	29	23	22	19	19
1985	45	43	41	39	36	36	32	32
1986	47	43	43	40	43	40	40	37
1987	48	45	41	40	38	38	36	36
1988	48	38	27	25	22	21	20	19
1990	45	37	38	36	32	30	22	22
1991	52	41	42	37	39	37	38	36
1992	28	26	26	25	14	14	10	10
1993	40	40	28	28	25	25	20	20
1994	40	35	32	29	28	26	23	21
1995	55	54	46	45	45	44	39	38
1996	57	46	41	31	32	22	26	15
1997	49	49	39	39	36	36	28	28
1998	43	43	36	36	34	34	26	26
Mean	45	41	35	33	31	29	26	25
Min	28	26	25	25	14	14	10	10
Max	57	54	46	45	45	44	40	36
Range	29	28	21	**20**	31	30	30	26
S.D.	7.53	6.75	6.85	**6.00**	8.39	8.35	8.38	8.41
C.V.%	17	16	20	**17**	27	28	32	33

Table III. *Accumulated Heat Units (base 11°C) and accumulated GDD°C (base 11°C) after chilling period.*

	H. U.	GDD°
1982	63	126
1983	77.8	133
1984	57	127
1985	82.9	147
1986	90.2	147
1987	125	160
1988	48.4	95
1990	79.5	127.6
1991	95.4	127.8
1992	31.3	100.5
1993	76.4	135.7
1994	70.4	125
1995	112.8	121
1996	51.15	115
1997	79	126.4
1998	73.1	123.1
Mean	76	127.3
Min	31.3	95
Max	125	160
S.D.	23.6	16.1
C.V.%	30	12

Table IV. *Accumulated maximum temperatures (Σ°C Mx) and mean maximum temperature (MnMx°C) from the end of chilling period until pollination.*

	Σ°C Mx	MnMx°C
1982	1015	16.7
1983	873	18.1
1984	1198	16.1
1985	1081	17.4
1986	955.4	18
1987	1005.6	18.2
1988	779.8	16.6
1990	800.2	19
1991	798	18.5
1992	738	18
1995	878	18.7
1996	1116.8	19.2
1997	886.5	17.7
1998	948.1	16.7
Mean	892.4	17.7
Min	738	16.1
Max	1198	19.2
S.D.	133.5	1
C.V.%	15	5

showed lower SD and CV values when the latter method was used.

The same calculations were made for other methods based on maximum temperatures (Table IV). For the $\sum$°CMx, the maximum value (1198°C) was recorded in 1984 and the minimum in 1992 (738°C), the mean being 892.4°C. When using the mean minimum temperature method (Mn Mx), the difference was lower because the accumulative temperature was divided by the number of days and the range between data was lower; 19.2°C was the maximum in 1996 and 16.1°C in 1984. The mean value was 17.7°C and both S.D. and C.V. were extremely low (1 and 5, respectively).

Lastly, Table V shows the differences between the predicted and observed pollination dates for the five methods. Deviation from the real pollination date was calculated using absolute values, regardless of whether the predicted date was negative (before the observed date) or positive (delayed). The regression equations provide the predicted ratio versus the observed ratio. In all cases, R^2 coefficients were high and P values were significant for $P \geq 0.001$. The method with the greatest predictive value appeared to be the GDD° method, given its higher coefficient of determination (R^2 0.87). Results obtained when using this method suggest that after chilling, 127.3 ± 16.1 GDD°C are required for the beginning of the *Quercus* pollination period. Every future year may be predicted by adding calculated GDD° values, shown in Figure 2, for every day after the cold period. The start of the Quercus pollen season for the next day may be calculated on the day on which 127.3 GDD° are recorded. Forecasting start dates for 1999 and 2000 were tested using this value (obtained without 1999 and 2000 pollen and temperature data). In these two years, the difference between predicted and observed dates was only 1 day after.

DISCUSSION

Most of papers that have studied *Quercus* pollen behaviour have focused on the relationship between pollen and meteorological data during and before the pollen season. However, they fail to propose forecasting models before the season that may benefit both allergy sufferers and agriculture.

In general, all the forecasting methods used here reveal the clear relationship between the *Quercus* pollination start date and air temperature. Specifically, the forecast prediction made in this paper should also be useful for *Q. rotundifolia* Lam., since, although it is difficult to distinguish the pollen morphology between *Quercus* species, phenological observations carried out directly in the field reported that this species flowers before the others that are also present in the area (*Q. coccifera* L. and *Q. suber* L.). A phenological study in the field therefore constitutes a necessary complement to aerobiological studies in order to better explain airborne pollen data recorded in laboratories (Fornaciari et al.1996).

Many methods have been proposed for determining pollination start and end dates. In some taxa, such as *Alnus* and *Populus*, insignificant differences have been recorded using various calculation methods have (Frenguelli et al. 1991). However, in other taxa such as grasses, the predicted start date may vary by up to 10 days (Emberlin et al. 1994).

As regards the definition of the pollen season described in the section on "Materials and methods", a nonpercentage-based method was adopted. One drawback of this type of method is its reliance on the total pollen catch (Emberlin et al. 1994). Very high *Quercus* pollen counts were recorded in many of years, and even 1% would be too high to use for defining the start date. Moreover, all these definitions can

Table V. *Difference between predicted and actual pollination dates using five method of prediction. Regression equations predicted versus observed are also showed.*

[1]Mean of 16 data

Method		SD	Regressions equations real pollination		
Deviation from real pollination date (days)[1]					
N° days Tm > 11°	7.1	±8.2	y = 0.824x + 16.8	$R^2 = 0.68$	P = 0.000
Heat Units	4.3	±6	y = 0.856x + 13.1	$R^2 = 0.73$	P = 0.000
GDD°	2.8	±4.1	y = 0.934x − 1.43	$R^2 = 0.87$	P = 0.000
∑°C Mx	3.1	±7.1	y = 0.868x + 8.18	$R^2 = 0.75$	P = 0.000
MnMx	7.7	±9.5	y = 0.759x + 30.6	$R^2 = 0.58$	P = 0.000

only be used after the pollen season ends and checking every year is not very useful from a predictive standpoint.

Higher temperatures recorded in the South of Spain, with minimum temperatures of over 5°C on most days, even in winter, may explain the interesting results obtained using a threshold temperature of 11°C. Moreover, some studies on olive trees under greenhouse conditions (Hartmann & Porlingis 1957, Hartmann & Whisler 1975) and normal conditions in Córdoba (Alcalá & Barranco 1992) reported that 12.5°C was the optimum temperature for flowering. These results coincide with those obtained here, probably because *Quercus* species in Córdoba are adapted to the same meteorological conditions, although they flower earlier.

As regards the day to begin heat accumulation, different authors have used both fixed days after chilling and 1st January. According to the results obtained in this study, the fixed day as a reference point yields better predictive results although differences are not very great. It may therefore be useful to use 1st January on some occasions given its simplicity.

The shortest chilling requirements coincided (except for 1996) with the years in which flowering, and therefore pollination, started was very early. However, no significant relationships were observed between chilling units and pollination day (the coefficient of determination was very low), suggesting that these data are therefore not productive in terms of their predictive value in this warm area.

Heat accumulation over an 11°C threshold appears to be an effective forecasting method. In general, all statistical results after application of the formulae were positive, especially Number of days, GDD° and MnMx°C. Although the ∑°CMx method failed to yield very good statistical results, S.D.: 133.5°C was not high if we bear in mind that in early Spring maximum temperatures in South Spain can reach 20°C, hence this would really mean a deviation of less than one week. Analysis of the regression equations (predicted versus observed) showed that the GDD° method was the best predictor. The ∑°CMx method, presenting the second higher R^2, ranked second. Moreover, the results obtained using the GDD° method for predicting *Quercus* pollination start dates in 1999 and 2000 were very positive since a difference of only one day was recorded in both cases.

It may therefore be concluded that although all the methods tested were useful for forecasting the start of the *Quercus* season in Córdoba, the GDD° method affords a better statistical basis. Both the ∑°CMx and MnMx°C methods are also very useful in view of the good results obtained and their easy management.

ACKNOWLEDGEMENTS

The authors are very grateful to the M.E.C. for funding projects PB96-0513 and AMB97-0457-CO701 and for the grant awarded for the second project.

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