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Agricultural and Forest Meteorology 110 (2002) 247–257

AGRICULTURAL AND FOREST METEOROLOGY

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Modelling start of oak pollen season in different climatic zones in Spain

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Received 2 April 2001; received in revised form 18 December 2001; accepted 7 January 2002

Abstract

Quercus pollen and meteorological data for several years from eight sites in Spain have been statistically analysed to select the threshold temperature and calculate the mean heat accumulation for predicting the *Quercus* pollination start in different climatic areas. The growing degree days method, which assumes the daily temperature varies as a sine wave, was used for heat accumulation calculations. Threshold temperatures between 4 and 12 °C were chosen using linear regression equations forced through the origin and their root mean square error (RMSE) of predicted against the observed dates for each observation site. Above the threshold, the average growing degree days (up to 1999) for the studied years was taken as the predictor value. Results showed a relationship between the selected threshold and elevation and a stronger and statistically significant correlation between threshold and yearly mean temperature, for each site. Regression analysis indicated that the selected threshold and the calculated heat accumulation were optimum for most of the localities. The validity of the results was tested using the meteorological data for the year 2000 as independent variable and this confirmed that there were only a few days difference between the predicted and observed day of the first pollen release for most of the studied localities.

Keywords: Oak forest; Pollen; Aerobiology; Phenology; Threshold temperature

1. Introduction

Adaptation of phenology to temperature is a topic that is receiving increasing attention (Hari and Häkkinen, 1991; Schwartz, 1999; Wielgolasky, 1999). In plants, the starting dates for growth and development

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PII: S0168-1923(02)00003-5

of vegetative and reproductive organs may vary greatly both between and within the species (Larcher, 1995; Snyder et al., 1999). In areas with non-tropical climates, such as the Iberian peninsula, a number of different climatic factors (including photoperiod, rainfall and evapotranspiration) affect tree blooming. Temperature seems to be the factor which most influences the timing of flowering in early-spring-flowering tree species (Faust, 1989; Hunter and Lechowicz, 1992; Heide, 1993; Frenguelli and Bricchi, 1998; García-Mozo et al., 2000; Galán et al., 2001). To forecast the start of pollination it is necessary to consider when the plant begins to accumulate heat units (also known as growing degree days), and how much it requires.

The problems involved in estimating the best threshold temperature for plant development in a range of climates have been discussed for several years both in agronomy and botany, and more recently in phenology and aerobiology. Threshold temperatures actually vary according to several factors in both, the plant and the environment (Snyder et al., 1999; Chuine and Cour, 1999; Wielgolasky, 1999). In addition, in recent years a slight increase has been recorded in global mean temperatures, which are expected to rise by 1.5–4.5° C by the year 2030, and this increase is predicted to be greatest at high latitudes during winter (Boer et al., 1990). One of the crucial consequences will be a disturbance in the annual cycle of plants (Hari and Häkkinen, 1991). Aerobiology is an interesting tool to study the reproductive phenology in anemophilous species. Recent studies in aerobiology show that over the last 20 years the pollen season of some tree species has started substantially earlier in response to the recent warmer springs (Emberlin et al., 1997; Corden and Millington, 1999).

The effects of temperature on oak pollen season start dates were studied at eight different localities (Barcelona, Córdoba, Granada, Madrid, Málaga, León, Priego and Santiago) in Spain. There are 10 indigenous *Quercus* species in Spain, all of which are anemophilous trees and shrubs widely distributed throughout the climatic zones of the country. They produce and release considerable amounts of pollen grains (Tormo et al., 1996) that are recorded in large quantities by a high number of Spanish aerobiology centres (Belmonte and Roure, 1991; García-Mozo et al., 1999). The pollen grains of *Quercus* genus cannot be used as a diagnostic trait for distinguishing between the species as they are stenopalinous which means they share the same morphological characteristics when viewed through a microscope. The main pollination period is in early spring, although it varies depending on the species, the zone, and the annual climatic characteristics. Oaks are of great ecological importance, being dominant species in three of the main Iberian ecosystems (Rodá et al., 1999): (1) in the Mediterranean forest, with evergreen species such as cork-oak (*Quercus suber* L.), holm-oaks (*Q. ilex* subsp. *ilex* L. and *Q. ilex* subsp. *ballota* (Desf.) Samp.), and with deciduous species including gall oak (*Q. faginea* L.) and *Q. canariensis* Willd in the wetter areas of this forest; (2) in the 11 “dehesa”, a semi-natural landscape for animal breeding which takes up large areas of the Iberian territory, *Q. ilex* subsp. *ballota* is the most abundant arboreal species; (3) finally, in the oak forests in the north of the peninsula (where the continental climate in some areas reflects Eurosiberian influences), predominate *Quercus* deciduous species such as the oak (*Q. robur* L.), *Q. pyrenaica* Willd, *Q. faginea*, *Q. humilis* Miller and *Q. canariensis*.

The study of *Quercus* airborne pollen and its relationship with fruit production is great economic importance in Spain (Galán et al., 2000), given the earlier-mentioned widespread distribution of these species and the importance of their fruits for animal breeding and conservation ecology (Cecich and Sullivan, 1999; Rodá et al., 1999). On the other hand, although it is traditionally assumed that European *Quercus* pollen has a low allergenic effect, allergic sensitisation has yet to be fully clarified. Recent studies consider this pollen type responsible for some cases of allergy in areas with abundant *Quercus* vegetation. (Subiza et al., 1987; Negrini and Arobba, 1992; Ross et al., 1996; Butland et al., 1997).

The present paper reports on geographical variations in the start of the *Quercus* pollen season, determining the most accurate threshold temperature and the heat accumulation required in different sites in Spain. Several methods have been used in plant phenology to find the best starting date and the best threshold temperature for growth (Zalom et al., 1983; Alcalá and Barranco, 1992; Yang et al., 1995; Snyder et al., 1999; García-Mozo et al., 2000; Galán et al., 2001). In the present study, growing degree days (D°) were calculated following the method proposed by Snyder in 1985 from 1 January to the pollen start date every year (from 1982 in the case of Córdoba and from either 1992, 1993 or 1994 for other sites) above the different thresholds. The threshold temperature of the series of D° with the lowest root mean square error (RMSE) and the best linear regression forced through the origin between observed and predicted dates, was chosen as the most appropriate threshold temperature for each area.

2. Materials and methods

Quercus pollen data from eight cities (Barcelona, Córdoba, Granada, Madrid, Málaga, León, Priego and Santiago) situated in different climatic zones of Spain were used in this study. In all these sites, pollen traps were maintained by aerobiology centres that belong to the Spanish Aerobiology Network (Red Española de Aerobiología, REA) and take part in nationally co-ordinated research projects to develop predictive models for the occurrence of pollen and spores in the atmosphere. Pollen data were recorded using Hirst volumetric traps (Hirst, 1952) located about 15 m above ground level. The pollen was counted under light microscopy. Data management procedures were the same at all sites, and followed the rules proposed by Domínguez-Vilches et al., 1992. The start of the pollen season was defined as the first day on which one pollen grain/m^3 was reached, with subsequent days containing one or more pollen grains/m^3 (García-Mozo et al., 1999, 2000). Data were available from either 1992, 1993, 1994 (depending on the sites) to 2000, and from 1982 to 2000 (except for 1989) in the case of the city of Córdoba (Table 1).

National weather centres supplied the meteorological data used in this study. Heat accumulation before the flowering period for each year was calculated using maximum, mean and minimum daily temperature data. Heat units are expressed in D°, where 1 D° is equal to 1 °C above threshold temperature over 24 h (Snyder, 1985). To determine the most accurate threshold temperature for heat accumulation at each site a wide range of possible thresholds were tested (from 4 to 12 °C). The D° calculations were made using a sine wave to approximate the daily temperature curve as follows:

$$D^\circ = 0, \qquad \text{for } T_L > T_x$$

$$D^\circ = \frac{1}{\pi}\left[(T_m - T_L)\left(\frac{\pi}{2} - \theta_1\right) + R\cos(\vartheta_1)\right], \quad \text{for } T_x > T_L > T_n$$

where

$$\vartheta_1 = \frac{s^{-1}(T_L - T_m)}{R}$$

$$R = \tfrac{1}{2}(T_x - T_n)$$

$$D^\circ = T_m - T_L, \qquad \text{for } T_L < T_n$$

where T_x, T_n, T_m and T_L are the maximum, minimum, mean and threshold temperature, respectively and R is daily temperature range.

The most accurate threshold temperature was chosen for each zone, taking into account:

- The best linear model through the origin in the regression analysis. The observed against the predicted dates for all the tested threshold temperatures were analysed.
- The lowest RSME of the predicted (d_1) minus the observed (d) days for all the studied years (n)

$$\varepsilon_{\mathrm{RMSE}} = \sqrt{\frac{(d_1 - d)^2}{n}}$$

For identifying patterns in the time series data trend analysis was used. The trend analysis was estimated by the least squares method that calculates the linear equation which best fitted to the data. STATISTICA and SPSS for Windows 98 were the statistical computer programs used for this work.

3. Results

The *Quercus* pollen season start date variation among studied years at the different sites is represented in Fig. 1. There is not a locality where the *Quercus* pollen season start firstly in all the studied years, although the cities situated in the southern part of the peninsula tend to be the earliest. However, the year 1997 stands out because seven of the eight sites

Table 1
Site characteristics: geographical setting in the peninsula, elevation (metres above sea level), coordinates, mean air temperature, average annual rainfall in millimetres, years of analysed data and the studied period and *Quercus* species present at each site

Zone	Site	Elevation (m)	Coordinates	Mean air temperature (°C)	Mean annual rainfall (mm)	Years of data (studied period)	*Quercus* species
Northwest	Santiago	270	42°53′N, 8°32′W	12.9	1288	8 years (1993–2000)	*Q. robur* L., *Q. pyrenaica* Willd
Northeast	Barcelona	90	41°24′N, 2°9′E	16.5	595	7 years (1994–2000)	*Q. ilex* subsp. *ilex* L., *Q. humilis* Miller, *Q. coccifera* L., *Q. suber* L.
Center	León	830	42°34′N, 5°35′W	10.0	550	7 years (1994–2000)	*Q. ilex* subsp *ballota* Desf, Samp. *Q. ovrenaica* Willd, *Q. fainea* Lamk
Center	Madrid	600	40°27′N, 3°45′W	14.0	440	8 years (1993–2000)	*Q. ilex* subsp. *ballota* Desf, Samp *Q. pyrenaica* Willd, *Q. coccifera* L., *Q. fanea* Lamk
South	Córdoba	123	37°50′N, 4°45′W	18.0	600	18 years (1982–1989, 1990–2000)	*Q. ilex* subsp. *ballota* Desf, Samp *Q. coccifera* L., *Q. suber* L.
South	Priego	650	37°26′N, 4°11′W	14.4	650	7 years (1994–2000)	*Q. ilex* subsp. *ballota* Desf, Samp *Q. coccifera* L.
South	Granada	685	37°11′N, 3°35′W	15.1	400	9 years (1992–2000)	*Q. ilex* subsp. *ballota* Desf, Samp *Q. coccifera* L., *Q. suber* L.
South	Málaga	5	36°47′N, 4°19′W	18.0	575	9 years (1992–2000)	*Q. ilex* subsp. *ballota* Desf, Samp *Q. coccifera* L., *Q. suber* L.

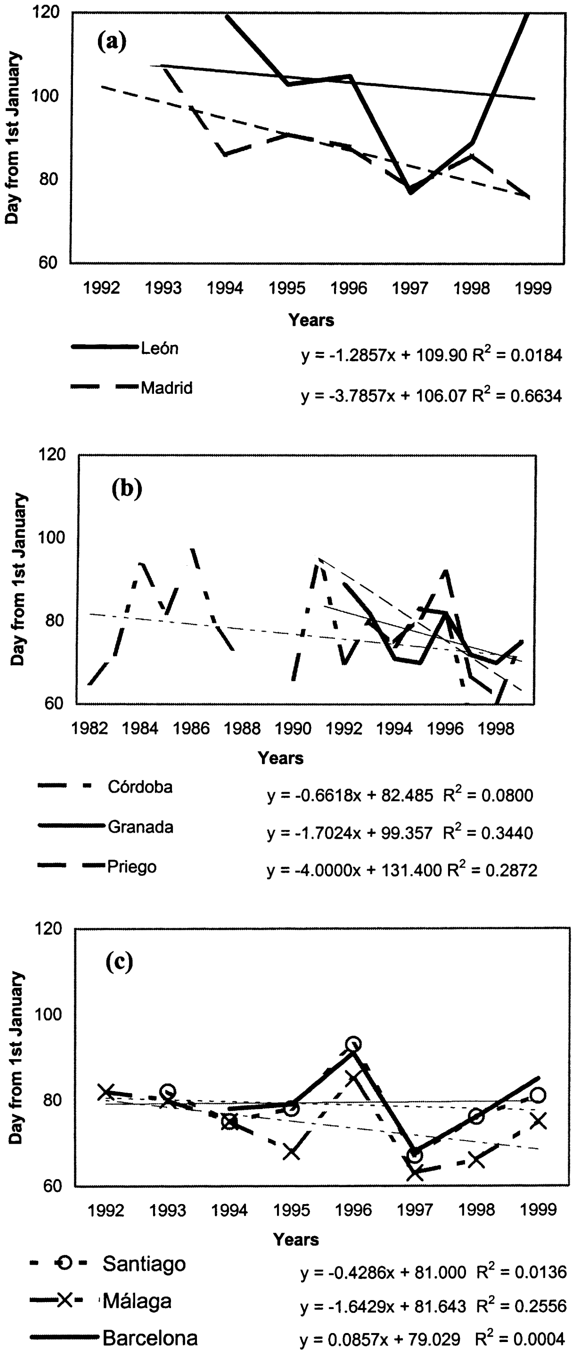

Fig. 1. Start date variations among the years at the eight studied sites. Localities are grouped according to similar start-date patterns. Linear line is represented by narrow lines in the same pattern. The estimation equations and the coefficient of determination (R^2) for each locality is also indicated.

recorded the earliest start dates of the observation period. The variation was plotted in three graphs representing the different sites grouped according to similar start-date patterns. Fig. 1a provides start-dates from León and Madrid (inland north and central, respectively). Of the different species present in these areas (Table 1), *Q. ilex* subsp. *ballota* is the first species of flower. These sites displayed the latest start dates and the greatest year to year variation. The difference between the earliest and the latest date is 47 days, (S.D. 7.7) in León, and 37 days (S.D. 11) in Madrid. Fig. 1b presents data for Córdoba, Priego and Granada. These are in southern Spain, where the most abundant species is the early-spring-flowering *Q. ilex* subsp. *ballota*. The maximum differences are, 29 days (S.D. 11.8) in Córdoba, 30 days (S.D. 11.8) in Priego and 20 days (S.D. 7.2) in Granada. Fig. 1c shows the coastal cities of Málaga, Barcelona and Santiago, where totally different species are present. The species, which flower earliest, are *Q. ilex* subsp. *ballota* in Málaga, *Q. humilis* in Barcelona and *Q. robur* in Santiago. In these cases, even for different species, smoother curves with a very similar pattern are observed. The maximum differences are, 20 days (S.D. 7) in Málaga, 23 days (S.D. 7) in Barcelona and 26 (S.D. 7) in Santiago.

In Fig. 1, the trend over the years is plotted for each site. In all the localities (except for Barcelona) the regression equations present a negative slope coefficient which indicates that the start of the flowering season tend to be earlier in the later years. This characteristic is more evident for Madrid, Priego and Granada, all inland localities (data plotted in graphs a and b). The R^2-coefficients are not high because the start dates varied among years, and logically, they are not well adjusted to a linear model.

A wide range of possible threshold temperatures (from 4 to 12 °C) was tested, using intervals of 0.5 C° to calculate the D° required for cumulative pollen emission from 1 January up to the pollination start date. Results are shown in Table 2. Selected thresholds varied among sites. Logically, the number of calculated average D° before oak pollination also varied among cities, although differences between computed D° for different years in the same city were not significant. It is noticeable that in Santiago and Barcelona, coastal cities with different species, the selected threshold was the same, 5 °C and the calcu-

Table 2
Average growing degree days above the selected threshold temperature and the relative coefficient of variation for the studied years data set. The base temperature was chosen according to the better coefficient of regressions through the origin and the lowest RMSE of the observed and expected start dates (Fig. 3)

Site	Selected threshold (°C)	Average growing degree days (°C)	Coefficient of variation (%)
Santiago	5	420.3	11.0
Barcelona	5	416.7	12.0
León	4	352.5	12.4
Madrid	8	205.1	21.0
Córdoba	11	153.4	17.0
Priego	8	250.9	19.0
Granada	4	406.4	15.3
Málaga	9	309.3	11.0

lated D° were similar, 420.3 and 416.7, respectively. On the other hand, León and Granada, situated in the different climatic areas although the same species, *Q. ilex* subsp. *ballota*, flowers first, presented the same selected threshold temperature, 4 °C but different calculated D°: 352.5 and 406.4, respectively. This could result from accumulated D° before 1 January.

Fig. 2 represents the elevation, the annual mean temperature and the selected threshold for all sites. For the highest elevation the threshold temperature is the lowest value. For the correlation analysis we used a relationship where the two biogeographical variables are multiplied together and forced through the origin, i.e. $y = Axz$. The results were assessed using the Pearson correlation test. Results in Table 3 indicates a possible association between the threshold temperature and the other two biogeographic features. This correlation is strongest and significant at 95% for the mean temperature and the threshold temperature. A parametric test was used due to the normality of all the data (Table 3) which was measured by the Shaphiro Wilks normality test using the relationship forced through the origin, i.e. $y = Axz$.

Predicted dates for each year were calculated using the cumulative D° above the selected threshold temperatures at each site from 1 January, averaged over all the studied years. The comparison between the predicted and actual dates used a linear regression forced through the origin (Fig. 3). The R^2 represents the proportion of explained variability about the origin; this value cannot be compared to the R^2-value when the intercept is included.

Finally the D° accumulative method was tested for the forecasting of the beginning of the oak pollen

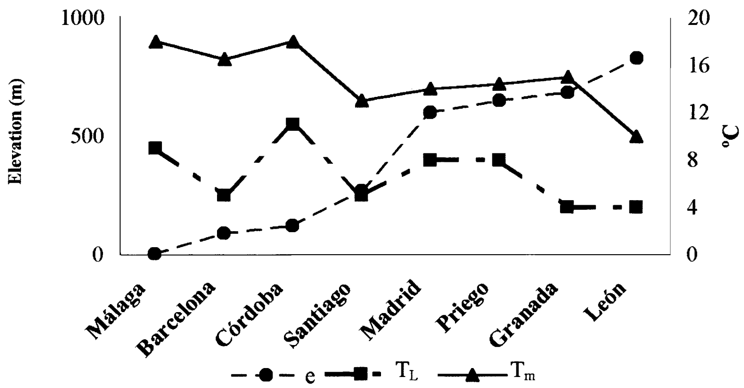

Fig. 2. The elevation (e) (metres above sea level) (left hand axis), mean temperature (T_m) and the selected threshold (T_L) (right hand axis) for each observation site.

Table 3
Shapiro Wilk's normality test and Pearson correlation (parametric test) comparing biogeographical parameters and threshold temperatures selected from the eight studied sites. Mean temperature and the selected threshold show stronger and significant correlation

Shapiro Wilk's normality test			Pearson correlation test		
Variables	W	p-Level	Pair of variables	P-value	p-Level
T_L	0.89	0.257	T_L and e	−0.47	0.24
e	0.89	0.247	T_L and T_m	0.74	0.05
T_m	0.92	0.521			

T_m: mean temperature; T_L: threshold temperature; e: elevation.

Table 4
Actual and expected dates of the *Quercus* season start for the year 2000 (not included in the model). The differences are shown in the fourth column

Site	Actual date (day of year)	Expected date (day of year)	Expected − actual (days)
Santiago	70	75	+5
Barcelona	83	77	−6
León	116	110	−6
Madrid	61	74	+13
Córdoba	64	65	+1
Priego	70	74	+4
Granada	75	72	−3
Málaga	68	74	+6
Mean absolute value			5.5

season in the year 2000 (which was not included in the model data) for all the localities (Table 4). The average D° (Table 2) were computed daily in 2000 in order to determine the *Quercus* pollination start date in that year. The difference between the expected and actual dates is shown in the fourth column of Table 4. Negative and positive signs indicate in advance or delayed previsions respectively. The mean absolute value was 5.5 days. The best forecast was obtained for the city of Córdoba, with a discrepancy of only 1 day.

4. Discussion

4.1. Start date variations

In general, the results obtained reveal a clear relationship between the oak pollination start date and air temperature. Specifically, the forecasting made should be useful for *Q. ilex* subsp. *ballota* start date in central and southern Spain, for *Q. robur* in northwestern Spain and for *Q. humilis* in northeastern Spain (Cabezudo, 1999). In general, *Quercus* pollen season in Spain starts in early April, although there are annual temperature-related variations. From these results, it is deduced that a similar pattern may be observed in cities with similar climatic conditions, for example Madrid and León lie in the central and central-northern Spain, respectively. The same species, *Q. ilex* subsp. *ballota*, flowers first in both sites (Cabezudo, 1999), although as the graph shows, this species always flowers earlier in Madrid, where temperatures are higher. Both cities have severe weather conditions with cold winters and hot summers. They register high intra-annual and inter-annual temperature fluctuations. These fluctuations may be responsible for the considerable variation in start dates over the study period. Córdoba, Priego and Granada are situated in inland southern Spain, with hot summers and warm springs. At all of these sites, the dominant species is *Q. ilex* subsp. *ballota*, which flowers first (García-Mozo et al., 1999). Granada and Priego are situated in mountain chains and register low temperatures in winter (below 0 °C on several days). Nevertheless, a very similar pattern may be observed for the studied period. In Barcelona (northeastern Spain),

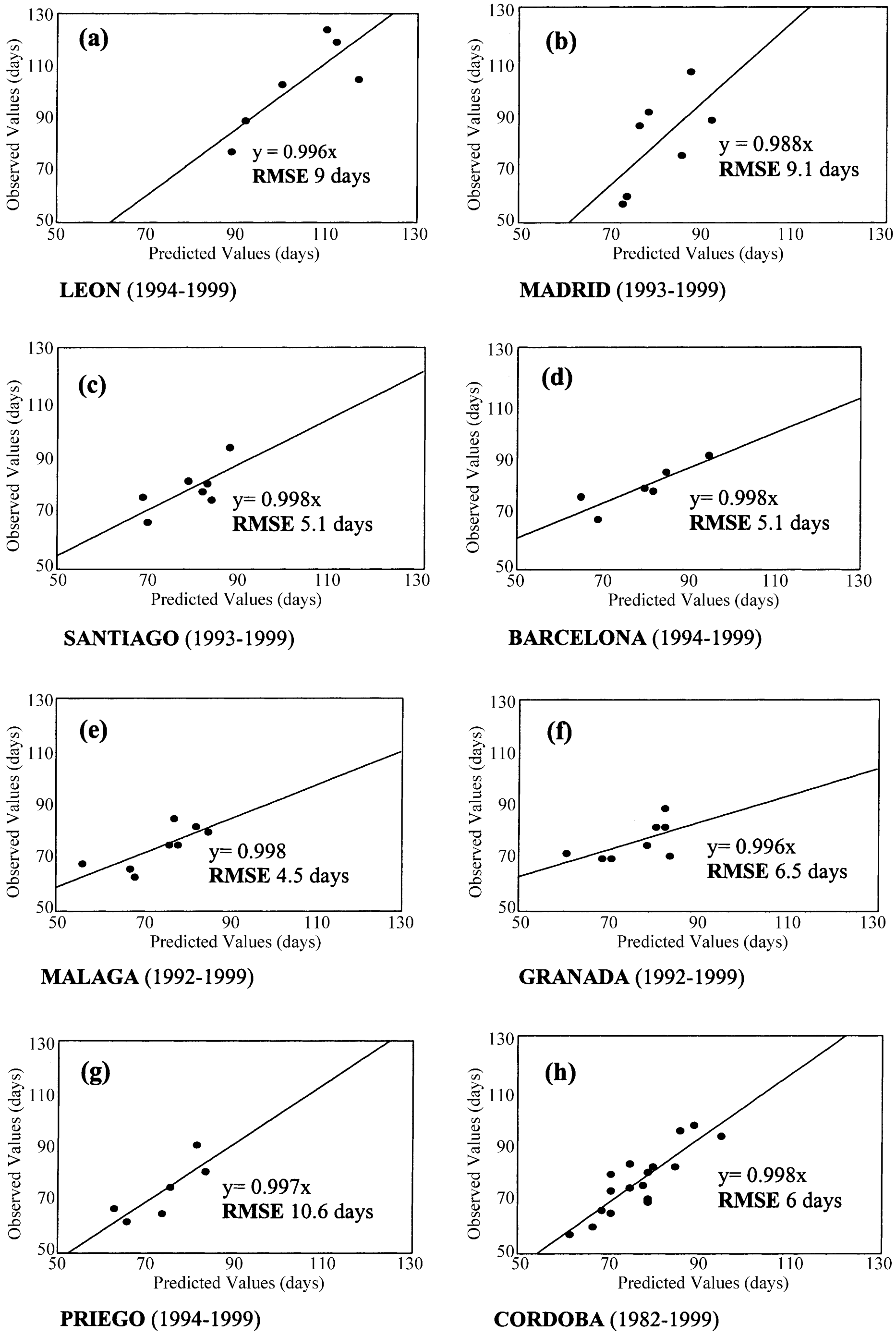

Fig. 3. Linear regression forced through the origin of the predicted against the independent observed start of pollen release for (a) León, (b) Madrid, (c) Santiago, (d) Barcelona, (e) Málaga, (f) Granada, (g) Priego, (h) Córdoba. The RMSE values are also shown for each site. The linear regression line (not forced through the origin) is also shown.

Q. humilis is the first to flower, in Santiago (northwestern area) the earliest and most abundant species is *Q. robur* whereas in Málaga (south area) it is *Q. ilex* subsp. *ballota* (Cabezudo, 1999) and all of them showed the same pattern. Moreover, for Barcelona and Santiago (both in north Spain) the same threshold temperature, 5 °C, was selected and a similar number of D° were calculated. Different threshold and D° were calculated for Málaga, which is also a coastal city of South Spain, with a warm climate all year. These results suggest that geographical conditions and consequently climate may be even more important than species when determining *Quercus* pollen season start dates.

It is noticeable that most of the localities uniformly display slightly earlier start dates. The R^2-coefficients are not high because the start dates among years are not adjusted to a linear model, but the negative slopes indicate earlier pollen release dates along the period of study. Other authors in north Europe have already described this phenomenon for *Quercus* (Corden and Millington, 1999) and also for other species (Emberlin et al., 1997), being attributed to global climatic change. Moreover, the adaptation of other tree species phenology to a supposed climate warming is being widely accepted (Murray et al., 1989; Hari and Häkkinen, 1991; Kramer, 1995). The low coefficient of variation of the D° recorded every year in our work indicates that the same amount of heat is recorded in a shorter time. The amount of analysed years in our work is not enough for establishing a clear relationship between global temperature increase and phenology changes, but this first approach could be fundamental in order to plan future phenological studies in Spain.

4.2. Different thresholds in different studied areas

In plants, in general, and more specifically in the case of non-cultivated plants, climatic variables seem to be the major factor influencing the production and release of pollen and therefore the fruit production (Cecich and Sullivan, 1999). Moreover, in temperate climates, it is generally agreed that temperature is the most important variable (Faust, 1989; Frenguelli and Bricchi, 1998; Alcalá and Barranco, 1992; Galán et al., 2001). The phenological characteristics of each species are adapted to the climate conditions of its own geographical area. Taking this fact into account many possible threshold temperatures were tested in the present study. Results indicate that for each site a different threshold temperature provided the most accurate modelling. On this basis, the number of D° computed can be seen to represent the average forcing temperature for the start of *Quercus* pollination at each site. The same trend of the selected threshold temperature, inverse of elevation and mean annual temperature at each site has been detected. A possible correlation has been found between elevation and threshold, this correlation is strongest and statistically significant at 95% for the mean temperature and threshold.

Regions such as Spain present many different types of vegetation and landscape due to particular geographic characteristics. Spain has many mountain systems and three coastal zones (Atlantic, Cantabrian and Mediterranean), and thus a wide range of microclimates. Trees that flower in early spring, such as *Quercus* species, require a period of stress in order to break the dormancy of their buds (formed in the previous summer). Summer temperature, winter chilling units and forcing temperature or heat accumulation in trees have been widely researched by numerous authors (Arnold, 1959; Frenguelli and Bricchi, 1998; Chuine et al., 1999; García-Mozo et al., 2000; Galán et al., 2001) in order to clarify their involvement in the settlement and intensity of dormancy as well as cold acclimatisation. In Mediterranean climates, the temperatures of the preceeding summer seem to have no significant effect on the timing of budburst, and some *Quercus* species have been found to show a very weak response to the duration of chilling (Chuine et al., 1999). On the other hand, our results indicate that they have a systematic response to a determinate amount of heat. In the Iberian peninsula, the coldest temperature is recorded during November, December and January. The date 1 January was taken as a reference date for the end of the chilling period because D° was calculated in all the studied cities from both of the dates (actual end of chilling period and 1 January) and little difference was detected (data not shown). It could be because the end of the chilling time is always near early January and in this short period the plant can accumulate few heat units. So, 1 January was selected as the reference day for heat summation in order to simplify the calculations.

4.3. Adapted responses to the environment

A wide range of mean annual temperatures is recorded in the Iberian peninsula, including warm winters and damaging frost temperatures during spring (García-Mozo et al., 2001), so the use of different threshold temperatures for forecasting the start of the pollen season is useful. The most relevant example of climate adaptation is *Q. ilex* subsp. *ballota*. This species is found in six of the study sites (not in either Santiago or Barcelona), where it flowers before the other species. The same species in different localities show adaptations to different environmental conditions. This phenomenon has been observed in other studies (Spano et al., 1999; Castro-Díez and Montsserrat-Martí, 1998). This species is very well adapted to most of the climates of the Iberian peninsula. Similar behaviour is reported in France for seedlings of *Q. humilis* grown at two sites at different altitudes under different climates (Chuine and Cour, 1999) and in California for *Q. agrifolia* Neé and *Q. lobata* Neé (Fairley and Batcheler, 1996).

4.4. Internal and external validity

The regression equations and RMSE confirm the internal validity of the data. In all the cases, good statistical results were obtained, although the best results were obviously found at sites with the largest data series available (Córdoba and Málaga) and in Barcelona. Finally, the external validity was tested for all the localities for the year 2000. The results are good and excellent in the case of Córdoba with only a single day of error. The mean absolute difference was of 5.5 days. Nowadays, general start pollen season forecasting are not easily done due to the high variability among years. Both the threshold temperature and the calculated D° reported here are valid tools for the future predictions of the start of *Quercus* pollen season.

5. Conclusions

The beginning of the *Quercus* pollination in Spain varied greatly among the years. This variation is highly influenced by temperature. Selecting the best threshold temperature for each of the eight studied sites for computing the average growing degree days (D°) has been demonstrated to be very useful in modelling the start of *Quercus* pollen season.

Different thresholds have been selected for different localities. These threshold are related to the mean air temperature for each site. The average estimated D° were tested using the independent meteorological data for the year 2000 and difference of a few days between the predicted and observed dates were detected. Therefore, the model that we proposed here can be used in future aerobiological and phenological prediction for *Quercus* flowering in Spain.

Acknowledgements

The authors wish to thank the CICYT for providing financial support for projects AMB-0457-CO7 and PB96-0513. They wish to thank the anonymous reviewers for their helpful comments and to Prof. Paul Comtois of the University of Montreal for his valuable comments on the revised manuscript.

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