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ORIGINAL PAPER

Airborne-pollen map for *Olea europaea* L. in eastern Andalusia (Spain) using GIS: Estimation models

F. Alba · D. Nieto-Lugilde · P. Comtois ·
C. Díaz de la Guardia · C. De Linares ·
L. Ruiz

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Abstract Estimations based upon geostatistics and mapping have enabled the construction of a spatial model to predict the presence of biological particles in a particular region. This methodological proposal has been tested in a case study, at a regional scale, of airborne *Olea* pollen, using the data acquired from various sampling stations that are designed for the aerobiological monitoring of pollen levels. These sampling stations have been set up in cities throughout the region of Andalusia (southern Spain) at sites with very different characteristics in terms of biogeography, bioclimate, topography and vegetation. Pollen counts were made daily at all sites during 2003 using a volumetric spore-trap. Data were comparatively analysed in classical diagrams and by means of spatial-temporal maps. Space-time models were constructed using three coordinates, *x*, *y* (the UTM coordinates of each sampling station) and *z*, (the aerobiological data compiled for a specific period). The aerobiological data were interpolated by applying the traditional geostatistical method of Kriging. The introduction of the variable ''space'' into the model allowed us to predict pollen levels in different areas throughout the region. The interpolation method was used to make weekly estimations of *Olea* pollen values in areas where there was no aerobiological sampling station. In addition, the maps generated present a two-dimensional vision of the study area, showing that bioclimatic diversity of this region promotes a step-wise flowering of *Olea*.

Keywords Aerobiological networks · Aerobiology · GIS · Kriging · Modelling · Regional scale · Spatial interpolation · *Olea* pollen

Introduction

Aerobiology is both an old science (underlying hypotheses) and a new science (recent adoption of physical principles and use of standard methods). The earliest research endeavors in this field were mostly individual enterprises. Aerobiology was seen more as the study of the temporal distribution of airborne micro-organisms at one site by one researcher, and spatial distribution was not often considered.

F. Alba (✉) · D. Nieto-Lugilde · C. Díaz de la Guardia ·
C. De Linares
Departamento de Botánica, Facultad de Ciencias,
Universidad de Granada, Avda. Fuentenueva,
18071 Granada, Spain
e-mail: falba@ugr.es

P. Comtois
Laboratoire d'Aérobiologie, Département de Géographie,
Université de Montréal, Quebec H3C 3J7, Canada

L. Ruiz
Departamento de Biología Animal, Vegetal y Ecología,
Facultad de Ciencias, Universidad de Jaén, 23071 Jaén,
Spain

However, in the last 20 years, aerobiology has become a highly standardized science, thanks to the formulation of sampling networks that have adopted standard methodologies. One example of the latter is the Hirst-type volumetric sampler, which is very widely used to register the hourly qualitative and quantitative changes of pollen and spore content in the atmosphere. The adoption of this sample has greatly facilitated and encouraged the exchange of information between investigating teams and, consequently, aerobiological networks were put together. These are now so prominent that comparisons are possible at different scales (regional, national, and even international). This cooperation has been instrumental in the rapid progress made in the field aerobiology in the few past years, to the point where we have a better understanding of the complexity of aerobiological processes.

However, this evolution in the aerobiology practical side (data collection) has not been matched by a parallel evolution of tools by which to analyse the collected data and, to date, only a few research projects have considered the inclusion of other variables, such as phenology (Puppi & Zanotti, 1992) or climatology and topography (Hidalgo et al., 2002), together with the variable ''space''. Geostatistical tools would open new perspectives to aerobiological data sets, as has occurred when these tools were applied in other fields related to aerobiology, such as geology, hydrology and climatology. Many environmental subjects have incorporated spatio-temporal modelling (Antonic, Križan, Marki, & Bulovec, 2001; Chuanyan, Zhongren, & Guodong, 2005). In atmospheric research, geostatistics are widely used to estimate air pollution and chemical deposition (Holland, Caragea, & Smith, 2004; Nanus, Campbell, & Ingersoll, 2003).

In aerobiology averaged data are sometimes presented under an integrated format, such as atmospheric-concentration isoline maps (see, for example, Jager & Mandrioli, 1991, 1993), but they are used only as a presentation tool, and no spatial analysis *per se* has as yet been applied to original data. The application of geostatistics to aerobiology opens a new and promising field of study: spatial aerobiology that could have a large number of applications in aerobiological networking but also in dispersal studies.

The objective of this paper is to put forward a methodological proposal using geostatistics, which will also be illustrated with a case study, where we were able to estimate airborne concentrations for a whole region from data collected at only four sites. *Olea* pollen type was selected for its presence in southern Spain, being the most abundant type within the annual pollen spectrum, due both to the ubiquity of this crop as well as to the intense flowering of the trees. As a result, the human population of Andalusia is exposed to extremely high levels of *Olea* pollen during the spring, making this airborne allergen the principal cause of seasonal allergic rhinitis and bronchial asthma.

Materials and methods

This study was conducted in four localities of southern Spain (Granada, Almería, Jaén and Motril) (Fig. 1). Biogeographically, these cities belong to the Mediterranean Region, but they do show some diversity in terms of chorological unities (Table 1). These differences accurately reflect the heterogeneity of their physical environment and vegetation characteristics. The closeness of the sea to Almería and Motril maintains mean annual temperatures above those of the sites in the interior. Moreover, Almería is subject to less rainfall than the other localities.

A volumetric spore-trap was used at all sites (Hirst, 1952). During 2003, daily pollen counts were made using the methodology proposed by Domínguez, Galán, Villamandos, & Infante (1991), and the

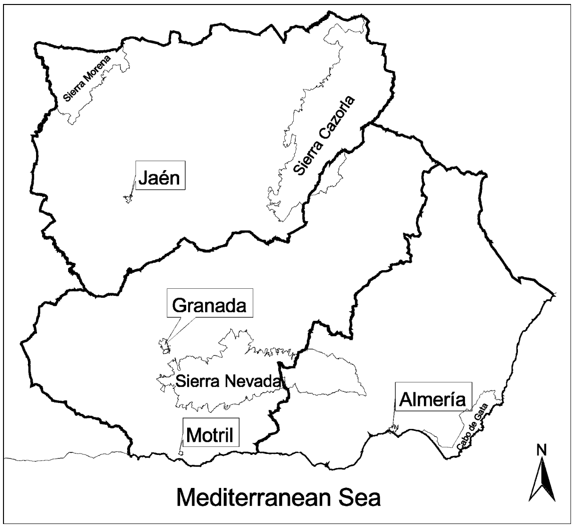

Fig. 1 Localization map of study area

Table 1 Chorological, bioclimatic and climatic characteristics at the sampling sites

	Climate	Biogeography			Bioclimatology	Potential vegetation	Altitude (m)	Mean annual temperature (°C)	Annual rainfall (mm)
		Region	Province	Sector					
Almería	Mediterranean-Oceanic	Mediterranean	Murciano Almeriense	Murciano Almeriense	Thermo-Mediterranean	Thermophilic forest	23	18	240
Granada	Mediterranean-Continental	Mediterranean	Bética	Malacitano Almijarense	Meso-Mediterranean	Oak forest	685	15	402
Jaén	Mediterranean-Continental	Mediterranean	Bética	Subbético	Meso-Mediterranean	Oak forest	560	16	583
Motril	Mediterranean-Subtropical	Mediterranean	Bética	Malacitano Almijarense	Thermo-Mediterranean	Oak/thermophilic forest	39	18	450

data were expressed as average daily pollen grains per cubic meter of air (grains/m^3). For the present study, airborne *Olea* pollen concentrations were expressed graphically and compared between stations using weekly averages. The main pollen season (MPS) was determined at 95%, taking the data compiled for January and December, following the methodology of Nilsson & Persson (1981).

The database was organized in the following way. Each aerobiological datum (pollen grains/m^3) is georeferenced, i.e. accompanied by two other variables that locate them spatially (UTMx and UTMy) at any chosen scale (Table 2). This provides an orthogonal and three-dimensional system of coordinates, where x and y specify a two-dimensional coordinates on a plane (the earth surface—in our case, the UTM projection—which facilitates their integration in a subsequent numerical map), while z represents the aerobiological values for a specific period (t). In our case, the temporal units were defined as weeks.

There are several geostatistical tools for interpolation (linear, inverse square of distance, spline, nearest neighbours, etc.). We used a kriging tool (Krige, 1951) because it is the only one that used, for aerobiological purposes, estimates of variability and spatial-correlation information. Moreover, this technique also gives an output with spatial continuity.

To analyse the spatial dependence of our data, we calculated the experimental variograms corresponding to each temporal unit considered (week). The low number of sampling stations in the present study prohibits the use of directional variograms, and anisotropy had been discarded in each of the analyses performed. The isotropic variograms were adjusted with theoretic variograms by the maximum-likelihood algorithm. The parameters derived from this analysis were used to apply the interpolation method, for which the Ordinary Kriging method was used, as it considers the data that lack trends.

Kriging restructures the input database under the form of a matrix, where columns represent the UTMx coordinates, while ranks represent the UTMy coordinates. In each cell of the matrix, airborne-pollen concentrations are represented, either the observed data from sampling sites, or estimated values for coordinates where no such station exists but which can be correlated to a specific spatial domain. The size of this matrix also constitutes a parameter for which the value (number of files and columns) is fixed by the

Table 2 Example of the database used in *Olea* case study

Sampling sites	Coord. x Coord. x UTM	Coord. y Coord. y UTM	Coord. zt_1[a] Mean week 1 concentration	Coord. zt_2 Mean week 2 concentration	Coord. zt_3 Mean week 3 concentration	... ...	Coord. zt_{11} Mean week 11 concentration	Coord. zt_{12} Mean week 12 concentration
Almería	548857	4078613	2	2	17	...	13	7
Granada	445717	4115452	0	2	7	...	51	30
Jaén	429945	4180902	1	88	297	...	64	38
Motril	453901	4067461	3	7	31	...	18	13

[a] zt, Pollen concentrations observed in each locality at the moment t

researcher as a function of the precision requested for the estimation of missing data. For the proposed analysis of the *Olea* pollen distribution in the study area, we considered a matrix of 206 × 239, in which each cell corresponded to a mesh of 1 km^2 of the earth's surface (Table 3). This whole process must be repeated for each selected period (t) of the time frame.

Finally, this numerical information generated was included into a digital cartography system (GIS) in order to manage and interpret it. In this way, we chose the logarithmic scale (pollen grains/m^3) proposed by Spieksma (1991) for the production of pollen calendars, and therefore we rescaled data to the Spieksma's ranges and assigned a different fill pattern to each interval of the scale. Some other cartographic information was included to facilitate the interpretation of the airborne-pollen maps.

To check the reliability of the interpolation described here, the models obtained with the data from all four sampling stations used were compared with those obtained when one of the stations was eliminated, in this case the station of Granada (located in the centre of the study area). The Wilcoxon test was applied to evaluate the performance of the model and to analyse the causes of estimation errors, comparing the numerical series observed and estimated for Granada, taking as units (1) daily averages during *Olea* MPS and (2) the weekly averages of *Olea*, both calculated during 2003.

The different software used was: R 2.1 and its library ''geoR'' (Ribeiro & Diggle, 2001) to analyse data and plot variograms, Surfer 6.01 to interpolate with kriging, GRASS 6.0.1 and ArcView 3.2 as GIS to manage data and plot the final airborne-pollen maps.

Results and discussion

Weekly behaviour

The weekly behaviour of the *Olea* pollen at four cities is shown in Fig. 2a and b. The detailed study of the seasonal dynamics revealed that the first pollen grains were detected in April in the coastal zones of Motril and Almería and the last were registered during June in the highest zones of the province of Granada. This suggests that the olive tree needs a certain amount of heat to initiate pollination, which occurs later in the mountain areas of Andalusia (Alba & Díaz de la Guardia, 1998).

In Almería and Jaén, the week of the maximum pollen count usually occurred in first two weeks of May, although in Granada and Motril this could lag

Table 3 Structure of the generated matrix with observed and estimated values at time t

206	4	4	4	4	4	4	4	4		0
...	...	...	...	...	...	...	...	...	...	...
8	49	49	49	49	49	49	50	50	...	7
7	49	49	49	49	50	50	50	50	...	7
6	49	49	50	50	50	50	50	50	...	7
5	50	50	50	50	50	50	50	51	...	8
4	50	50	50	50	50	51	51	51	...	8
3	50	50	50	50	51	z 51	51	51	...	8
2	50	50	51	51	51	51	51	51	...	8
1	51	51	51	51	51	51	51	52	...	8
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	...	**239**

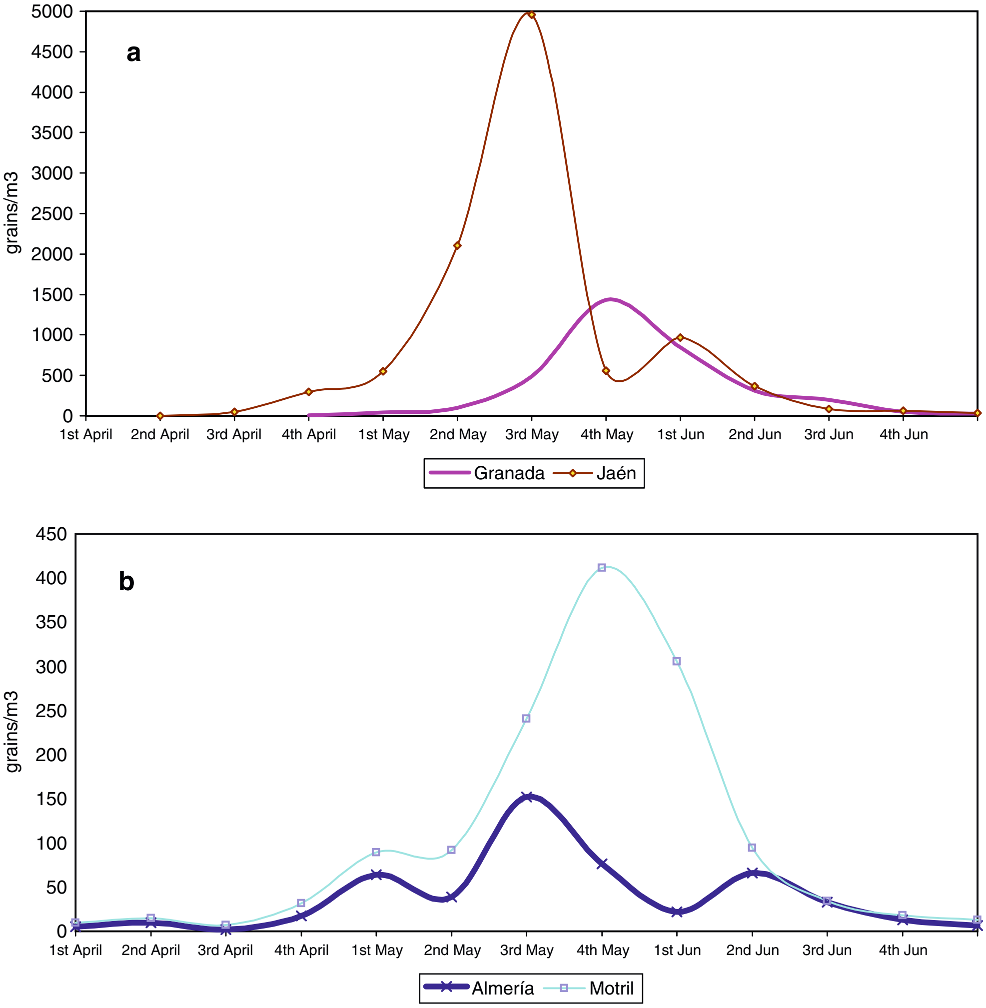

Fig. 2 Mean weekly concentration of *Olea* pollen during the analysed period at each of the sampling stations. (**a**) Granada and Jaén, (**b**) Almería and Motril

until the last week of May. Jaén registered the highest peak days, reaching 5000 pollen grains/m^3 during second week of May; Granada also reached a high seasonal peak day, of up to 1430 grains/m^3 during the fourth week of May; Almería and Motril were distinguished by reaching somewhat less intensive peak days.

Olea aeropalynological maps

The diagrams previously displayed give only a partial picture of the pollen spatial distribution because they do not cover the whole scope of the regional aerobiological environment. The use of the same weekly airborne pollen data from each sampling station has allowed us to produce a synthesis in the form of two-dimensional (temporal and spatial) *Olea* aeropalynological maps.

The analysis of the theoretic and experimental variograms shows a different spatial correlation as a function of the time of the Main Pollination Period considered. These were fitted with variable grades of reliability, with r^2 between 0.035 and 0.839. Figure 3 only shows two isotropic variograms, one at the third week of April (with high pollen concentrations reached at Jaén) and other at the second week of June (with decreasing concentrations at Jaén).

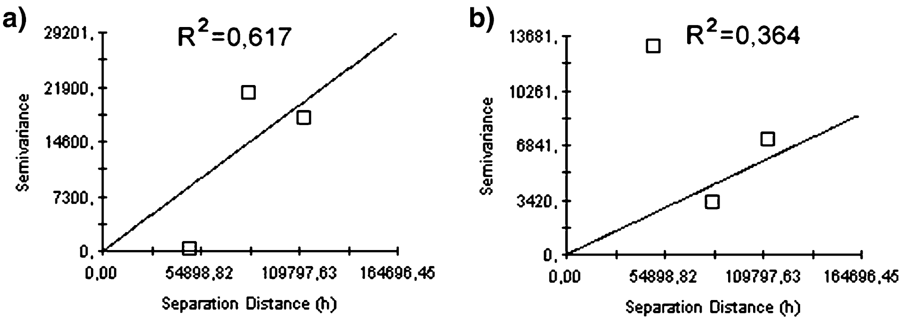

Fig. 3 Experimental and theoretic variograms at two different weeks: (**a**) Third week of April, (**b**) second week of June

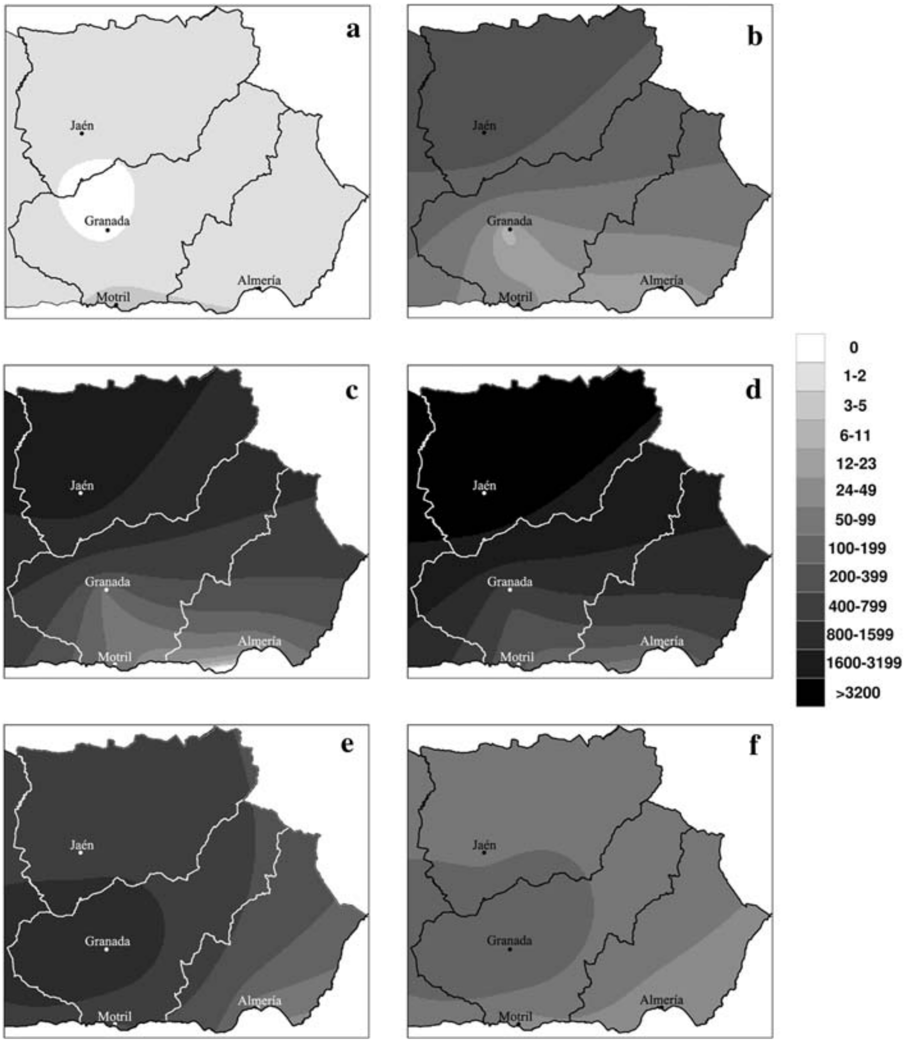

Fig. 4 Kriging estimation maps of weekly average concentrations (grains per cubic meter of air) of *Olea* pollen on a regional scale, southern Spain. (**a**) First week of April, (**b**) third week of April, (**c**) first week of May, (**d**) second week of May, (**e**) third week of May, (**f**) second week of June

By drawing up maps relying upon interpolation (Fig. 4), we were able to estimate pollen values in areas where there are no aerobiological stations but which can be included within a certain domain simply by taking into account only aerobiological data. In this, geostatistics helped us to solve a common problem in all studies reported to date: the provision of missing values estimated from those observed elsewhere. Even if this method does not produce exact values, they can generate satisfactory ones, i.e. values that would give rise to the same interpretation. Indeed, the important thing here is not the generated data *per se* but the estimation ranges and their spatial interpretations.

The preparation of pollen cloud maps follows a thin line between increasing their geographical amplitude without, on the other hand, significantly decreasing the precision of estimated pollen-concentration values in specific sites. However, in the specific case of pollen counts, the main reason behind aerobiological networks – their interpretation – is performed nominally, i.e. in the format of allergy-risk categories (Comtois & Clot, 2004). Therefore, there is a kind of analogy between the numerical intervals given by our graphic representations and the need for giving categorical allergy-risk forecasts.

These aeropalynological maps at the regional scale, together with the use of altimetry and distribution of olive orchards maps (Fig. 5) also enabled us to visualize and compare the influence of altitude and olive-tree distribution on flowering phenology. The results indicate that bioclimatic diversity of the Andalusia region promotes a step-wise flowering of the olive tree in such a way that the areas and periods of highest risk vary from April to June.

Figure 4a shows that the first *Olea* pollen grains are detected in the coastal zones (Motril and Almería), whereas Jaén and Granada (inner zones) present lower concentrations at this time because their continental climate promotes later flowering. This phenomenon also suggests that early flowering in coastal zones might serve as indicator of the onset of the pollination season in the southern Iberian Peninsula. Two weeks afterwards, the higher temperatures in the thermomediterranean level of the Guadalquivir Basin (Jaén) triggers the flowering of olive tree, with increasing values in the interior zones (Fig. 4b) (Diaz de la Guardia et al., 2003; Galán, Vázquez, García-Mozo, & E. Domínguez, 2004).

In early May (Fig. 4c), the highest concentrations are reached in the province of Jaén, the result of both intense flowering and the high abundance of this crop in this province. This phenomenon indicates the distribution and abundance of vegetation types as a fundamental factor in the determination of airborne-pollen indices. Jaén acts as a source of emission of airborne pollen (Fig. 4d), which are then dispersed according to the atmospheric fluxes characteristic of this region.

The altitudinal distribution of the olive crops in Granada allow moderate levels of olive pollen in this province to continue until late May and June (Fig. 4e, f), during which time concentrations decrease in the other areas. The city of Granada, due to its

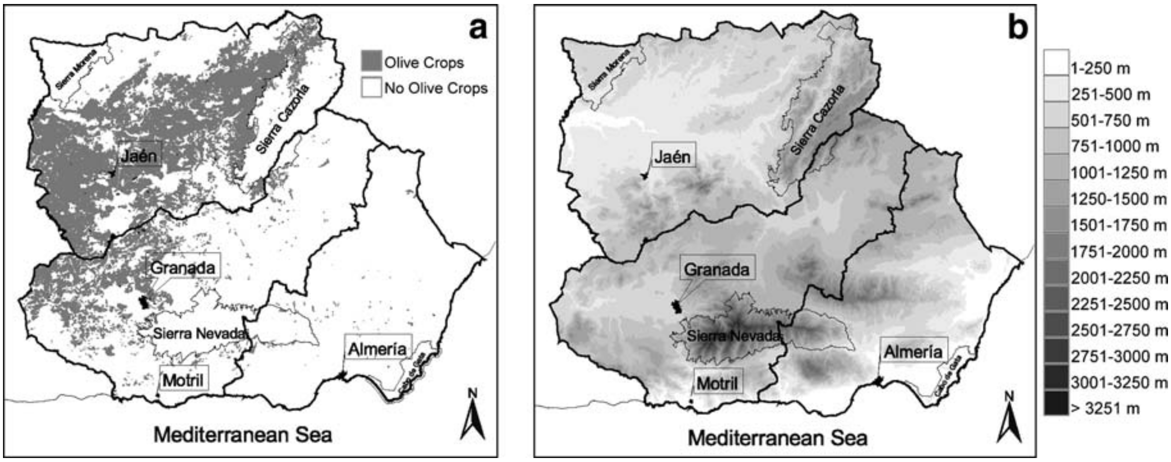

Fig. 5 *Olea* orchards distribution (**a**) and altitudinal map (**b**) of the study area

surrounding topographical characteristics, could be used to establish the end of the olive pollination season in Andalusia (Díaz de la Guardia et al., 2003).

The efficiency of this estimation method has already been corroborated for olive-pollen distribution (Alba et al., 2003). To validate the proposed model, we considered two phases. In the first, as a result of the contrast in the weekly series estimated and observed, we used the Wilcoxon test to validate the model (Table 4, row a). In the second, a more exhaustive model made by comparing the mean daily values of *Olea* during MPS (n=64) (Table 4, row b; Fig. 6) revealed that during May, the degree of reliability was low when the concentrations observed in Jaén were extremely high, thereby changing the reliable estimation of the concentration in Granada. The result of comparing the averages for the observed and predicted mean seasonal concentration by the Wilcoxon test indicated significant differences, consequently not verifying the interpolation model. However, no significant differences were found when the dates on which Jaén reached very extreme values

Table 4 Comparisons of averages by the Wilcoxon test between *Olea* pollen (observed) in Granada and data derived from kriging interpolations (expected) without the inclusion of data from the Granada sampling station at different time frames: row a, Weekly average; row b, daily *Olea* pollen counts during MPS; row c, daily *Olea* pollen counts during MPS except for those dates on which Jaén reached very extreme values

	Wilcoxon test						
	n	Mean rank		Sum of ranks		Z	Significance level two-tailed p
		Negative rank	Positive rank	Negative rank	Positive rank		
a	12	6.17	6.83	37.00	41.00	−0.157	0.875
b	64	33.63	29.38	1580.50	499.50	−3.615	0.000
c	48	21.79	30.47	719.00	457.00	−1.344	0.179

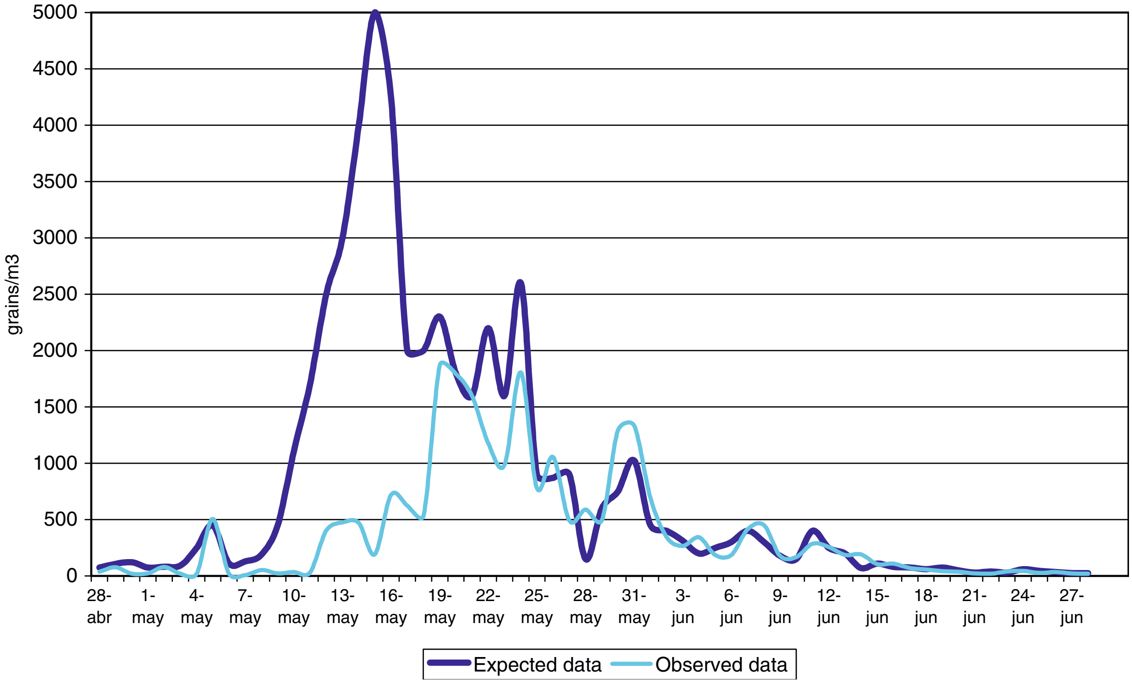

Fig. 6 Graphic representation of the *Olea* pollen concentrations (observed) in Granada during MPS of the period 2003 against the expected values obtained from kriging interpolations without this sampling station

(from the observed series) were eliminated (*n*=48) (Table 4, row c).

This fact corroborates that the predictions provided by the interpolation method are acceptably reliable when the data provided by all the stations falls within a fairly narrow range and when there are no great discrepancies in the abundance and phenology of the species. A greater number of sampling points would help to improve the spatial correlation analysis and, consequently, improve the model. Also, we could go more deeply into the anisotropic study, discounted in this study due to the lack of a larger number of sampling stations.

In the case of *Olea*, the distribution and altitude of the plant community (through its effect on phenology) were the most determinant external factors. The inclusion of these two variables in the geostatistical models would help improve the effectiveness of the estimation model. This could open a new era of collaboration between aerobiologists and other scientists, which could lead to the uncovering of new aerobiological processes.

Conclusions

The introduction of the parameter ''space'' into the model allows us to predict pollen levels in different areas on a regional scale.

The interpolation method permits an estimation of pollen values in areas lacking aerobiological sampling stations; although the degree of possible error will lessen the closer the site is to such a station.

The predictions provided by the interpolation method are acceptably reliable when the data provided by all the stations falls within a fairly narrow range and when there are no great discrepancies in the phenology of the species.

The pollen maps drawn bear reliable information concerning the onset of pollination according to geographic distribution, the estimation of critical periods of maximum pollen release, areas of influence of pollen clouds and determination of the end of the pollen season in altitudinal clisere.

Estimation by interpolation enabled simulations of pollen dispersion in future periods, with an acceptable error.

Geostatistics can help organize pollen-information networks via the strategic sitting of sampling stations.

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