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The reliability of geostatistic interpolation in olive field floral phenology

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Abstract Floral phenology, as most of natural phenomena, shows, as an inherent feature, a high degree of spatial continuity. Geostatistics are a family of statistics that describe correlations through space/time and they can be used for both quantifying spatial correlation and interpolating no monitored sampling points. The combined use of Geographical Information Systems (GIS) and geostatistics can be an essential tool for spatial analysis in phenological and aerobiological studies. In the present work, Kriging interpolation by using linear geostatistic analysis has allow us to estimate phenological data of a wide olive crop area of the province of Cordoba (Andalusia, Southern Spain), on the basis of a limited number of phenology sampling points. The main a priori hypothesis was that 7 traditionally observed sampling points (with 10 olive trees in each site) uniformly distributed through the main olive crop areas could be enough for interpolating phenological information of the whole Cordoba olive area. Geostatistical results reject this hypothesis. The optimum/minimum number and location of sampling points was determined in 13 sites (including the original 7 sites and 6 new sites). The obtained phenological maps will improve olive pollen aerobiological information and forecasting in the area. The application of such new combined space analysis tools on floral phenology allows optimising human and economic resources on field phenology campaigns. Moreover, an appropriate use of GIS and geostatistic software to create phenological maps will be an essential complement in pollen aerobiological studies, given the increased interest in obtaining automatic aerobiological forecasting maps.

Keywords Geostatistics · Olive · *Olea europaea* · Floral phenology · GIS

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Introduction

Floral phenology is considered as one of the most important tools in aerobiological studies (Fornaciari, Galán, Mediavilla, Domínguez, & Romano, 2000). Weather conditions control the beginning, duration, intensity and end of the season, but the effect depends on the types of vegetation and its location. Consequently, a system of forecasts, based on a methodological point of view must include weather and aerobiological parameters, but also floral phenology and vegetation/land cover data. Phenology can helps us to explain certain secondary peaks out of the main season, which correspond to second flowerings; it is also very useful when there are several species sharing the same pollen type whereas a correspondence can be established between each peak of the curve and the flowering time of different species (Hidalgo, Galán, & Domínguez, 2003). In the case of pollen curves with different peaks attributable to differences in altitude, latitude or sun orientation of the species, phenological data can help us to determine from which vegetation areas pollen are coming from (Galán, Vazquez, García-Mozo, & Domínguez, 2004; Fornaciari et al., 2000). Geographic Information Systems (GIS) are computer-based methodologies conceived for spatial data collection, storage, retrieval, transformation, display and analysis (Kitanidis, 1996). Georeferenced data, such as floral phenology of a population or aerobiological data can be incorporated in a GIS to produce map layers. While the advent of GIS allows for compiling and manipulating spatially referenced data, modelling spatial patterns from areas where no data are available is difficult without an adequate set of statistical tools (Liebhold, Rossi, & Kemp, 1993). Geostatistics is a family of statistical methods that describe correlations through space/time and that can be used for quantifying the spatial correlation and interpolating sample points via Kriging or other related procedures. This methodology has been widely used in mineral geology to improved predictions of the location of mineral and petroleum. In recent years GIS and geostatistics are being applied to environmental studies (Robertson, 1987). The combined use of GIS and geostatistics has been demonstrated as a very instrumental method for spatial analysis (Burrough, 2001).

In the present work we study if GIS and geostatistic interpolation by using Kriging analysis allow us to estimate phenological data of a wide olive crop area on the basis of a limited number of samples. The study was carried out in the province of Córdoba, Andalucia region, South Spain. Spain is the country holding the largest surface devoted to olive crop (45% of the world surface, 2.5 millions of ha) (Beaufoy, 2000). Sixty-five percent of these areas are located in the Andalucia region. The province of Cordoba is the second by importance as regards to olive crop, being the 23% of the Andalusia olive surface (INE, 2002). The main olive crop areas are located in the south-eastern part of the province.

In Cordoba, olive trees are cultivated in different conditions due to the diversity of landscapes and geomorphological characteristics of the province, with flatted river valleys, terraces (in the Campiña area) and high mountains chains. Previous studies on phenology and aerobiology of *Olea* pollen in the province showed us that the different peaks of the *Olea* curve correspond to different olive populations located along a steeping altitude transept (Fornaciari et al., 2000). The average *Olea* pollen curve from the city of Cordoba shows three main peaks clearly reflecting the phenology of the different areas located at different altitude (Galán et al., 2004; Vázquez, Galán, & Domínguez, 2003).

Given the importance but also the financial and time cost of taking phenology field data from distant sites, the number and location of sampling points must be optimised. In the present work the main a priori hypothesis to be verified was whether 7 sampling points (with 10 olive trees in each site), uniformly distributed at different altitudes through the main olive crop areas of the Cordoba province, were enough to obtain valuable fenological data suitable for an aerobiological characterisation of the whole area. These 7 sites had been regularly monitored from 1992, 3 of them, and from 1999 the other 4 sites. They have offered helpful information on *Olea* aerobiological interpretation researches (Fornaciari et al., 2000; Galan et al., 2004). Nevertheless the use of GIS and geostatistic analysis in the present research could provide higher objectivity in determining the optimum/minimum number and location of sampling points.

In brief, the objectives of the present work are: (1) to integrate olive field phenology data for a better understanding of olive aerobiology pattern in the province of Cordoba; (2) to create geostatistic olive phenology maps for improving olive pollen forecasting; (3) to estimate the optimum number and location of phenology monitored sites required to obtain valid geostatistic interpolation data and maps in order to optimise human and economic resources.

Materials and methods

Phenological data were collected along an altitudinal gradient from Cordoba city (123 m a.s.l.) up to Priego de Córdoba situated in the Subbetica Mountains (775 m a.s.l.). All sites are distributed trough extended olive crop area, around a transect from the city of Córdoba (37°55′N, 4°45′W) up to the Subbetica mountains (37°26′N, 4°11′W) in the south–west of the province, (Fig. 1; Table 1).

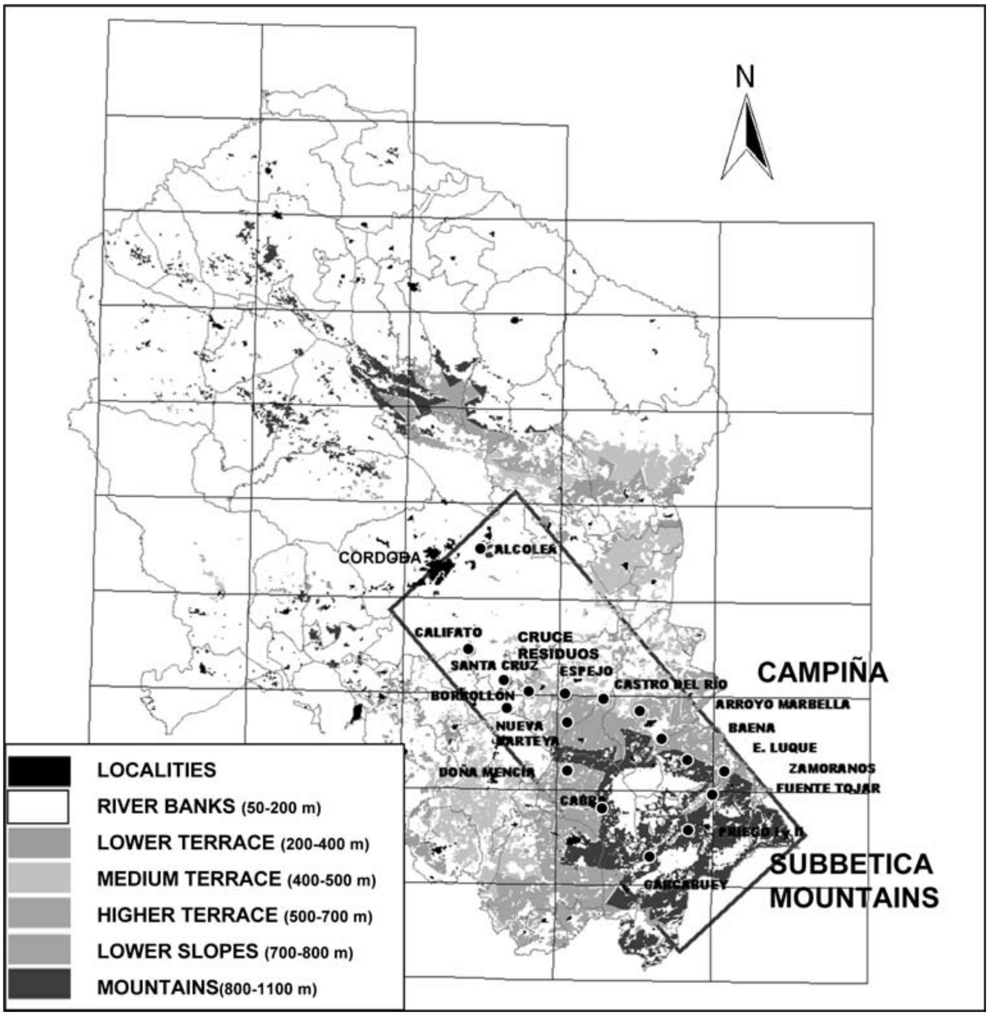

Fig. 1 Olive crop distribution in the province of Cordoba. Different shades of grey indicate differences in altitude. The 19 analysed phenological sampling points are indicated in the studied grid area

The climate of the study area is Mediterranean with some degree of continentality. In Cordoba city, situated in the Guadalquivir River banks, the average annual rainfall is 536 mm and the annual average temperature is 17.5°C (mean from 1971 to 2000) (Ministerio de Medio Ambiente, 2001); at the other extreme, in Priego, located on the top of the Subbetica Mountains, the average annual rainfall is 773.5 mm and the annual average temperature 14.4°C (SINAMBA, 1999).

Meteorological data used in the present study were obtained from 12 meteorological stations located in the area, 11 belonging to the Andalucian Agriculture and Fisheries Government Meteorological Network (http://www.juntadeandalucia.es/agriculturaypesca), and one being the meteorological station of the University of Córdoba located in the Campus of Rabanales (Table 1). For each phenological site, data from the nearest meteorological station was obtained. Vertical negative Thermal Adiabatic Index (−0.5°C/100 m) was also applied.

Phenological observations were recorded for trees of the same age range (30–40-years old), and the phenological methodology was that proposed by Maillard (1975). Numerical values were given to the different phenological phases; 1 = dormancy, 2 = budburst, 3 = floral bud formation, 4 = floral bud growing, 5 = corolla differentiation, 6 = flowering

Table 1 Altitude (m) and location (UTM coordinates) of the phenological sampling sites and of the meteorological stations

Phenological sampling sites	Altitude (m a.s.l.)	UTM X	UTM Y	Meteorological stations	Altitude (m a.s.l.)	UTM X	UTM Y
Alcolea	135	353257	4198830	Cordoba	117	391543	4214915
Califato	135	353085	4180835	Rabanales	140	349382	4198095
Santa Cruz[1]	165	358401	4174113	Guadalcazar	150	343287	4174792
Santa Cruz [2]	190	358514	4174223	Carpio	165	367901	4197541
Espejo	350	363687	4171884	Hornachuelos	157	309705	4206727
Castro	250	366449	4171837	Santaella	207	333494	4154701
Cruce Residuos	245	376312	4170062	La Rambla	280	254813	4659004
Arroyo Marbella	265	379046	4167091	Baena	430	384896	4162091
Baena	430	384896	4162091	Lucena	435	314953	4132828
Estanción Luque	495	389242	4159135	Nueva Carteya	520	373142	4159524
Zamoranos	385	395200	4156986	Carcabuey	585	386151	4147557
Fuente Tojar	535	397617	4153509	Cabra Met.	500	373445	4147557
Priego[1]	660	397675	4144875				
Priego[2]	775	398250	4146023				
Carcabuey	585	386151	4147557				
Cabra	500	373445	4147557				
Dña. Mencía	520	371993	4153427				
Nueva Carteya	520	373142	4159524				
Borbollón	380	367115	4166318				

start, 7 = full flowering, 8 = petal fall, 9 = young fruits, 10 = fruit growing, 11 = seed lignifications. A total of 190 olive trees (*Olea europaea* L.) grouped by 10 trees in 19 sampling sites were observed during all the pre-flowering and flowering period of 2003 (March–July). A 10-tree average phenological value was settled for each sampling point at each date.

The information about the olive crop distribution was obtained by means of a Geographic Information Systems (GIS) (SINAMBA, 1999). The software Arc View 5.0 was used to obtain olive crop distribution maps. The demarcated studied area was interpolated to a rectangular grid of 1675 km^2 (67 × 25). The software Geostatistic for Environmental Sciences© (GS+) was used for the geostatistic analysis. Spatial models were constructed by using three co-ordinates, x, y and z, were x and y are the UTM coordinates and z represents altitude. Variables used for the geostatistic analysis were: (1) floral phenological data taken following the phenophases proposed by Maillard (1975), an average numeric value from the 10 observed trees per site was used; (2) cumulated chilling hours below 7.2°C calculated following the Aron method (Aron, 1983; Orlandi et al., 2004); (3) cumulated Growing Degree Days after chilling period, above a temperature threshold of 12.5°C (Galán, García-Mozo, Cariñanos, Alcázar, & Domínguez-Vilches, 2001); (4) cumulated sunshine hours from the previous week; (5) cumulated rainfall from the previous week.

Results

Sampling sites distribution

The distribution of the 19 sampling sites is shown in Fig. 1 where their homogeneous distribution throughout the area is documented. Three of the sites (Santa Cruz, Castro and Baena) are surveyed since 1992, and four more sampling points were included in the phenological campaigns from 1999 (Alcolea, Nueva Carteya, Zamoranos and Priego). The rest were included in 2003 specifically for this study. Sampling site locations were chosen having in mind (a) a homogeneous distribution through the grid, (b) the proximity with the meteorological stations, and (c) differences in altitude and sun orientation. The coordinates and altitude of all of them are reported in Table 1. Data from new sites nearby where taken due to their differences in altitude and sun orientation. These cases are indicated with numerical subscript where [1] indicates lower altitude in the less exposed base of a hill (i.e. Santa Cruz[1]; Santa Cruz[2]).

Phenological results

Figure 2 shows the floral phenological results during the spring. Different places registered a characteristic phenology progression pattern, showing ‘‘parallel’’ curves delayed in time. Lower altitude sites as Alcolea and Santa Cruz show an early phenological development. On the contrary, higher places such as Priego and Baena show very delayed phenological phases.

Geostatistical analysis

The steps followed for the geostatistic analysis were as follows:

Descriptive statistical analysis

1. Correlation among phenological phases at each date and altitude, Chilling Units, Growing Degree Days (GDD), cumulated sunshine hours and cumulated rainfall were analysed by means of the Spearman test. The Spearman’s test results indicated that altitude and cumulated GDD after chilling were the most correlated variables with the phenological values found in the field. Significant results are shown in Table 2. These two variables together with geo-referenced phenological data were included in the geostatistic analysis.
2. Frequency distribution analysis performed by mean of cumulative frequency graphs for the different dates indicated the percentage of redundant results (Fig. 3a).
3. A quartile plot scattergram provides a map of sample location values grouped defined classes (Fig. 3b).

Structural analysis

The variance characteristics and the spatial correlation between variables were estimated. Several

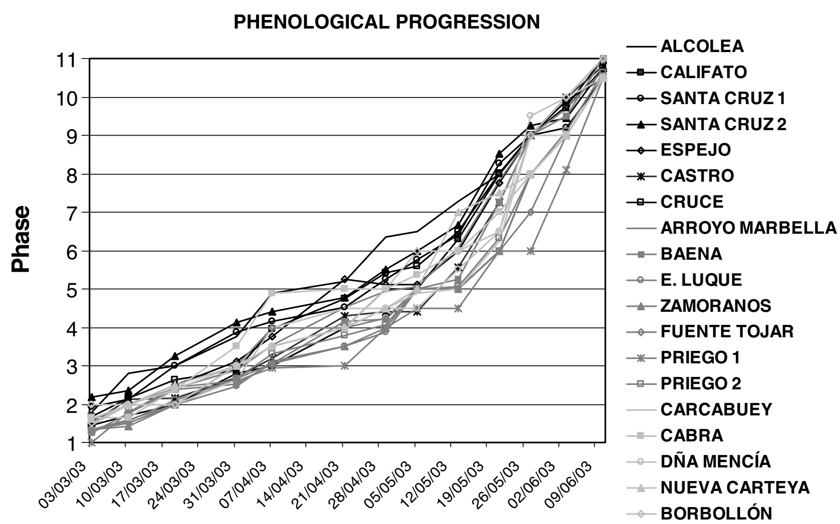

Fig. 2 Phenological data evolution from the 19 sampling points during the year 2003

Table 2 Spearman’s test results

Date	Phenological values and altitude (m a.s.l.)	Phenological values and GDD°)	Phenological values and Sunshine hours
March 03	−0.46*	0.82**	0.58**
March 10	−0.55**	0.34**	−0.02
March 19	−0.55**	0.54**	0.18
March 31	−0.54**	0.34**	0.23
April 07	−0.46**	0.33**	−0.38
April 21	−0.67**	0.50**	0.24
April 29	−0.70**	0.63**	−0.23

Correlation coefficients between phenological values and altitude, Growing Degree Days (GDD) and sunshine hours (*95%; **99%)

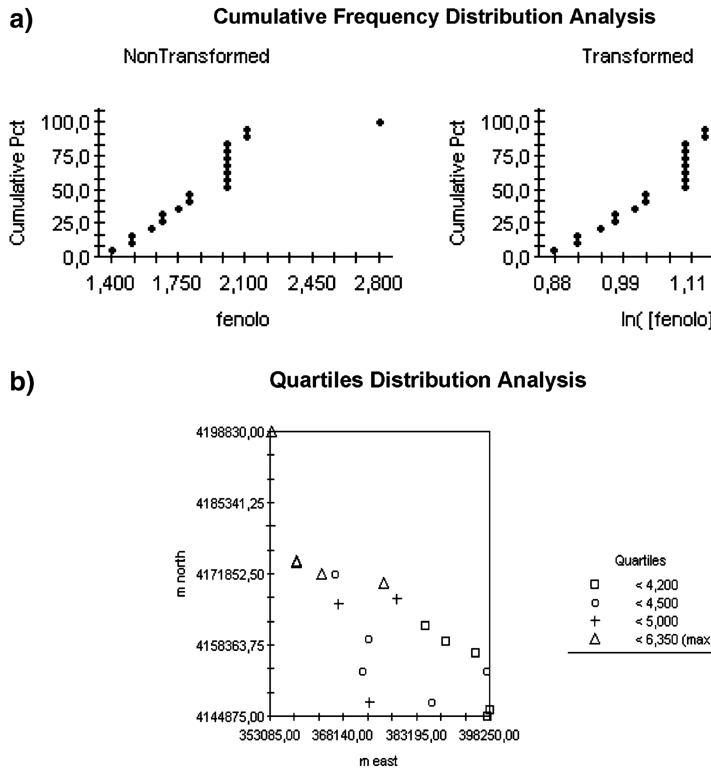

Fig. 3 Redundant phenological data analysis. Results from April 29 are showed. (**a**) Frequency distribution analysis of non transformed and transformed data. *Cumulative Pct*: cumulative percentage; *fenolo*: phenological data. (**b**) Quartile plot scattegram. Phenology values are grouped by categories indicated by symbols

variograms in different spatial directions were calculated. The variogram that most reflected the theoretical model was chosen. In all the analysed dates, the spatial variance of data follow an Exponential Isotropic Model, with $R^2 = 0.87 \pm 0.04$. Isotropic variograms indicate that there are no differences due to spatial directions (i.e. N–S; W–E) (Fig. 4). Following these theoretical models, data for the whole area were analysed by mean of Simple Kriging (Schaug, Iversen, Pedersem, 1994):

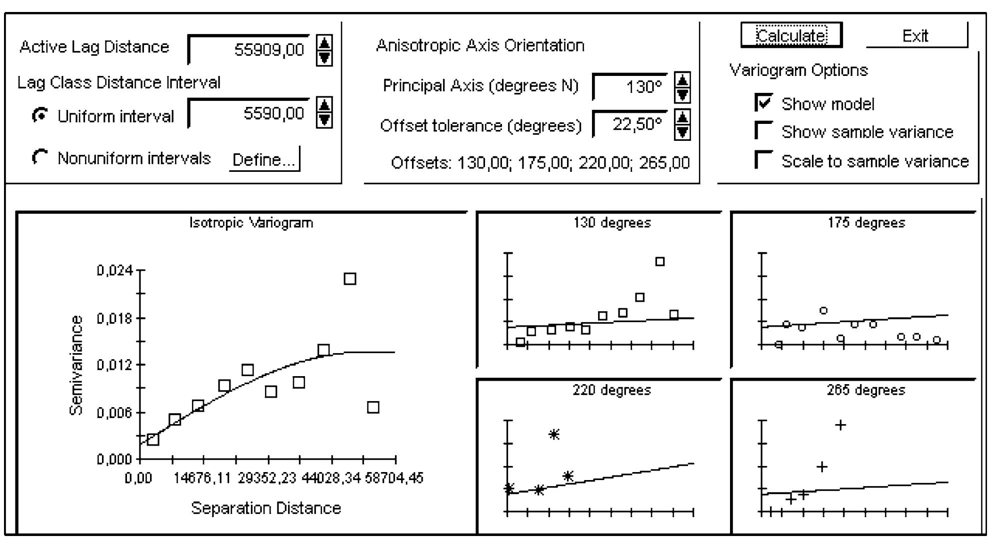

Fig. 4 Variogram semivariance analysis. Lag distance indicates the average separation distance for pairs of points (m). Values for five isotropic models along several space directions were calculated. The Isotropic variogram most fitted to a linear model is enlarged

$$Z^*(v) = \Sigma\lambda_i Z(x_i) + m(1 - \Sigma\lambda_i)$$

$Z(x_i)$, $i = 1,\ldots, n$ are the sampling value, $Z^*(v)$ the estimated value, λ_i = linear estimation constant which reduces the variance up to zero, $m = x_{(i+1)/2}$ if i is an odd number, and $m = x_{(i/2)} + x_{(i/3)}$ if i is an even number.

Interpolation

From the 19 study sites we obtained phenological data equivalent to 500 sites located into the grid (Table 3). Interpolation data were used to obtain phenological maps of the area during spring. As the

Table 3 Kriging interpolation results indicating phenological values for no surveyed sites in the area (*Z*-estimate)

X-Coordinate	*Y*-Coordinate	*Z*-Estimate	EstStdDev	*n*
353085.00	4144875.00	2.03	6.724E-01	16
353085.00	4145692.50	2.03	6.643E-01	16
353085.00	4146510.00	2.02	6.561E-01	16
353085.00	4147327.50	2.02	6.478E-01	16
353085.00	4148145.00	2.01	6.393E-01	16
353085.00	4148962.50	2.01	6.362E-01	16
353085.00	4149780.00	2.01	6.274E-01	16
353085.00	4150597.50	2.00	6.184E-01	16
353085.00	4151415.00	1.99	6.092E-01	16
353085.00	4152232.50	1.98	6.000E-01	16
353085.00	4153050.00	1.97	5.907E-01	16
353085.00	4153867.50	1.96	5.812E-01	16
353085.00	4154685.00	1.96	5.660E-01	16
353085.00	4155502.50	1.95	5.578E-01	16
353085.00	4156320.00	1.94	5.495E-01	16
353085.00	4157137.50	1.93	5.409E-01	16
353085.00	4157955.00	1.92	5.321E-01	16
353085.00	4158772.50	1.91	5.231E-01	16
353085.00	4159590.00	1.90	5.138E-01	16
353085.00	4160407.50	1.89	5.043E-01	16
353085.00	4161225.00	1.88	4.946E-01	16
353085.00	4162042.50	1.87	4.846E-01	16
353085.00	4162860.00	1.86	4.743E-01	16
353085.00	4163677.50	1.85	4.638E-01	16
353085.00	4164495.00	1.84	4.529E-01	16
353085.00	4165312.50	1.83	4.418E-01	16
353085.00	4166130.00	1.82	4.303E-01	16
353085.00	4166947.50	1.81	4.186E-01	16

EstStdDev: Standard Deviation

GS+ Output: Block Kriging Interpolation File v3.0

Set:

Dimensions: 2; Interval source: Calculated

Interpolation interval (*x*; *y*): 836.3889; 817.5

X-coor: m east

range: 353085.00–398250.00

Y-coor: in north

range: 4144875.00–4198830.00

Z-est:

range: 1.19–2.03

Z-sd: (SD)

range: 0.000E+00–8.024E-01

Mean *Z*-estimate (sd): 1.62 (3.318E-02)

Valid *N*: 3685; Missing *N*: 0; Missing Value Indicator: −99 flowering season advances, the differences among sites are higher. In the first dates of March the phenological results were more homogeneous through the whole grid. The biggest differences were found from March 31 (Fig. 5). Datasets from this date until April 29 were analysed to determine the minimum number of sampling points required to obtain reliable maps of the area. The results of the cumulative frequency, variance analysis and quartiles distribution analyses were taken into account to determine the sites where redundant data were obtained.

Statistical optimum data set determination

Gradually reduced datasets, taking away possible redundant data sites, were studied by analysing the most important variogram parameters: intercept of the model (C_0), model asymptote ($C_0 + C$) and range of A (A_0) which is the grid separation distance over which a spatial dependence is apparent. The main variogram statistics were also analysed, i.e. the Residual Sum of Squares (RSS) and the R^2 coefficient, Table 4. Both of them provide an indication of how well the model fits the variogram data. The lower the RSS, the better the model fits, and the higher the R^2 coefficient, the better the model fits.

Table 4 shows that in all the analysed dates the R^2 coefficients of the variogram analysis increased and RSS decreased after taking away the first two sites, Castro and Doña Mencía. Although the best results were obtained with that 17-site data set (mean $R^2 = 0.872 \pm 0.037$), the optimum minimum data set was determined for 13 sites. R^2 coefficient of the 13-site variogram was 0.842 ± 0.025, very close to the of 17-site R^2 coefficient, but the RSS value was lower (Table 4). Taking away a higher number of sites results were statistically poor.

Kriging interpolation and mapping were calculated for the new 13 site dataset. No significant differences in phenological values for the eliminated sites were obtained. Similar maps were therefore produced based in the new reduced datasets, as it can be observed in Fig. 6 where results for April 29 are showed as an example. In Fig. 7 it is possible to observe the spatial distribution of the new reduced site dataset.

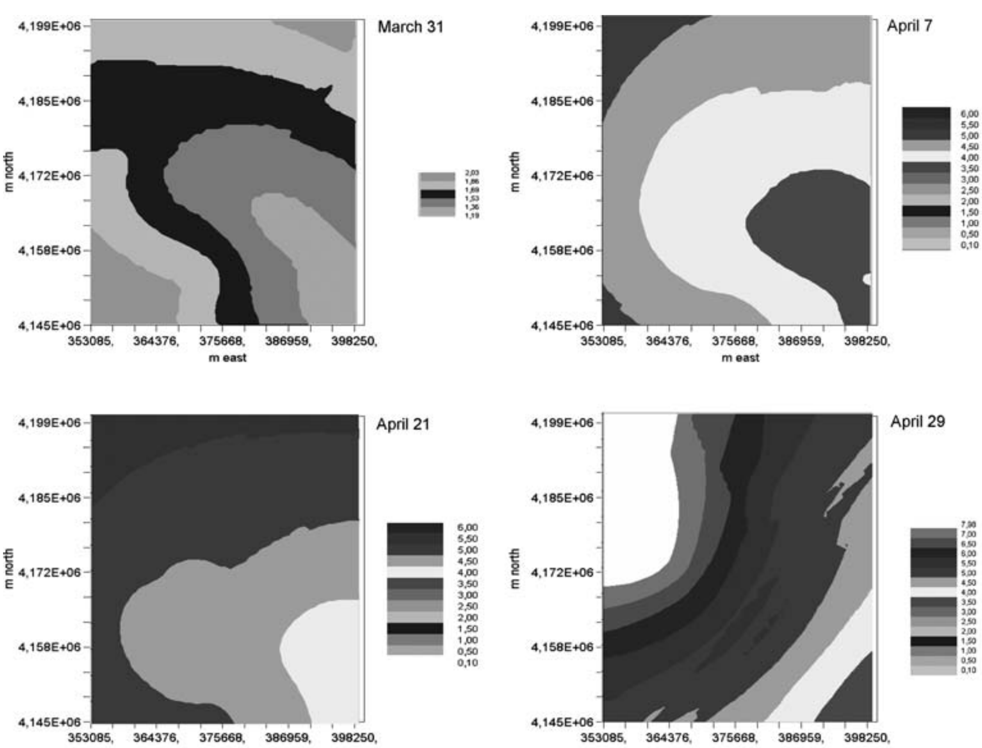

Fig. 5 Phenological maps for the studied grid area on different dates

Table 4 Residual Sum of Squares (RSS) and R^2 coefficients of the variograms calculated for the different datasets

Date	19-site data set		17-site data set		13-site data set	
	RSS	R^2	RSS	R^2	RSS	R^2
March 31	2.147	0.855	1.882	0.879	1.634	0.834
April 7	1.945	0.921	1.742	0.934	1.342	0.878
April 21	2.102	0.834	1.733	0.874	1.241	0.823
April 29	2.030	0.878	1.679	0.924	1.532	0.833
Mean value	2.056	0.872	1.759	0.903	1.437	0.842
SD	0.088	0.037	0.087	0.031	0.178	0.025

The mean values of the coefficients and also the Standard Deviation (SD) is also showed

Discussion

Most of natural phenomena show, as an inherent feature, a high degree of spatial continuity (Moral-García, 2003). This is the reason because in last years GIS and geostatistics are being applied to environmental studies such as entomology (Liebhold et al., 1993), plant distribution (Legendre & Fortin, 1989) and general ecology (Robertson, 1987) with excellent results. Traditionally, aerobiological and floral

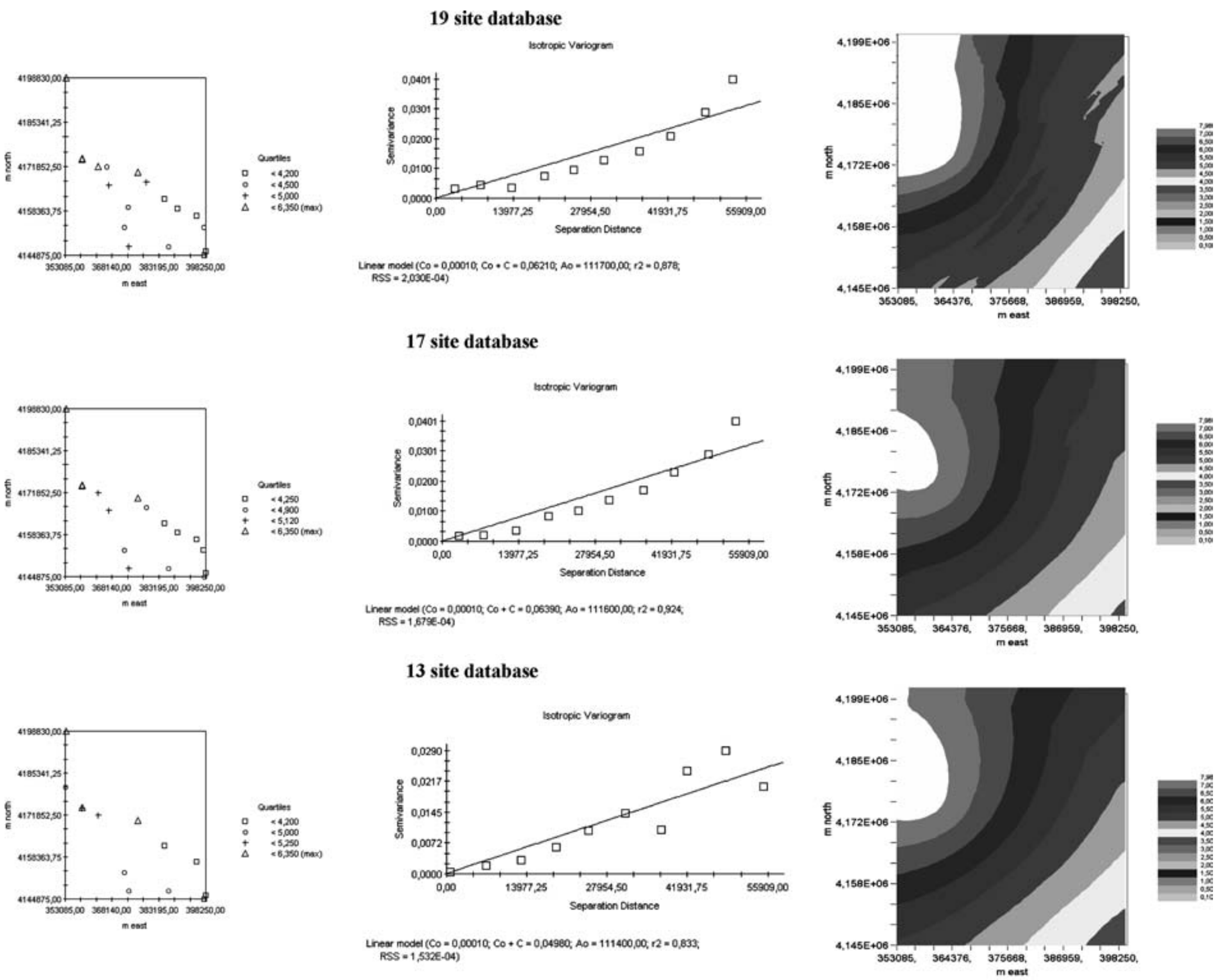

Fig. 6 Original versus reduced datasets geostatistic analysis. Quartiles analysis, semivariance analysis and phenological maps are shown

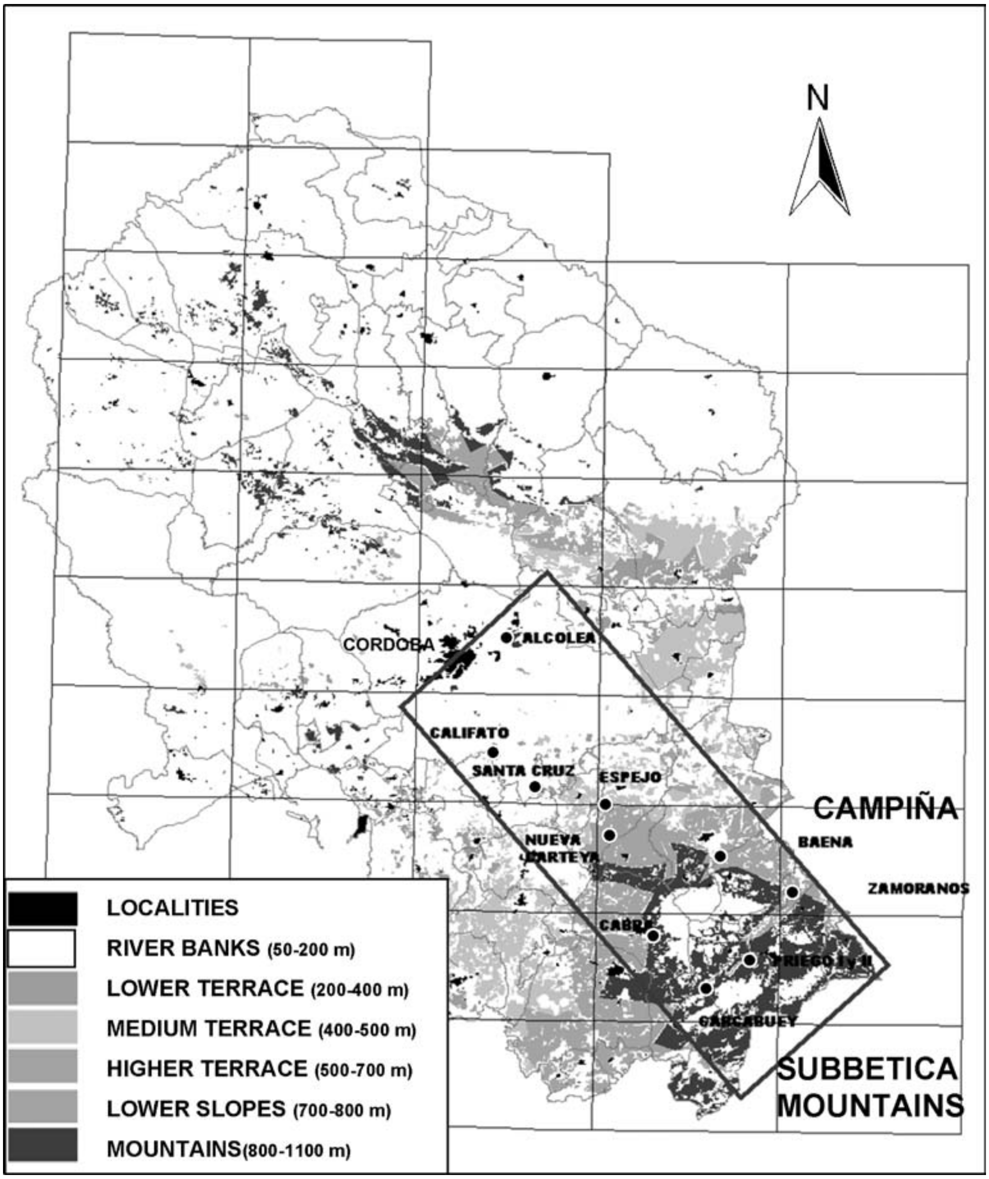

Fig. 7 Location of the selected 13 sampling points in the province of Cordoba. Different grey shades indicate differences in altitude

phenological studies have been concentrated on changes through time, but patterns across spatial dimensions remain largely unexplored. Only few works have developed models in terms of both space and time (Hidalgo et al., 2002; Kawashima & Takahashi, 1995; Puppi & Zanotti, 1992). There are many instances in ecological research where it is necessary to interpolate among spatially stratified samples. The existence of strong spatial dependence in olive floral phenology associated to meteorological and geographical characteristics of different locations indicates that there is a value in estimating phenological data from values at nearby locations. The combined study of weather parameters and aerobiological data could not to be enough for large areas aerobiological predictions and reports.

The knowledge of anemophilous floral phenological data are of great value for aerobiological studies (Fornaciari et al., 2000; Galán et al., 2004; Orlandi et al., 2004). Currently there is an emphasis on studies related to meteorology influence on pollen atmospheric presence, but often they can only offer results for the surrounding nearest area of the pollen trap. Nevertheless, depending on topography, meteorology and pollen taxa characteristics, pollen grains from distant areas is often detected. The benefit of using phenological maps constructed by interpolation could help us in better understanding the dynamics of several peaks or interrupted pollen curves. Moreover, an optimisation of number and location of sampling points is required, given the economic and timing cost of taking field data from faraway sites

In the present paper GIS and geostatistic analysis have proven as valuable instrumental for an objective analysis to determine the optimum number and location of phenological sampling sites to obtain reliable phenology maps. Although any phenological survey is an interesting source of information for aerobiological interpretation analysis, our priori hypothesis that seven sampling points uniformly distributed through the province of Cordoba could be enough to obtain valuable phenological information, was rejected due to the obtained poor results. The geostatistical analysis of the 19 and 17-site data sets indicated a high degree of reliability. Nevertheless, 13 sites were revealed as the optimum number for the data set taking into account the statistical results avoiding redundant information. The obtained phenological maps will improve olive pollen aerobiological information and forecasting in the area. The application of such new combined space analysis tools on floral phenology allows optimising human and economic resources on field phenology campaigns. Moreover, an appropriate use of GIS and geostatistic software to create phenological maps will be an essential complement in pollen aerobiological studies. Given the increased interest in obtaining automatic aerobiological current and forecasting information maps, future applications of these tools may extend to the spatial analysis of aerobiological data, especially on the location of main pollen emission areas and airborne spatial dispersion.

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