



ELSEVIER

Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

SCIENCE @ DIRECT®

Europ. J. Agronomy 21 (2004) 209–222

European  
Journal of  
Agronomy

[www.elsevier.com/locate/eja](http://www.elsevier.com/locate/eja)

## Leaf nutrient spatial variability and site-specific fertilization maps within olive (*Olea europaea* L.) orchards

F. López-Granados<sup>a,\*</sup>, M. Jurado-Expósito<sup>a</sup>, S. Álamo<sup>b</sup>, L. García-Torres<sup>a</sup>

<sup>a</sup> Instituto de Agricultura Sostenible, CSIC, Apartado 4084, 14080-Córdoba, Spain

<sup>b</sup> Dpto. Economía Agraria, Universidad de Córdoba, Apartado 3048, 14080-Córdoba, Spain

Received 10 December 2002; received in revised form 12 August 2003; accepted 12 August 2003

### Abstract

Spatial variability of leaf nutrients (N, P, K, B and Fe) in a 30 ha olive orchard located in southern Spain was examined in two consecutive years for determining their spatial distribution for the implementation of a site-specific fertilization programme. A regular 75 m × 75 m sampling grid was established and intersection points (nodes) were georeferenced. Every sampling node was composed of an experimental unit of four nearest olive trees. Leaf samples were collected within every experimental unit. The leaf nutrients were analysed statistically and geostatistically. Based on the semivariograms, kriged estimates were used to draw contour maps for each leaf nutrient and to study the possibility of saving fertilizer recommendations. Positive correlations existed during both years between N and P ( $r = 0.8$ ,  $P \leq 0.01$ ), N and B ( $r = 0.48$ ,  $P \leq 0.01$ ), and P and B ( $r = 0.37$  and  $0.51$  for 1999 and 2000, respectively,  $P \leq 0.01$ ). Correlation between K with B was strong in 1999 ( $r = 0.54$ ,  $P \leq 0.01$ ), and not so strong in 2000 ( $r = 0.22$ ,  $P \leq 0.05$ ). Fe did not show any significant correlation during both years, except with K ( $-0.29$ ,  $P \leq 0.05$ ).

Geostatistical analysis of leaf nutrients revealed that N had both strong and moderate patchy distribution depending on the year, whereas P, K and B had strong patchy distributions both years. Fe showed a lack of spatial dependence both years. Contour maps of each leaf nutrient achieved by kriging were used to estimate the percentage of farm surface needing fertilization where concentration of the respective nutrients did not exceed the fertilization threshold. The study revealed the necessity of determining spatial variability in nutrient status of olive trees before planning a differential fertilizer programme. A consistent saving in N, K and B fertilizers could be achieved in the studied olive orchard both years, for example only 3 and 17% of the surface should be fertilized with N in 1999 and 2000, respectively.

© 2003 Elsevier B.V. All rights reserved.

**Keywords:** Geostatistics; Ordinary point kriging; Saving inputs; Precision farming

## 1. Introduction

### 1.1. Olive orchards in Spain

Olive (*Olea europaea* L.) is one of the main crop in the Mediterranean basin with a cultivated area of about 8.2 M ha, of which 2.3 M is in Spain (Civantos,

\* Corresponding author. Tel.: +34-957-499219; fax: +34-957-499252.

E-mail address: [cs9logrf@uco.es](mailto:cs9logrf@uco.es) (F. López-Granados).

1999). Traditionally, fertilizers or other crop inputs have been applied to olive orchards without considering spatial variability of field characteristics. Such agricultural management may be inefficient due to under-application and over-application of field inputs in specific orchard areas. Under-treated zones do not reach optimum levels of yield whereas in over-treated ones there may be high risk of pollution of the environment and an increase of costs (Bouma, 1997).

In the past decades, yield of most Spanish olive orchards was limited by water supply and soil management was mainly based on plough-, disk- and harrow-tillage operations. At present, farmers are making considerable investments to obtain modern olive orchards which are usually drip-irrigated (Civantos, 1999), kept under no-tillage techniques to overcome soil erosion problems (García-Torres, 1999, 2000), mechanized harvesting (Porrás, 1999), fertirrigated (Troncoso et al., 1999) and planted with quick-growing young olive plantings (Navarro and Parra, 1999). However, farmers still manage fields as if fields were homogeneous regarding fertilization.

### 1.2. Leaf nutrients and traditional fertilization in olive orchards

Nitrogen (N), phosphorus (P), potassium (K) and boron (B) are essential nutrients in olive orchards. Application of N is the main aspect of the olive orchard fertilization requiring annual soil and leaf applications. N fertilization is usually applied to the soil at 0.5–1.5 kg per olive tree at the end of winter, using urea, ammonium sulphate, or ammonium nitrate; and to the foliage in spring using urea solution at 4%. If only foliage solution is applied, several applications take place (Fernández-Escobar, 1999). N fertilization consistently increases olive yield but only when leaf N is below the sufficiency threshold (Hartmann, 1958).

Low K and B levels are common in olive orchards in Andalusia which reveal deficiency symptoms such as leaf chlorosis and necrosis. In the case of K, these deficiencies can be corrected with soil applications of 1–3 kg per tree of potassium sulphate, or with repeated leaf applications of 1–3% of potassium nitrate (Fernández-Escobar, 1999; Ferreira et al., 1984). B deficiencies can be overcome by applying 25–40 g B per tree or with a leaf application of 0.1% before flower-

ing. P deficiency can be alleviated with soil applications of 0.5 kg per tree.

Concentration of any of these nutrients can be correctly detected through a leaf analysis, being the best diagnosis method to determine the nutrient status and to plan fertilizer recommendations (Fernández-Escobar, 1999). However, olive fertilization is not generally based on recommendations from a leaf analysis, but rather from intuitive and visual practices. Thus, in an exhaustive study averaging 79 farms from the most productive area of Andalusia, Fernández-Escobar et al. (1994) observed that the range of N, P and K applications were 9–350 kg ha<sup>-1</sup>, 0–720 kg ha<sup>-1</sup>, and 0–210 kg ha<sup>-1</sup>, respectively, indicating that olives were either under-fertilized or over-fertilized. Also, low cost of fertilizers has encouraged farmers to make excessive applications with the belief that high yields would be ensured. However, this management adversely affects productivity, fruit quality and groundwater quality (Weinbaum et al., 1992; Marín and Fernández-Escobar, 1997). Further, Marín and Fernández-Escobar (1997) reported that annual application is not necessary to obtain good productivity of olive. Scientific evidences suggest that N application in pecan (*Carya illinoensis* Wangenh. K. Koch) orchards proves beneficial only when leaf N drops below the sufficiency threshold (Worley, 1990). Consequently, farmers are becoming aware that to sustain the environment and to increase their net economic returns, it is necessary to economize on fertilizer adopting a strategy for site-specific management based on spatial variability of the field.

### 1.3. Site-specific management

To plan a decision support scheme for site-specific management, the geostatistical analysis has proven to be an excellent way of exploring the structure of the spatial variation of weeds (Heisel et al., 1996; Jurado-Expósito et al., 2003; Zanin et al., 1998), soils (López-Granados et al., 2002; McBratney and Pringle, 1999; Webster and Oliver, 1992) or pests (Crist, 1998; Weisz et al., 1995). These works provided very precise information for site-specific recommendations. However, most of the spatial variability studies about fertility are referred to soil analysis and they have been carried out in various temperate countries, e.g. UK (Blackmore et al., 1998), Belgium

(Geypens et al., 1999) or at Iowa, USA (Cambardella and Karlen, 1999).

The widespread availability of machinery with positioning technology (global positioning system (GPS)), yield monitors and spraying devices to vary the dose of crop input has spurred increasing interest in the site-specific application. There is an increasingly amount of information about site-specific treatments in many different crops, i.e., winter wheat (Machet et al., 2001), winter barley (Baxter et al., 2001), peanut (Vellidis et al., 2001), soybean (Silva et al., 2001), corn (Ma et al., 1996), sugar beet (Walter et al., 1996), sunflower (Jurado-Expósito et al., 2003) or potatoes (Booij et al., 2001). However, no references have been found about site-specific management in olive orchards and, at present, this agricultural management is possible due to the existence of electronic devices designed to reduce the pesticide inputs by adjusting the dose of chemicals for citrus and olive orchards (Moltó et al., 1998, 1999).

In olive orchards, leaf nutritional status has been studied by several authors such as Benlloch et al. (1991), Fernández-Escobar et al. (1993) and Delgado et al. (1994). However, none of them dealt with the spatial variability of the main leaf nutrients and this is needed to develop the basic information supporting the convenience of implementing a site-specific fertilization strategy in olive orchards. So, the objectives of this study were to: (1) study the spatial variability of leaf nutritional status in olive orchards using geostatistics for describing and understanding the spatial distribution of nutrients, (2) develop accurate leaf nutrient maps using kriging, and (3) design site-specific fertilizer application maps based on treating areas not exceeding the sufficiency threshold and determining potential fertilizer savings.

## 2. Materials and methods

### 2.1. Study area, sampling design and laboratory analysis

Leaf sampling was performed in an olive orchard of 30 ha, 50-year old, located at Martos (Jaén, Spain) in 1999 and 2000. Sampling area was at 50 m from borders of the field. Olive trees were spaced 11 m × 11 m and without any irrigation system (rain-fed). The orchard was fertilized by soil application of 1.15 kg N

per tree in mid-March, and foliar feeding of 9 mg N, 6 mg P, 6 mg K and  $156 \times 10^{-7}$  mg B per tree in May, during both years.

A 75 m × 75 m grid pattern was established, following a modified standard procedure described by Fernández-Escobar et al. (1994). Each intersection point (node) was composed of an experimental unit of four nearest olive trees, and leaf samples were collected from every experimental unit. Each leaf sample comprised of four subsamples of 25 healthy, fully expanded, mature leaves collected from middle portion of non-bearing current-season shoots, about 1.5 m above the soil surface, at the four cardinal points from every olive tree in mid July in 1999 and 2000. These four subsamples were mixed in paper bags to provide a bulked sample with 100 leaves to ensure that it was representative of the surrounding area. The leaves were taken to the laboratory in portable ice-boxes, and washed with deionized water and a 0.1 N HCl solution, dried at 80 °C for 2 days, and finally ground to pieces of 0.5 cm.

N was analysed by Kjeldahl digestion, and P, K and Fe by dry ashing and subsequent dissolution in hot HCl (Jones et al., 1991). Leaf B was analyzed according to Barbier and Chabannes (1953).

### 2.2. Statistical analyses

#### 2.2.1. Exploratory statistical analysis

The data were analyzed statistically for determining classical descriptors, such as mean, maximum, minimum, standard deviation and skewness of data distribution. The descriptive statistics suggested a normal distribution (skewness between  $-0.77$  and  $1.28$ ); therefore, no transformation was used for the geostatistical analyses. Also, correlation matrix were calculated between all leaf variables.

#### 2.2.2. Geostatistical analysis

A semivariogram was calculated for each leaf nutrient as follows (Goovaerts, 1997; Isaaks and Srivastava, 1989; Webster and Oliver, 2001):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i + h) - z(x_i)]^2$$

where  $\gamma(h)$  is the experimental semivariogram value at distance interval  $h$ ;  $N(h)$  the number of sample value

pairs within the distance interval  $h$ ;  $z(x_i)$ ,  $z(x_i + h)$  sample values at two points separated by the distance interval  $h$ . All pairs of points separated by distance  $h$  (lag  $h$ ) were used to calculate the experimental semivariogram. Lag  $h$  was within 60 m and 70 m depending on the leaf nutrient and year. Several semivariogram functions were evaluated to choose the best fit with the data. Semivariograms were calculated both isotropically and anisotropically. The anisotropic calculations were performed in four directions (0, 45, 90 and 135°) with a tolerance of 22.5° to determine whether the semivariogram functions depended on sampling orientation and direction (i.e., they were anisotropic) or not (i.e., they were isotropic). Direction 0° corresponds to E-W and 90° to the N-S direction. Semivariogram models were fitted by the least square procedure using VARIOWIN software.<sup>1</sup> No nested semivariogram structures were used, as adequate fits were obtained with a simple structure

Spherical and pure nugget models were fitted to the empirical semivariograms. The parameters of the model: nugget semivariance, range, and sill or total semivariance, were determined. Nugget semivariance is the variance at zero distance; sill is the lag distance between measurements at which one value for a leaf nutrient does not influence neighboring values; and range is the distance at which values of leaf nutrient become spatially independent of the neighboring values. The ratio between nugget semivariance and total semivariance or sill was used to define different classes of spatial dependence for leaf nutrients (Cambardella et al., 1994; López-Granados et al., 2002). If ratio was  $\leq 25\%$ , the leaf nutrient was considered to be strongly spatially dependent, or strongly distributed in patches; if ratio was between 26 and 75%, the leaf nutrient was considered to be moderately spatially dependent; if ratio was greater than 75%, the leaf nutrient was considered weakly spatially dependent; if the ratio was 100%, or the slope of the semivariogram was close to zero, the leaf nutrient was considered as not being spatially correlated (pure nugget).

Semivariogram models were cross-validated (trial-and-error procedure) by comparing leaf nutrient values estimated from the semivariogram model with

actual values (Isaaks and Srivastava, 1989). Differences between estimated and experimental values are summarized using the cross-validation statistics, i.e., mean squared error (MSE) and standardised mean squared error (SMSE) (Isaaks and Srivastava, 1989; Hevesi et al., 1992).

Once cross-validated, the parameters of the semivariogram models described above were used to map every leaf nutrient for each year by kriging. Ordinary point kriging was performed on a regular grid of 15 m and it produced unbiased estimates of each leaf nutrient value at unsampled points as follows:

$$z^*(x_0) = \sum_{i=1}^n \lambda_i z(x_i),$$

when

$$\sum_{i=1}^n \lambda_i = 1$$

being  $z^*(x_0)$  the estimated value,  $z(x_i)$  the  $n$  available data values and  $\lambda_i$  is a weight assigned to the value  $x_i$ .

Cross-validation and kriging were carried out using WinGslib<sup>2</sup> software (Deutsch and Journel, 1992), and contour maps were generated using SURFER,<sup>3</sup> contour mapping software based on WinGslib kriged values showing the leaf nutrients estimated.

### 2.3. Optimization of fertilization

The fertilization threshold of every leaf nutrient, i.e., the nutrient limit for the sufficient range, was estimated at  $N \geq 1.5\%$ ;  $P \geq 0.1\%$ ;  $K \geq 0.8\%$ , and  $B \geq 19 \text{ mg kg}^{-1}$  (Marín and Fernández-Escobar, 1997; Fernández-Escobar, 1999). Leaf nutrient maps achieved by kriging were used to estimate the percentage of farm surface susceptible to be fertilized with the deficient leaf nutrients when concentration of these nutrients did not exceed the fertilization threshold, as stated above.

<sup>1</sup> VARIOWIN: Software for Spatial Data Analysis in 2D. Spring Verlag, New York, USA.

<sup>2</sup> WinGslib: Geostatistical Software Library and User's Guide. Oxford University Press.

<sup>3</sup> SURFER (Win 32): Surface Mapping System. Golden Software Inc. 809, 14th Street. Golden, CO 80401-1866. USA.

Table 1  
Summary descriptive statistics of leaf nutrients concentrations during two sampling years

Sampling year	Leaf nutrient	Mean	Min	Max	SD	CV (%)	Kurtosis	Skew
1999	N (%)	1.59	1.44	1.76	0.08	5.03	−0.87	0.21
	P (%)	0.07	0.06	0.09	0.007	10.1	−0.10	0.24
	K (%)	0.86	0.57	1.21	0.17	19.7	−0.87	0.04
	Fe (mg kg <sup>−1</sup> )	62.28	28.0	193.0	25.37	40.7	10.6	1.19
	B (mg kg <sup>−1</sup> )	19.76	14.0	27.0	3.26	16.5	−0.57	0.38
2000	N (%)	1.55	1.26	1.74	0.10	6.6	0.11	−0.54
	P (%)	0.096	0.07	0.11	0.009	9.37	0.66	−0.63
	K (%)	0.827	0.59	1.01	0.102	12.3	0.06	−0.77
	Fe (mg kg <sup>−1</sup> )	107.6	72.0	292.0	42.05	39.1	10.7	1.28
	B (mg kg <sup>−1</sup> )	24.25	18.0	32.0	2.94	12.1	−0.17	0.17

Table 2  
Correlation matrix between leaf nutrient content pairs

Sampling year		N	P	K	Fe	B
1999	N	1				
	P	0.80**	1			
	K	0.18	0.08	1		
	Fe	0.06	−0.06	0.13	1	
	B	0.49**	0.38**	0.54**	0.04	1
2000	N	1				
	P	0.9**	1			
	K	0.24*	0.10	1		
	Fe	−0.04	0.08	−0.23*	1	
	B	0.48**	0.51**	0.22*	−0.05	1

\*, \*\* Significant at 0.05 and 0.01 levels, respectively.

Table 3  
Geostatistical analysis of the leaf nutrients in the two sampling years

Sampling year	Leaf nutrient	Nugget Semivariance Ratio <sup>a</sup> (%)	Sill	Range (m)	Spatial distribution model <sup>c</sup>	MSE <sup>b</sup>	SMSE <sup>b</sup>
1999	N	0.0007 (10.14)	0.0069	212.8	S, spherical	0.004	0.971
	P	0.00003 (50)	0.00006	243.2	M, spherical	0.00004	0.982
	K	0.0021 (7.3)	0.0288	380.7	S, spherical	0.009	0.971
	Fe	630.0 (100)	630.0	0	Pure nugget	686.5	0.998
	B	3.85 (38.1)	10.12	235.2	S, spherical	8.66	0.987
2000	N	0.0035 (34)	0.0103	257.6	M, spherical	0.007	0.986
	P	0.00001 (14.3)	0.00007	245.0	S, spherical	0.0001	1.007
	K	0.0043 (7.1)	0.0603	396.8	S, spherical	0.0073	1.003
	Fe	1728.0 (100)	1728.0	0	Pure nugget	1947.8	1.002
	B	0.170 (2.02)	8.41	302.4	S, spherical	5.8	0.99

<sup>a</sup> Percentage of the sill due to the nugget.

<sup>b</sup> MSE: mean squared error expressed as percentage of the sample variance; SMSE: standardised mean squared error.

<sup>c</sup> Spatial distribution (S, strong spatial dependence; M, moderate spatial dependence; pure nugget: no spatial correlation), and spatial distribution model.

### 3. Results and discussion

#### 3.1. Exploratory statistical analysis

The summary of the statistics for leaf nutrients are shown in Table 1. Low coefficients of variation (CV <

20%) for all parameters were found, except for Fe which showed a medium CV (around 40% both years). Comparing mean values, lower P and B were observed in 1999, while similar values of N and K were found both years. Leaf N, P, K and B concentrations are consistent with previous results of a wider leaf nutrient

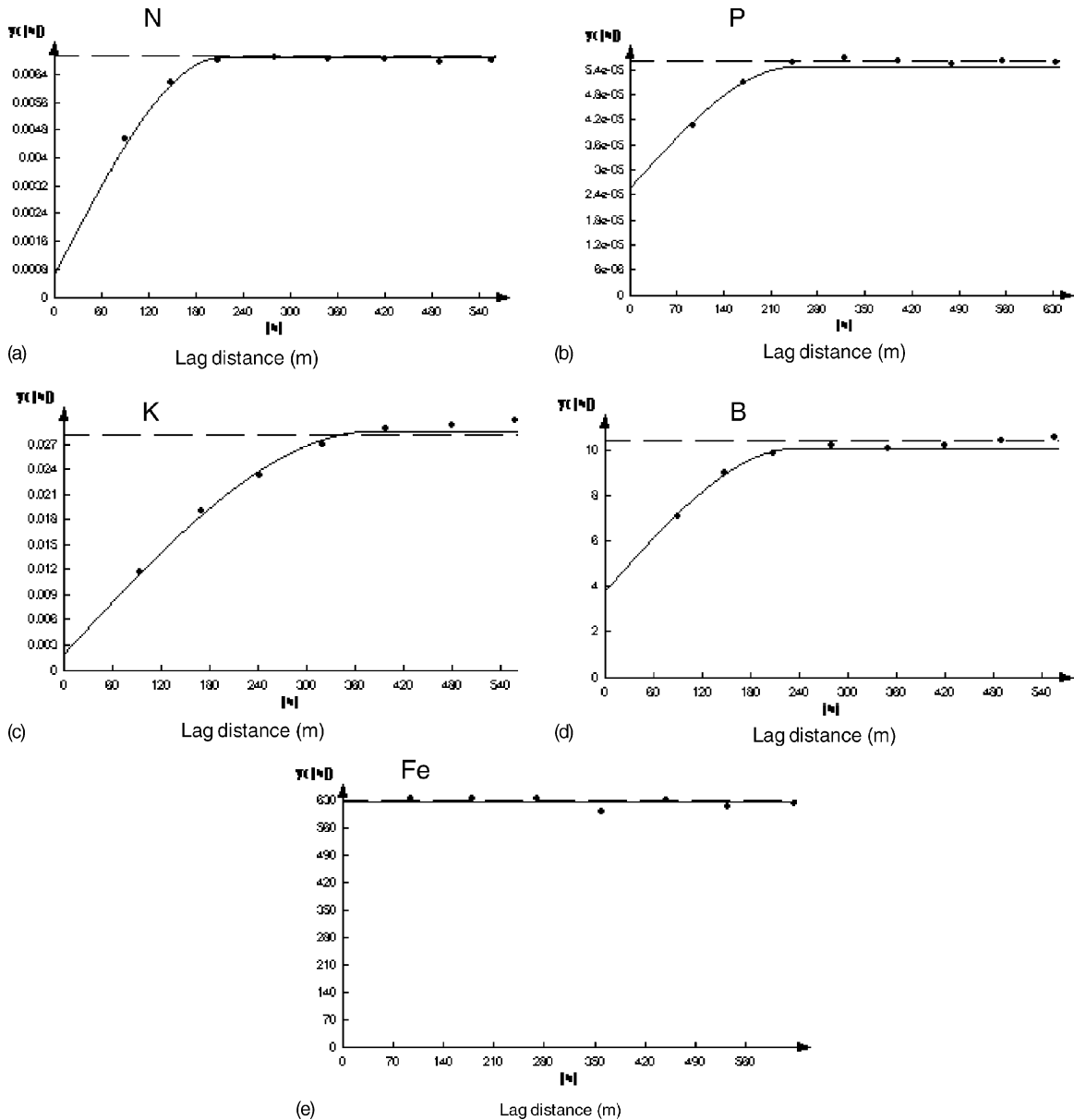


Fig. 1. Experimental (circles) and modelled semivariograms of: (a) N (spherical); (b) P (spherical); (c) K (spherical); (d) B (spherical); and (e) Fe (pure nugget), corresponding to sampling from 1999.

study in 79 olive orchards located in Southern Spain (Fernández-Escobar et al., 1994). Correlation matrix for leaf nutrients are shown in Table 2. There were significant positive correlations both years between N and P ( $r = 0.8$  and  $r = 0.9$ ,  $P \leq 0.01$  for 1999 and 2000, respectively), between N and B ( $r = 0.48$ ,

$P \leq 0.01$ ), and between P and B ( $r = 0.38$  and  $0.51$ ,  $P \leq 0.01$  for 1999 and 2000, respectively). K showed a strong correlation with B in 1999 ( $r = 0.54$ ,  $P \leq 0.01$ ) and less strong in 2000. Fe did not show any high correlation except with K in 2000 ( $-0.23$ ,  $P \leq 0.05$ ).

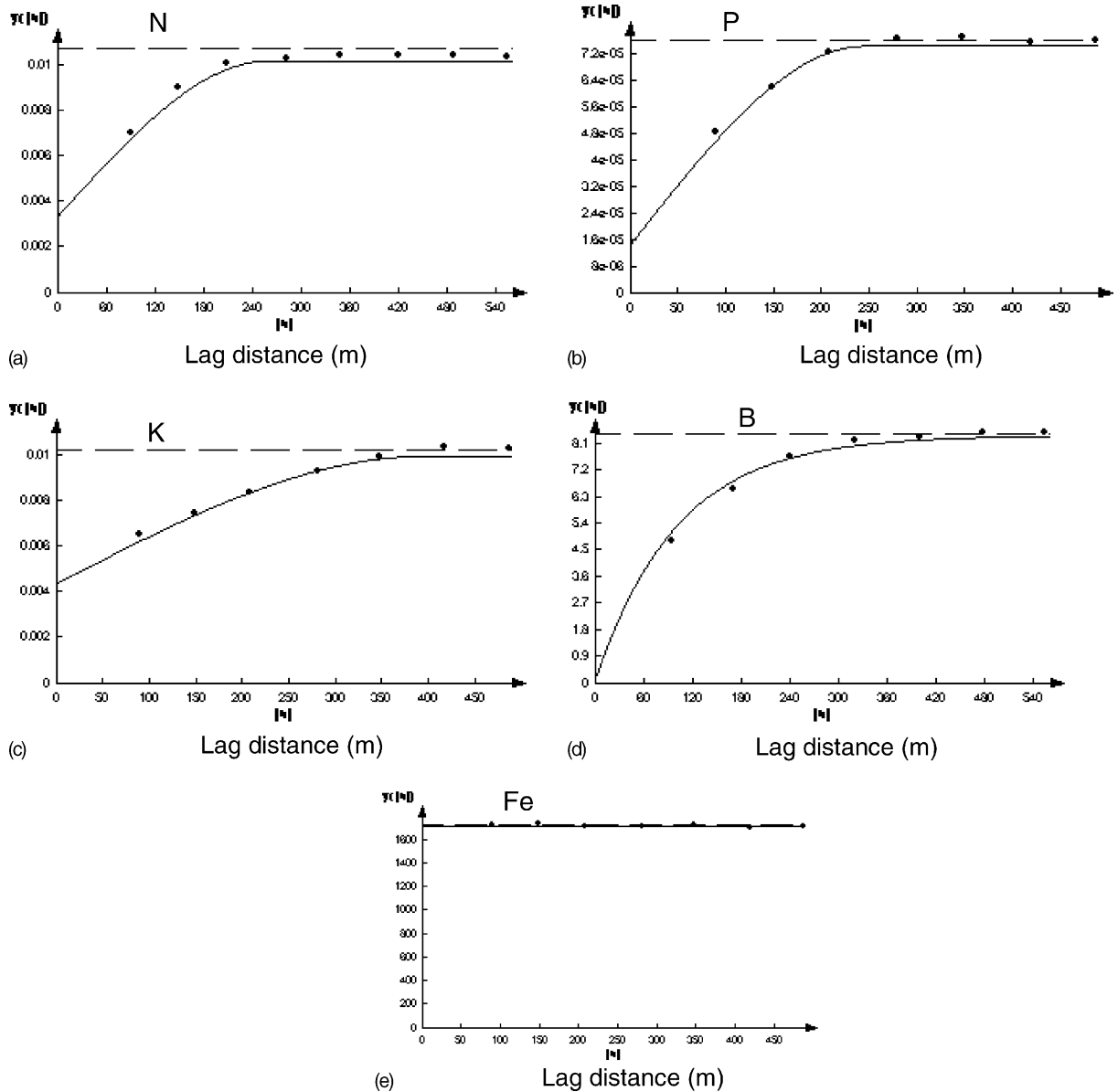


Fig. 2. Experimental (circles) and modelled semivariograms of: (a) N (spherical); (b) P (spherical); (c) K (spherical); (d) B (spherical); and (e) Fe (pure nugget), corresponding to sampling from 2000.

### 3.2. Geostatistical analysis

Anisotropic semivariograms did not show any differences in spatial dependence based on direction, for which reason isotropic semivariograms were chosen. The geostatistical analysis indicated that the K and B showed the same spatial distribution models and spatial dependence levels both years (Table 3). Thus, K and B followed a strong spatially correlated distribution in patches defined through spherical model in 1999 and 2000 (Table 3, Fig. 1c and d, Fig. 2c and d). Fe did not follow a spatially correlated distribution

both years (Table 3, Figs. 1e and 2e, slope of the semivariogram was close to zero or maximum, 100%, nugget semivariance/sill ratio). The large nugget semivariance and the non-spatial dependence for Fe reflect the poor or null correlation coefficients between Fe and the each other leaf nutrient.

In contrast, N and P exhibited a strong or moderate spatial distribution depending on the year (Table 3, Figs. 1a, b, 2a and b), and concentration of both leaf nutrients was defined by spherical models. The spatial variation in leaf parameters observed was not surprising, since the values of the variables are usually

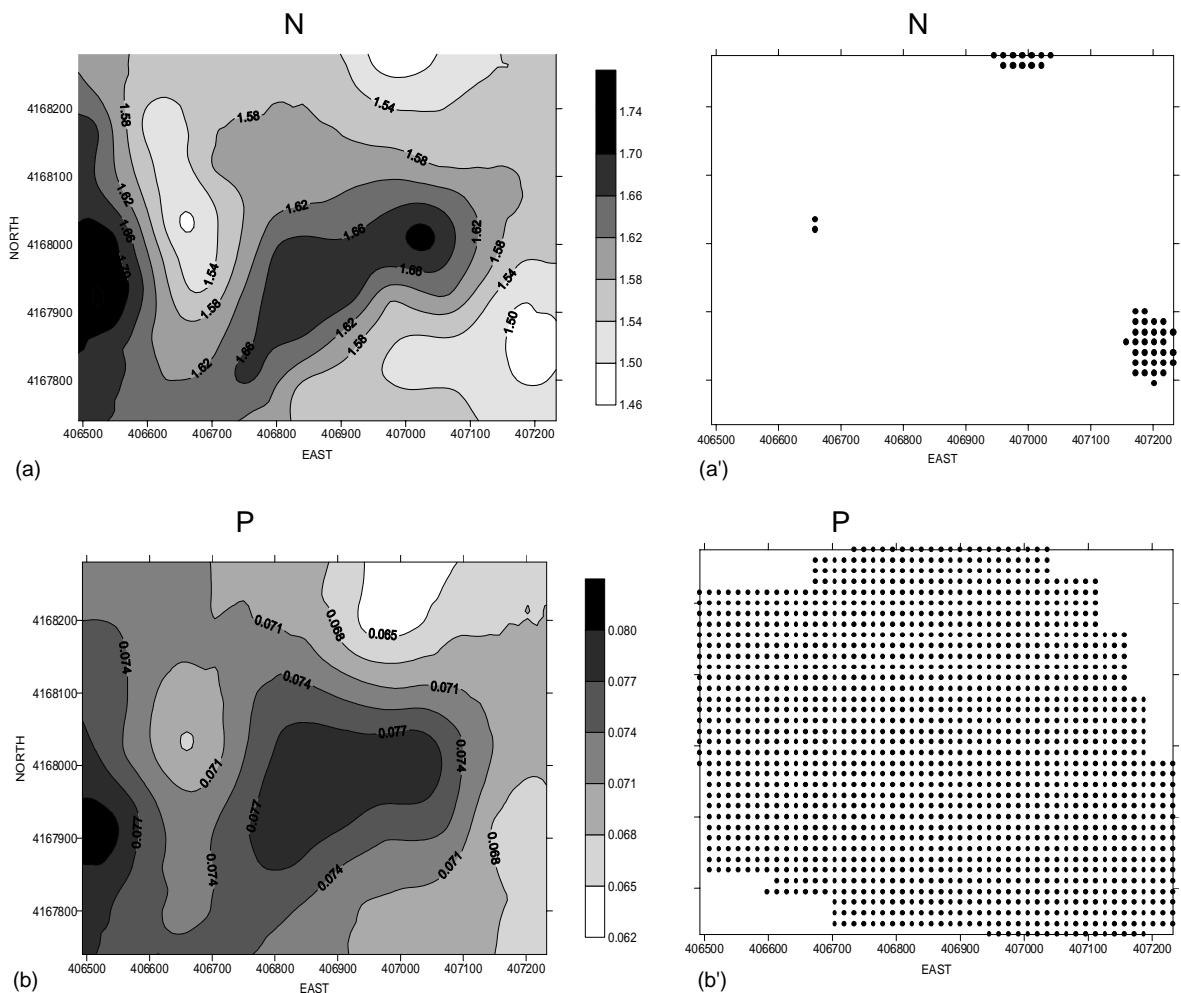


Fig. 3. Isoline maps of estimated (a) N; (b) P; (c) K; and (d) B. Site-specific fertilization maps obtained according to each leaf nutrient and the sufficient threshold of (a') N; (b') P; (c') K; and (d') B, corresponding to the sampling from 1999.

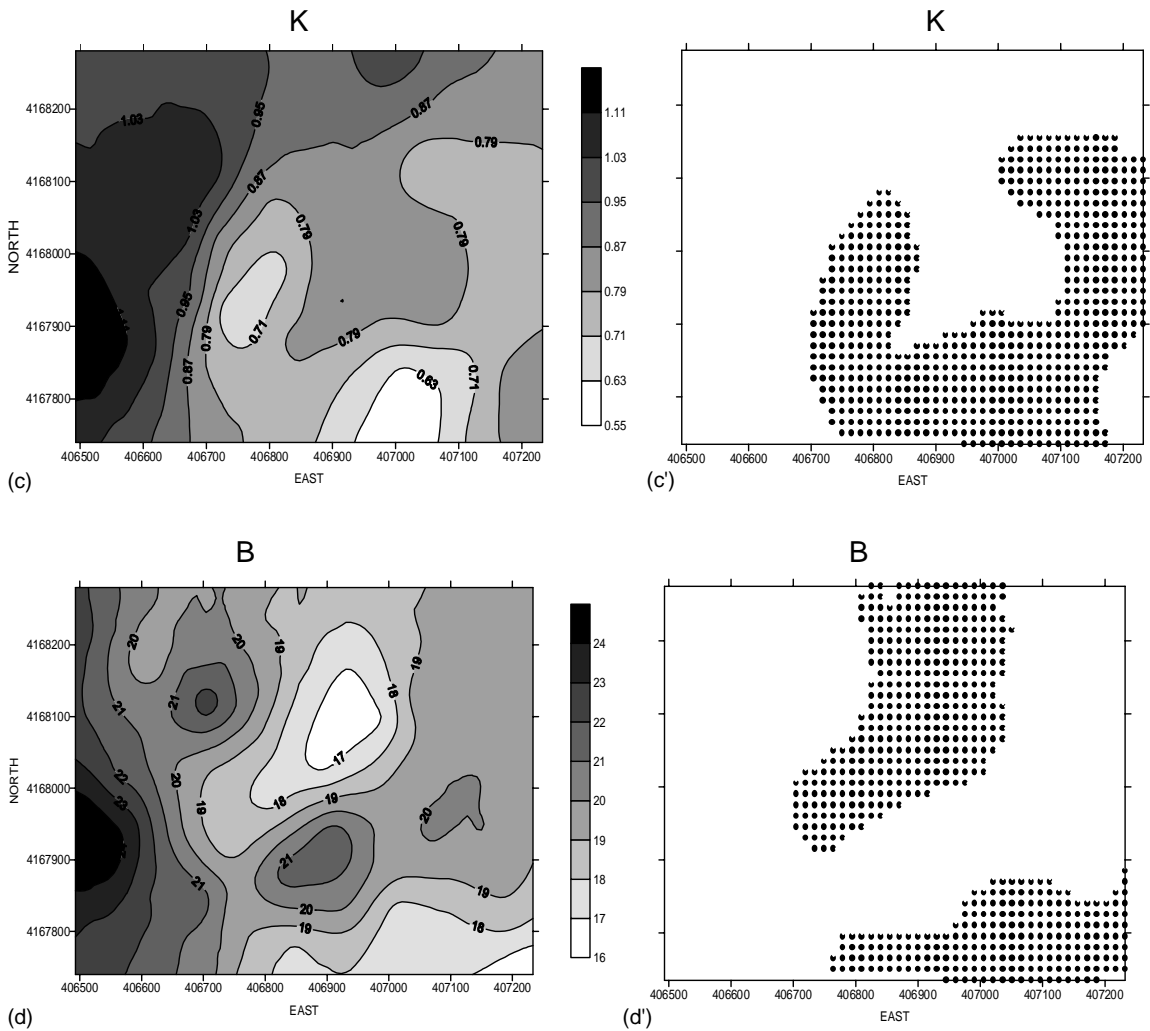


Fig. 3. (Continued).

the result of an intrinsic variation in leaf nutrient and external or environmental conditions as previously reported [Mallarino et al. \(1999\)](#). Classical statistics did not show the strongly patchy distribution of N, P, K and B (with some small differences depending on the year) and showed the classical way to study the nutritional status of leaves without taking into account the spatial variation of leaf nutrients.

The nugget semivariance of the semivariogram function for N, P, K and B was very small and approached zero ([Table 3](#)), suggesting that the scale of lag  $h$  and the sampling closely matched their spatial

variation. However, a large nugget semivariance (e.g. Fe both years, [Table 3](#)) suggests that the lag  $h$  apparently did not characterize the spatial variation of Fe and an additional sampling of this leaf variable at smaller lag distances and in larger numbers might be needed to detect spatial dependence, if any is indeed present. However, according to [Fernández-Escobar et al. \(1993\)](#) and [Fernández-Escobar \(1999\)](#) the leaf analysis of Fe is not appropriate to detect Fe deficiencies because Fe is accumulated in leaves, even though olive tree shows deficiency visual symptoms. So, the large nugget semivariance observed for Fe would be

also due this aspect and would reflect the problems to detect properly Fe concentration.

The range of the semivariogram gives the average extent of the patches when the distribution of leaf nutrients is strongly or moderately spatially correlated. Range values varied from 212 m (N in 1999) to 396 (K in 2000) (Table 3). A larger range indicates that the observed values of the leaf nutrient are influenced by other values of this variable over greater distances than leaf nutrients which have smaller ranges

(Samper-Calvete and Carrera-Ramírez, 1996). Thus, K had a range of more than 380 m both years (Table 3), and this suggests that K values influenced neighbouring values of K over greater distances than other leaf nutrient, e.g., N which had a range of 212 and 257 m in 1999 and 2000, respectively. Several other studies have reported similar big differences between ranges of different soil variables trying to map soil variation at a field scale (Robertson et al., 1997; Bocchi et al., 2000; López-Granados et al., 2002).

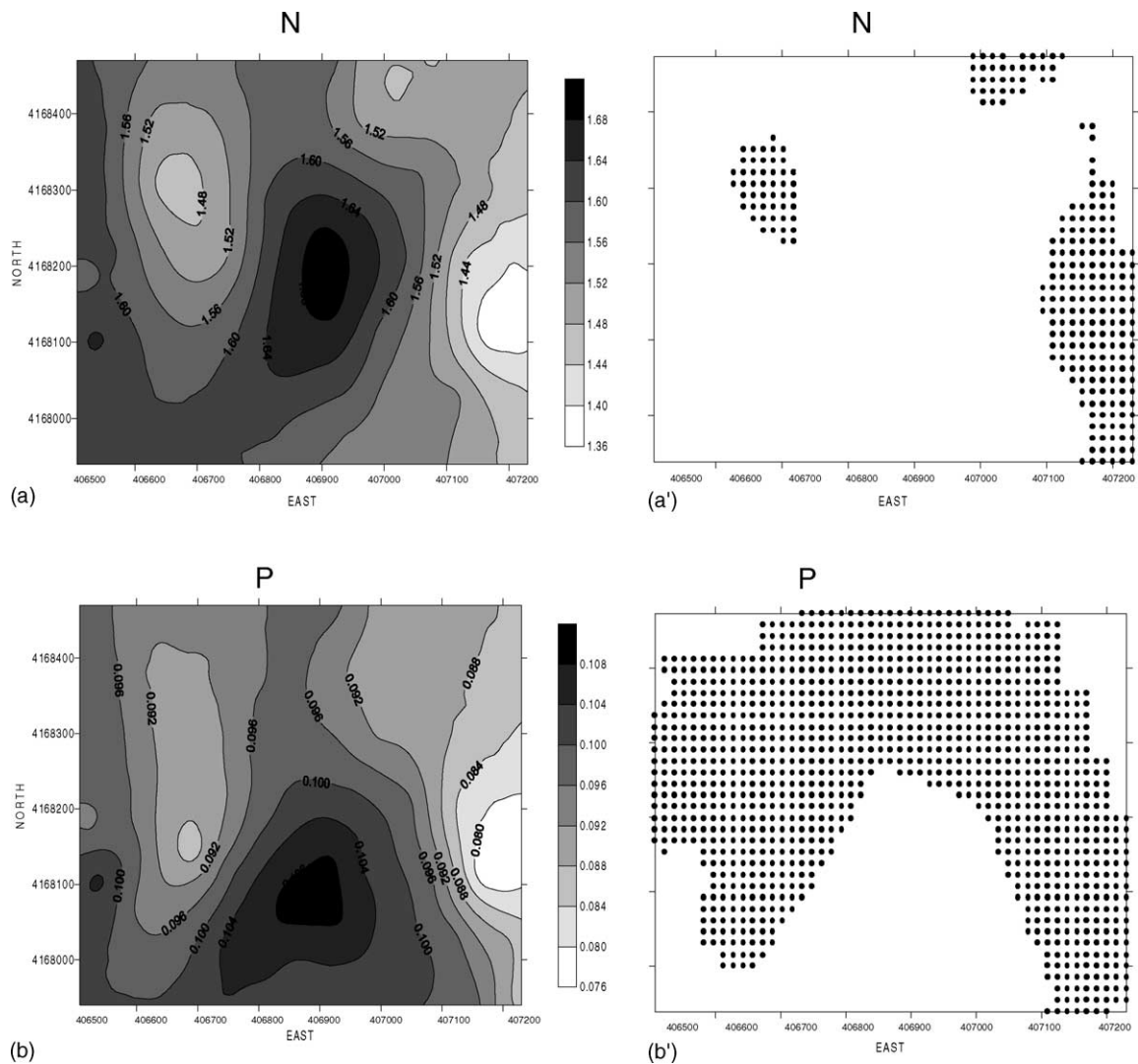


Fig. 4. Isoline maps of estimated (a) N; (b) P; (c) K; and (d) B. Site-specific fertilization maps obtained according to each leaf nutrient and the sufficient threshold of (a') N; (b') P; (c') K; and (d') B, corresponding to the sampling from 2000.

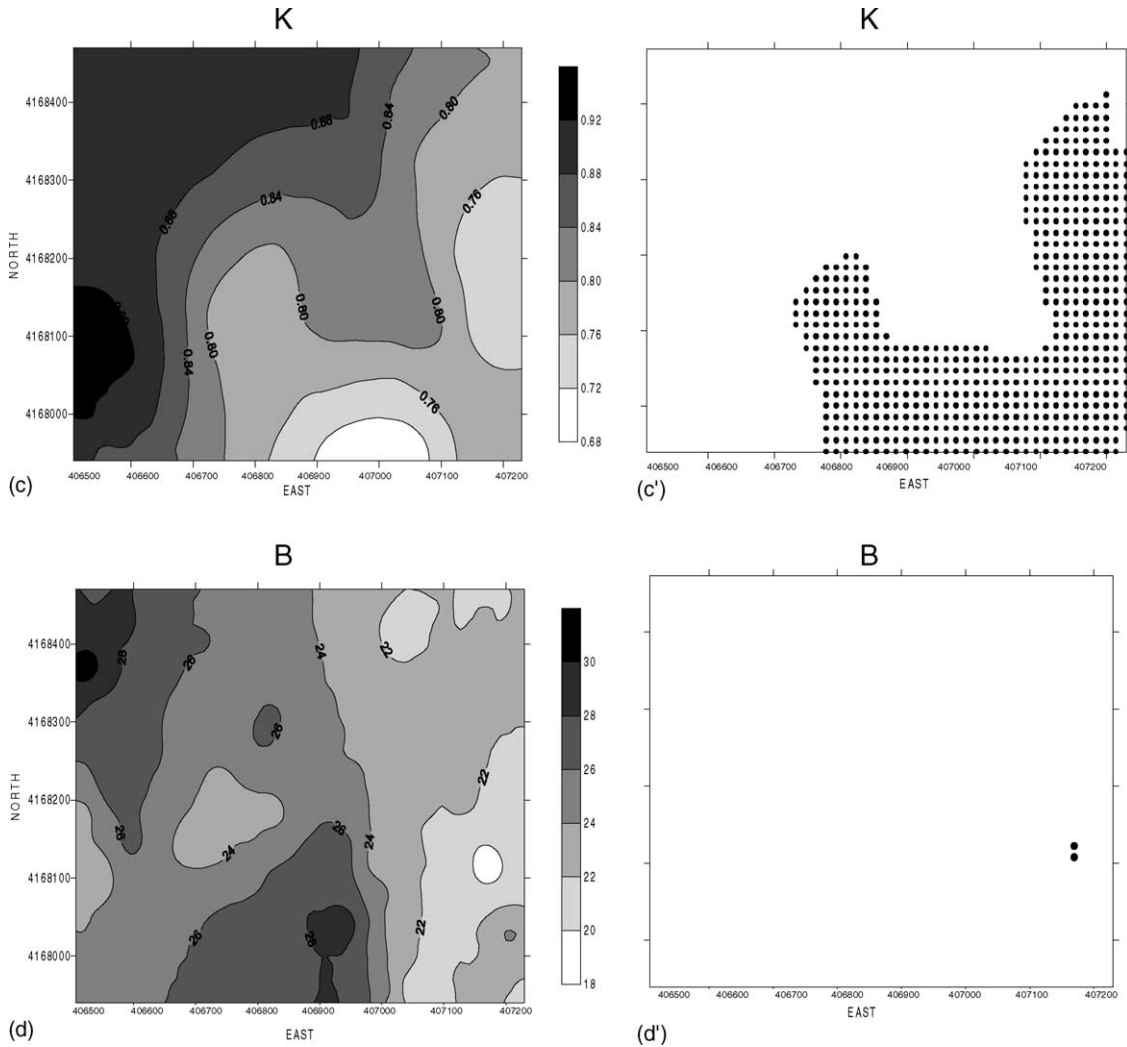


Fig. 4. (Continued).

The clearly patchy distribution of N, P, K and B (Figs. 3 and 4) has demonstrated that the olive orchard is divided into homogeneous small zones (or discrete patches) depending on the different ranges. This spatial variability pattern indicates the feasibility of developing a strategy for a site-specific application of N, P, K and B.

### 3.3. Optimization of fertilization

Table 4 shows the percentage of the farm surface susceptible to be fertilized with the different leaf nu-

trients when concentration of these nutrients does not exceed the fertilization threshold. A consistent reduction in fertilization could have been achieved both years. Thus, N, the main nutrient involved in the olive orchard fertilization would have to be applied only in the 3 and 18% of the field, for 1999 and 2000, respectively (Figs. 3a' and 4a'). These results are consistent with those reported by Marín and Fernández-Escobar (1997) about the non necessity of applying N fertilizer when leaf nitrogen is above the fertilization threshold. In addition, Fernández-Escobar et al. (2002) have reported that an excess of N fertilization by annual

Table 4

Percentage of surface susceptible to be fertilized when concentration of every leaf nutrient does not exceed the fertilization threshold as affected by sampling year (from Fernández-Escobar, 1999)

Sampling year	Fertilization threshold			
	N $\geq$ 1.5%	P $\geq$ 0.1%	K $\geq$ 0.8%	B $\geq$ 19 mg kg <sup>-1</sup>
1999	3	100	37.4	36.6
2000	17.4	72.4	34.3	0.2

soil N application when N leaf content is  $\geq$ 1.5%, not only adversely affects groundwater quality and the farming economy, but also affects negatively the olive oil quality due to a decrease of the polyphenols content.

A similar result is observed for B, which shows the possibility of saving inputs in fertilization by applying only in 36.6 and 0.2% of the whole field in 1999 and 2000, respectively (Figs. 3d' and 4d'). The reduction in the fertilization with P varied very widely between years. Thus, while the whole surface would have to be fertilized with P in 1999 (Fig. 3b'), a 72% of the olive orchard surface did not exceed the fertilization threshold in 2000 (Fig. 4b'). In the case of K, reduction of fertilization was very similar both years (Table 4, Figs. 3c' and 4c'). It is important to emphasize that an adequate K fertilization allows a better tolerance of a drought season (Restrepo et al., 2002), which is very frequent under our Mediterranean conditions

#### 4. Conclusion

The geostatistical procedures are useful for describing spatial variability of nutritional status in olive orchards, which could be used to design site-specific application strategies. Moreover, annual leaf analysis provides an appropriate guide for formulating a possible precision fertilization programme of N, P, K and B, to avoid economic and potential environmental problems derived from a homogeneous fertilization scheme. The clearly patchy distribution of N, P, K and B has demonstrated that the olive orchard is divided into homogeneous small zones (or discrete patches) depending on the different ranges. It is important to emphasize that leaf nutrients with a strong spatial dependence will have a more reliable site-specific fer-

tilization programme for precision farming, which involves a consistent reduction in fertilizers.

#### Acknowledgements

The present research was partially financed by the Spanish Commission for Science and Technology (projects: AGL 2001-2808 and AGF2002-04468-CO3-02). Fertiberia S.A. performed the leaf laboratory analyses.

#### References

- Barbier, G., Chabannes, J., 1953. Contribution a l'etude du bore dans le sol et les plantes. *Ann. Agron.* 1, 1–17.
- Baxter, S.J., Oliver, M.A., Gaunt, J., 2001. Understanding the spatial variation of mineral nitrogen and potentially available nitrogen at the field scale. In: Grenier, G., Blackmore, S. (Eds.), *Proceedings of the Third European Conference on Precision Agriculture*, Montpellier, France, pp. 887–892.
- Benloch, M., Arboleda, F., Barranco, D., Fernández-Escobar, R., 1991. Response to young olive trees to sodium and boron excess in irrigation water. *HortScience* 26, 867–870.
- Blackmore, S., Godwin, R.J., Taylor, J.C., Cosser, N.D., Wood, G.A., Earl, R., Knight, S., 1998. Understanding variability in four fields in the United Kingdom. In: Robert, P.C., Rust, R.H., Larson, W., (Eds.), *Proceedings of the Fourth International Conference on Precision Agriculture*. ASA, CSSA, SSSA, Madison, WI, USA, pp. 3–18.
- Booij, R., Uenk, D., Lokhorst, C., Sonneveld, C., 2001. Monitoring crop nitrogen status in potatoes, using crop light reflection. In: Grenier, G., Blackmore, S. (Eds.), *Proceedings of the Third European Conference on Precision Agriculture*, Montpellier, France, pp. 893–899.
- Bocchi, S., Castrignanò, A., Fornaro, F., Maggiore, T., 2000. Application of factorial kriging for mapping soil variation at field scale. *Eur. J. Agron.* 13, 295–308.
- Bouma, J., 1997. Precision agriculture: introduction to the spatial and temporal variability of environmental quality. In: Lake, J.V., Bock, G.R., Goode, J.A. (Eds.), *Precision Agriculture: Spatial and Temporal Variability of Environmental Quality*. Ciba Foundation Symposium, 210. Wiley, Wageningen, The Netherlands, pp. 5–17.
- Cambardella, C.A., Karlen, D.K., 1999. Spatial analysis of soil fertility parameters. *Precis. Agric.* 1, 5–14.
- Cambardella, C.A., Moorman, T.B., Novak, J.M., Parkin, T.B., Karlen, D.K., Turco, R.F., Konopka, A.E., 1994. Field-scale variability of soil properties in central Iowa soils. *Soil Sci. Soc. Am. J.* 58, 1501–1511.
- Civantos, D., 1999. La olivicultura en el mundo y en España. In: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds.), *El cultivo del olivo*. Mundi-Prensa, Madrid, pp. 19–33.
- Crist, T.O., 1998. The spatial distribution of termites in shortgrass steppe: a geostatistical approach. *Oecologia* 114, 410–416.

- Delgado, A., Benlloch, M., Fernández-Escobar, R., 1994. Mobilization of boron in olive trees during flowering and fruit development. *HortScience* 29, 616–618.
- Deutsch, C.V., Journel, A.G., 1992. *GSLIB: Geostatistical Software Library and User's Guide*. Oxford University press, p. 340.
- Fernández-Escobar, R., Barranco, D., Benlloch, M., 1993. Overcoming iron chlorosis in olive and peach trees using a low-pressure trunk-injection method. *HortScience* 28, 192–194.
- Fernández-Escobar, R., García-Barragán, T., Benlloch, M., 1994. Estado nutricional de las plantaciones de olivar en la provincia de Granada. *ITEA* 1, 39–49.
- Fernández-Escobar, R., 1999. Fertilización. In: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds.). *El cultivo del olivo*. Mundi-Prensa, Madrid, pp. 247–265.
- Fernández-Escobar, R., García-Novelo, J.M., Sánchez-Zamora, M.A., Uceda, M., Beltrán, G., Aguilera, M.P., 2002. Efecto del abonado nitrogenado en la producción y la calidad del aceite de oliva. *Dirección General de Investigación y Formación Agraria y Pesquera* (Ed.), *Jornadas de Investigación y Transferencia de Tecnología al Sector Oleícola*, Córdoba (Spain), pp. 299–302.
- Ferreira, J., García-Ortiz, A., Frías, L., Fernández, A., 1984. Los nutrientes N, P, K en la fertilización del olivar. *X Aniversario Red Cooperativa Europea de Investigación en Oleicultura*. Córdoba.
- García-Torres, L., 1999. *Conservation Agriculture in Europe: Environmental, Economic and EU Policy Aspects*. European Conservation Agriculture Federation (ECAAF) (Ed.), Brussels, Belgium, 23 pp.
- García-Torres, L., 2000. *Agricultura de Conservación en el Olivar: Cubiertas Vegetales*. Edita: Asociación Española Agricultura de Conservación/ Suelos Vivos, Córdoba, Spain, 36 pp.
- Geypens, M., Vanongeval, L., Vogels, N., Meykens, J., 1999. Spatial variability of agricultural soil fertility parameters in a Gleyic Podzol of Belgium. *Precis. Agric.* 1, 319–326.
- Goovaerts, P., 1997. *Geostatistics for Natural Resources Evaluation*. Oxford University Press, New York, 483 pp.
- Hartmann, H.T., 1958. Some responses of the olive to nitrogen fertilizers. *Proc. Am. Soc. Hort. Sci.* 72, 257–266.
- Heisel, T., Andersen, C., Ersbøll, A.K., 1996. Annual weed distributions can be mapped with kriging. *Weed Res.* 36, 325–337.
- Hevesi, J.A., Flint, A.L., Istok, J.D., 1992. Precipitation estimation in mountainous terrain using multivariate geostatistics. Part I: Structural analysis. *J. App. Meteorology* 31, 661–676.
- Isaaks, E.H., Srivastava, R.M., 1989. *An Introduction to Applied Geostatistics*. Oxford University Press, New York, 561 pp.
- Jones, J.B., Wolf, B., Mills, H.A., 1991. *Plant Analysis Handbook*. Micro-Macro Publishing, Athens.
- Jurado-Expósito, M., López-Granados, F., García-Torres, L., García-Ferrer, A., Sánchez de la Orden, M., Atenciano, S., 2003. Multi-species weed spatial variability and site-specific management maps in cultivated sunflower. *Weed Sci.* 51, 319–328.
- López-Granados, F., Jurado-Expósito, M., Atenciano, S., García-Ferrer, A., Sánchez de la Orden, M., García-Torres, L., 2002. Spatial variability of agricultural soil parameters in Southern Spain. *Plant and Soil* 246, 97–105.
- Ma, B.L., Morrison, M.J., Dwyer, L.M., 1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. *Agron. J.* 88, 915–920.
- Machet, J.M., Beaudoin, N., Mary, B., Boffety, D., Bernard, M., 2001. Characterization of the variability in grain production and quality within a winter wheat field. In: Grenier, G., Blackmore, S. (Eds.). *Proceedings of the Third European Conference on Precision Agriculture*, Montpellier, France, pp. 821–825.
- Mallarino, A.P., Oyarzabal, E.S., Hinz, P.N., 1999. Interpreting within-field relationships between crop yields, soil and plant variables using factor analysis. *Precision Agric.* 1, 15–26.
- Marín, L., Fernández-Escobar, R., 1997. Optimization of nitrogen fertilization in olive orchards. In: Val, J., Montañés, L., Monge, E. (Eds.), *Proceedings of the Third International Symposium on Mineral Nutrition of Deciduous Fruit Trees*, Zaragoza, Spain, pp. 411–414.
- McBratney, A.B., Pringle, M.J., 1999. Estimating average and proportional variograms of soil properties and their potential use in precision agriculture. *Precis. Agric.* 1, 125–152.
- Moltó, E., Martín, B., Fabado, F., Gutiérrez, A., Ramos, P., 1998. An automatic system for reduction of pesticide inputs in young citrus plantings. In: *Proceedings of the AgEng98 International Conference Of Agricultural Engineerin*. Oslo, Finland, Paper number: 98-A-018.
- Moltó, E., Martín, B., Fabado, F., Gutiérrez, A., Ramos, P., 1999. Two microcontroller based systems for precise application of pesticides in Mediterranean orchards. In: Stafford, J.V. (Eds.), *Proceedings of the Second European Conference on Precision Agriculture*, Odense, Denmark, pp. 789–796.
- Navarro, C., Parra, M.A., 1999. Plantación. In: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds.), *El cultivo del olivo*. Mundi-Prensa, Madrid, pp. 171–203.
- Porras, A., 1999. Recolección. In: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds.), *El cultivo del olivo*. Mundi-Prensa, Madrid, pp. 355–379.
- Restrepo, M., Benlloch, M., Fernández-Escobar, R., 2002. Influencia del estrés hídrico y del estado nutricional del olivo en la absorción foliar del potasio. *Dirección General de Investigación y Formación Agraria y Pesquera* (Ed.), *Jornadas de Investigación y Transferencia de Tecnología al Sector Oleícola*, Córdoba (Spain), pp. 307–310.
- Robertson, G.P., Klingensmith, K.M., Klug, M.J., Paul, E.A., Crum, J.R., Ellis, B.G., 1997. Soil resources, microbial activity, and primary production across an agricultural ecosystem. *Ecol. Appl.* 7, 158–170.
- Samper-Calvete, F.J., Carrera-Ramírez, J., 1996. Análisis estructural. In: *Centro Internacional de Métodos Numéricos en Ingeniería*. Universitat Politècnica de Catalunya, España (Eds.), *Geoestadística. Aplicaciones a la hidrología subterránea*, pp. 31–61.
- Silva, C.A., Bernardi, A.C.C., Machado, P.L.O.A., Meirelles, M.S.P., Carmo, C.A.F.S., 2001. Relationship between georeferenced soybean yield and soil fertility properties (Parana State,

- Brazil). In: Grenier, G., Blackmore, S. (Eds.), *Proceedings of the Third European Conference on Precision Agriculture*, Montpellier, France, pp. 857–862.
- Troncoso, A., Cantos, M., Liñan, J., Fernández, J.E., 1999. Fertilización. In: Barranco, D., Fernández-Escobar, R., Rallo, L. (Eds.), *El cultivo del olivo*. Mundi-Prensa, Madrid, pp. 289–314.
- Vellidis, G., Perry, C.D., Durrence, J.S., Thomas, D.L., Hill, R.W., Kvien, C.K., Rains, G., 2001. Field testing the peanut yield monitoring. In: Robert, P.C., Rust, R.H., Larson, W.E. (Eds.), *Proceedings of the Third European Conference on Precision Agriculture*, Minneapolis, USA, pp. 835–844.
- Walter, J.D., Hofman, V.L., Backer, L.F., 1996. Site-specific sugar beet yield monitoring. In: Grenier, G., Blackmore, S. (Eds.), *Proceedings of the Third European Conference on Precision Agriculture*, Montpellier, France, pp. 821–825.
- Webster, R., Oliver, M.A., 1992. Sample adequately to estimate variograms of soil properties. *J. Soil Sci.* 43, 177–192.
- Webster, R., Oliver, M.A., 2001. *Geostatistics for Environmental Scientist*. John Wiley and Sons, Ltd. (Eds.), England, pp. 47–131.
- Weinbaum, S.A., Picchioni, G.A., Muraoka, T.T., Ferguson, L., Brown, P.H., 1992. Fertilizer nitrogen and boron uptake, storage, and allocation vary during the alternate-bearing cycle in pistachio trees. *J. Am. Soc. Hort. Sci.* 119, 24–31.
- Weisz, R., Fleischer, S., Smilowitz, Z., 1995. Site-specific integrated pest management for high value crops: sample units for map generation using the Colorado potato beetle (*Coleoptera: Chrysomelidae*) as a model system. *J. Econ. Entomol.* 88, 1069–1080.
- Worley, R.E., 1990. Long-term performance of pecan trees when nitrogen application is based on prescribed threshold concentration in leaf tissue. *J. Amer. Soc. Hort. Sci.* 115, 745–749.
- Zanin, G., Berti, A., Riello, L., 1998. Incorporation of weed spatial variability into the weed control decision-making process. *Weed Res.* 38, 107–118.