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Regional Mapping of Perennial Weeds in Cotton with the Use of Geostatistics

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Perennial weeds constitute a serious problem in Greek cotton-growing areas, as they strongly competing against the crop and downgrade the final product. Monitoring weeds at a regional scale and relating their occurrence with abiotic factors will assist in the control of these species. Purple nutsedge, field bindweed, bermudagrass, and johnsongrass were studied in cotton crops for three consecutive growing seasons (2007 through 2009) in a large area of central Greece. Weed densities and uniformities per sampling site were assessed in relation to soil and climatic data. Abundance index (AI), which is highly dependent on abiotic factors, was also estimated, and revealed purple nutsedge to the most persistent and damaging species among the recorded weeds. Field bindweed showed the highest correlation with soil properties and especially with clay content. Furthermore, correlation analysis was used over the sampling years in order to assess the stability of weed occurrence in the sampling sites. Purple nutsedge, field bindweed, and bermudagrass proved to be stable in location and intensity. The weed density spatial distribution was evaluated by using local indicators of spatial autocorrelation (LISA) statistics, and was mapped by ordinary kriging and co-kriging interpolation methods. Only 1 to 3 spatial outliers were identified in each 1 of the 3 yr. Between the two interpolation methods co-kriging delivered better results for field bindweed and purple nutsedge, indicating that soil data could improve the estimation of weed occurrence. These co-kriging interpolated weed maps would be a very useful tool for decision makers in taking appropriate weed control measures.

Nomenclature: Purple nutsedge, *Cyperus rotundus* L. CYPRO; field bindweed, *Convolvulus arvensis* L. CONAR; bermudagrass, *Cynodon dactylon* (L.) Pers. CYNDA; johnsongrass, *Sorghum halepense* (L.) Pers. SORHA; cotton, *Gossypium hirsutum* L. GOSHI.

Key words: Spatial outliers, abiotic factors, co-kriging, abundance index.

Perennial weeds constitute a major problem in Greek cotton fields. PRE herbicide applications during the last decade have led to a significant decrease of annual weed populations. However, the common method to control perennials (cultivators) has proved ineffective, given their wide distribution recorded through extensive survey along the main cotton zone in Greece (Kalivas et al. 2010).

Actually, perennials' persistence in cotton crops may be due mostly to extensive mechanical soil cultivation, which favors the high regrowth of perennial weeds through their vegetative propagation (Monaco et al. 2002). Diverse subterranean organs constitute the main reproductive organs of bermudagrass, johnsongrass, purple nutsedge, and field bindweed (Abrahamson 1980). However, johnsongrass propagates asexually by rhizomes and sexually by seeds (Monaghan 1979). In general, perennial weeds are spatially persistent, especially when compared to annual species (Colbach et al. 2000).

At the same time, weed management has become more and more dependent on herbicides, causing weed populations to shift more rapidly than in previous years. Monitoring management programs and adjusting them appropriately before weed populations reach troublesome levels is crucial to an effective management strategy. Proper tillage timing and herbicide applications may reduce the competitiveness of perennial weeds that escape control and produce more seeds or vegetative organs that spread the weeds further.

Weed occurrence has been previously studied by using parameters such as density and frequency (Andreasen et al. 1991; Walter et al. 2002). Thomas (1985) introduced weed relative abundance (RA), which is estimated by summing relative frequency, relative uniformity, and relative density so as to assess weed importance. Moeini et al. (2008) proposed the abundance index (AI) in order to introduce a methodology capable of demonstrating the compatibility of weeds with soil and climatic conditions that other indexes failed to show until then. Furthermore, this index evaluates the weed populations and describes the weed ranking in an area. The AI is estimated by summing weed frequency, weed uniformity, and mean field density. The first two parameters contribute proportionally more to the final index estimation, making it more sensitive to abiotic factors, whereas RA estimation is mainly based on relative density, which indicates the competitive and reproductive ability of a species.

Several studies in the past have shown the important role that abiotic factors play on weed growth and occurrence. Particularly, Zimdahl (2007) has stated the crucial importance of temperature and precipitation effect on seed dormancy disruption, on seed germination, and on weed vigor. Heisel et al. (1999) and Walter et al. (2002) found that purple deadnettle (*Lamium purpureum* L.) densities and phosphorus content were steadily positively cross correlated. Medlin et al. (2001) reported that pitted morningglory (*Ipomoea lacunosa* L.) and sicklepod [*Senna obtusifolia* (L.) H.S. Irwin & Barneby] occurred in areas where phosphorus and potassium concentrations were higher, while their populations were negatively affected by high pH. Furthermore, sicklepod was favored by high organic matter.

The weed spatial distribution in relation to environmental factors constitutes a useful tool toward an efficient weed control program. The spatial data analysis is based on incorporating all possible information concerning weed abundance and abiotic factors that influence the weed occurrence (Andreasen et al. 1991). In previous studies, it was shown that weed species could also be correlated with soil properties. More specifically, Walter et al. (2002) and Andreasen et al. (1991) showed a positive correlation between

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field violet (*Viola arvensis* Murr.) and clay content. Purple deadnettle and phosphorus content were positively correlated too (Heisel et al. 1999; Walter et al. 2002). Dieleman et al. (2000) have studied the relationship of a number of species and soil properties and found that their populations were associated with loamy soils, high percent of organic carbon, and low levels of phosphorus and pH. Spatial analysis techniques contribute in assessing the weed importance in a more holistic way, aiming to control the weeds by means of integrated crop management (Kenkel et al. 2002). In many cases different weed species occur together in dense populations at a specific environment, favored by particular soil or climatic conditions. Factors such as weed biology, competition ability, seed-production capacity, and local environment may influence their geographical distribution (Andreasen and Skovgaard 2009). Decision makers may use observations on weed abundance in relation to their adaptation in a particular environment as baseline indicators for a more tailored weed control program. These spatially directed herbicide applications would lead to decreasing chemical inputs in cotton crops.

Specifically, interpolation techniques such as ordinary kriging and co-kriging were used in the past in relevant studies to map various types of vegetation, such as weed flora, obtaining a good knowledge for the weed distribution. The application of geostatistical analysis upon weed species is able to record the boundaries of perennials and also accurately correlate weed populations to underlying abiotic variables effecting their growth and distribution (Chicoine et al. 1985).

Co-kriging is considered as an outstanding tool in spatial mapping, leading to effective applications in monitoring invasive plants (Roberts et al. 2004). Furthermore, many researchers have been successful in associating weed distributions directly with the measured soil properties (Andreasen et al. 1991; Walter et al. 2002). Heisel et al. (1999), in order to avoid intensive weed sampling, used co-kriging to improve estimations over a specific variable such as weed distribution in sampling sites where no sampling had been conducted. The ancillary variables used toward this purpose were potassium (K), phosphorus (P), loss of ignition, silt, and sand content. It was observed that co-kriging improved the prediction variance on many occasions, especially when used instead of ordinary kriging. Jurado-Expósito et al. (2009) used elevation data in kriging with an external drift to determine the influence of field topography in order to predict weed densities.

During the last three decades cotton has become the dominant crop in central Greece. Farmers prefer this specific crop due to the high price the product can command, and the achievable high yields that in some cases exceed 5,500 kg ha^{-1}. This choice is viable because the farmers have access to large volumes of water for irrigation. The continuous and intensively applied PRE herbicides such as fluometuron and ethalfluralin resulted in effective control of annual species. On the other hand, perennial weeds such as purple nutsedge, field bindweed, bermudagrass, and johnsongrass are highly competitive with cotton, and as a result they are increasing the crop's financial overhead because of the intensive mechanical inputs required.

Field and regional weed mapping are two different approaches that may contribute toward studying weed appearance. Burkart and Buhler (1997) stated that regional analysis applies in weed science by presenting information on regional patterns of weed infestations and factors that regulate them. Thus, this analysis could be useful to estimate the changes from short- or long-term changes in abiotic factors (especially soil properties) that could enable more appropriate weed management strategies. Furthermore, the application of technologies at a regional scale and the knowledge of the weed distribution could increase the understanding of the abiotic and management factors, so as to control weed communities over large areas effectively and to provide important new information to plant ecologists and agricultural policy makers (Burkart and Buhler 1997; Laffan 2005). Regional data on the distribution and abundance of weeds are also needed by the researchers to establish bioeconomic models that will contribute toward the understanding of the weed biology, and thence to a better-informed weed management strategy (Doyle 1991).

Data from the same sampling sites were collected for three consecutive years in a cotton-growing region. The aims of this study were (1) to identify the most important perennial weeds and study if their occurrence is steady in time and space, (2) to relate perennial weed indicators with soil properties, (3) to study the spatial and temporal variability of cotton perennial weed indicators with the use of geostatistical theory.

Materials and Methods

Study Area. The survey was carried out in the main cotton production zone located in central Greece. The study area is a valley limited by mountains to the west, and contained within the area encompassed by the Thessaly plain. The climate is continental, characterized by cold, wet winters (temperature reaches −10 C) and dry hot summers (temperatures exceed 40 C).

Sampling Scheme—Data Collection. The survey was performed at a regional scale and was not designed to study the weed variability at farm level. The total infested area and the locations of infestations within cotton crop areas were recorded and correlated with existing soil and climatic data.

The survey area was 1,200 km^2. A grid was applied on the study area in order to follow a stratified randomized sampling scheme. One hundred eighty cells were designed with a cell size of 2.6 × 2.6 km. During a preliminary study large areas were identified without cotton crop, resulting in 117 sampling sites that were quite uniformly spatially distributed (Figure 1).

Each sampling site included five quadrats of 5 m^2 in each peak of a W pattern, that were situated between adjacent crop rows spacing each one from the other about 3 m. The survey was conducted from the middle of July until the beginning of August, just before the closing of crop canopy and the first mechanical weed control. At that period, cotton crop is at preanthesis stage (appearance of the first square until the flowering). Out of the 117 initially selected, the number of finally sampled sites was 101, 80, and 85 during 2007, 2008, and 2009, respectively. Changes in cultivation techniques, such as early mechanical weed control and crop rotation, were the reasons that reduced the number of the sampling sites.

According to the sampling procedure, the number of young to fully developed mature shoots m^{-2} of each perennial species was sampled, and stood for weed density. Furthermore, one surface soil sample (0–25 cm) was collected from each quadrat, of the 117 initially selected sampling sites. The five samples were mixed and constituted the soil sample of the

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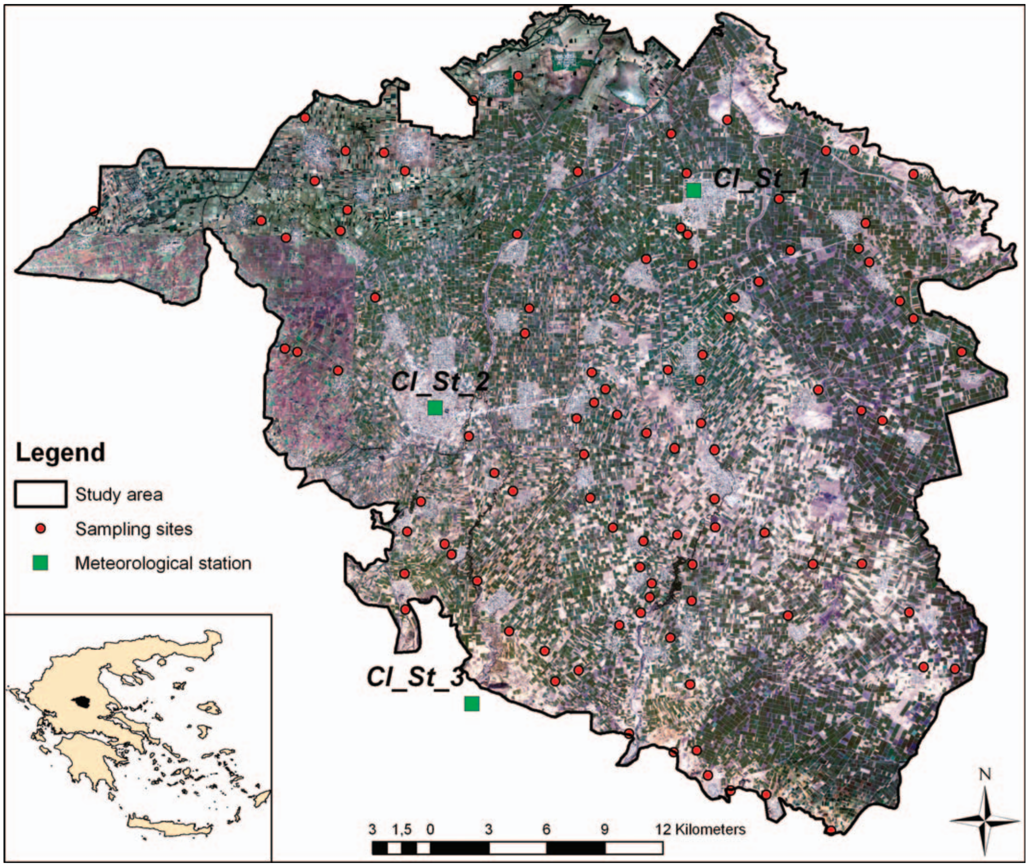

Figure 1. Study area and sampling sites.

sampling site. Finally the coordinates were recorded in each sampling site with the use of a Magellan Meridian Global Positioning System device.

Frequency and uniformity for each sampling site were computed afterwards. In particular, the species' presence or absence in a sampling site was taken to indicate weed frequency, and the time of a species' occurrence in the five quadrats of a sampling site was taken to indicate weed uniformity.

Agronomic and Climatic Data. The applied herbicides used in the area during 2007 were mainly mixtures of fluometuron with trifluralin, prometryn with trifluralin, and fluometuron with ethalfluralin. The situation concerning weed control changed in 2007 through 2008 because of license suspensions for certain active ingredients, obliging farmers to change herbicides. Because of this change, in 2009 prometryn and trifluralin were replaced by pendimethalin, which can be used to control the same weeds as its predecessors. The POST treatments are mainly applied to control narrow-leaf weeds, by using quizalofop-p-ethyl. However, this application has a tendency to be abandoned, because of increased cost of the pesticide.

The meteorological data gathered during 2007, 2008, and 2009 were taken from three meteorological stations situated in the study area (Figure 1). The yearly precipitation and mean yearly air temperature derived from the first meteorological station were 420.44 mm and 16.31 C in 2007, 352.84 mm and 15.78 C in 2008, and 591.4 mm and 15.31 C in 2009. The data for the second station were 529.7 mm, 17.47 C; 563.3 mm, 17.51 C; and 873.8 mm, 17.07 C; measurements taken from third station were 646 mm, 16.41 C and 273.6 mm, 16.65 C. Technical difficulties in 2009 resulted in a lack of data for the third meteorological station.

Soil Data. During 2007, the air-dried fine-earth fraction of the 117 collected surface soil samples was analyzed for carbonates, expressed as $CaCO_3$ equivalents; organic matter with the use of the Walkley–Black procedure; clay, silt, and sand percentage; cation exchange capacity (CEC); pH by glass/calomel electrodes in 1:1 soil–water ratio; and finally the sodium (Na), potassium (K), magnesium (Mg), and calcium (Ca) contents.

Additionally, 473 surface soil samples were collected from the study area and analyzed in the laboratory for the same properties. The purpose of the sampling was to collect two or three samples from each cell. Finally the coordinates were recorded for each sample.

Abundance Index. The AI of a species k is estimated as follows (Moeini et al. 2008):

$$AI_k = F_k + U_k + MFD_k.$$

F_k, U_k, and MFD_k stand for frequency, uniformity, and mean field density of a species k, respectively. More specifically, the uniformity (U_k) indicates the percentage of quadrats, whereas (F_k) indicates the percentage of fields infested by a species regarding the whole survey area. Finally, mean field density (MFD_k) indicates the weed density (weeds m^{-2}) and is here used in order to show the magnitude of the infestation in the survey area.

Nonspatial Analysis. The nonspatial statistical analysis included descriptive statistics (mean, maximum, standard deviation, coefficient of variation, skewness), and Spearman's rank correlation coefficients in order to examine the relationship between abiotic factors and weed occurrence. The SPSS version 18.0 statistical software package was used in order to conduct the nonspatial analysis tests. The associated two-tailed probabilities of the Spearman correlation values were calculated by taking into account the spatial information of the sampling sites, with the use of the MODTTEST Fortran program developed by Legendre (2000). The theoretical background was presented by Dutilleul (1993).

The observed differences of the meteorological data made it necessary to assess their effect on weed occurrence further. The sampling sites were separated into three groups, based on the distance from the three meteorological stations. Comparisons of means of weed densities of the three groups were performed with the use of one-way analyses of variance, by incorporating an autocorrelated error term through the use of generalized linear models. These tests were performed in *R* software, with the use of the *nlme* package (Pinheiro et al. 2011).

Spatial Outliers. Local indicators of spatial association (LISA), like local Moran, belong to the exploratory spatial data analysis (ESDA) techniques. It measures dependence in only a part of the whole study area, and identifies the autocorrelation between a single point and its neighboring ones in a specified distance from that point (Ping et al. 2004).

The local Moran's I can be used to study the spatial patterns of spatial association like local clusters and spatial outliers. When spatial outliers are detected for a variable, it means that they are differentiated by their neighboring values. Local Moran's I detects local spatial autocorrelation and breaks down Moran's I for each location, I_i (Anselin 1995). When a high negative value shows up for local Moran's I, then the studied sampling site is considered to be a spatial outlier, whereas the opposite (high positive value) means that the sampling site has similar values to the respective neighbors. Spatial outliers were defined with the use of the GIS software ArcMap ver 9.3.

Geostatistical Methods. Spatial variability concerning the studied perennial weeds for each year was described with the use of the semivariogram, whereas ordinary kriging and co-kriging were used for the weed interpolation mapping. Because in-depth discussion about geostatistical theory is given by Isaaks and Srivastava (1989) and Burrough and McDonnell (1998), only a short description of the geostatistical methods used will be given below.

The semivariogram of a variable does not only describe quantitatively the way in which the variable varies, but the semivariogram model also contains essential information for interpolation and hence for mapping regional distribution of the variable. The theoretical model is fitted to the experimental semivariogram with the use of spherical, gaussian, exponential, and other mathematical functions.

Ordinary kriging constitutes a spatial estimation procedure. It is the most commonly used type of kriging and assumes a constant but unknown mean that may vary among neighboring sampling sites within a study area. The accuracy of kriged estimates depends on the fitted semivariogram model.

Co-kriging was based on the ordinary kriging so as to improve the estimation of a studied variable by using information on other more densely recorded variables, which are spatially correlated to the first one. Co-kriging gives the best results in terms of theoretical foundation, because no assumptions are made on the nature of the correlation between the two variables. It exploits more fully the auxiliary information by directly incorporating the values of the auxiliary variable and measuring the degree of spatial association with the primary variable through the cross-variogram. A cross-variogram is considered positive when the values of the two variables have the tendency to vary jointly, whereas it is negative when the values of the two variables have the tendency to vary in opposite directions. Finally it is null when the two variables tend to vary independently.

Evaluation of the Spatial Interpolation Results. The performance of the interpolated methods was evaluated with the use of the cross-validation method, which involves the comparison of interpolated values at each data point with their corresponding observed values. Three statistical parameters were calculated (with the use of the cross-validation method): mean error (ME), root-mean-square error (RMSE) and standardized root-mean-square error (SRMSE). ME is a bias indicator of the prediction and should be close to zero for unbiased methods. It indicates whether the model-calculated estimates are overestimating or underestimating, compared to the observed values. The RMSE estimates the average precision of the prediction and should be as low as possible. It constitutes a sensitiveness indicator for the outliers (Nalder and Wein 1998). It is low when there is a central tendency and extreme errors are low. The best-performing model is the one that results in the lowest RMSE. The SRMSE values should be close to 1. When the SRMSE is greater than 1, then the variability of the predictions is underestimated, whereas when it is less than 1, it is overestimated. *R* software with *gstat* package (Pebesma 2004) was used for both variography and kriging analysis, and ArcMap (version 9.3.1) software was used for mapping the kriging results.

Results and Discussion

Nonspatial Analysis. *Perennial Weed Occurrence*. The recorded perennial weeds in cotton crops during the three study years were purple nutsedge, bermudagrass, field bindweed, and johnsongrass. During 2007 and 2008 mean field density (weeds m^{-2}) rank of the studied weeds was identical. Purple nutsedge was the most abundant weed, followed by field bindweed, bermudagrass, and johnsongrass in diminishing rank (Table 1), whereas field bindweed and bermudagrass densities were almost equal during 2009.

Purple nutsedge was also ranked first among the four studied perennial weeds, regarding the weed density, frequency, and uniformity showing its dominance in the cotton fields.

Weed Occurrence Stability over the Sampling Years. In order to assess the weed occurrence over the sampling years, a correlation analysis was conducted, taking into account the weed density and the uniformity per sampling site. The positive correlation coefficients regarding weed densities and uniformities ranged from 0.23 to 0.68 (Table 2), and the highest positive values were recorded between 2007 and 2008 purple nutsedge densities. Overall purple nutsedge, bermudagrass, and field bindweed densities and uniformities presented

Table 1. Frequency (F), uniformity (U), mean field density (MFD), and abundance index (AI) for the most important perennial weeds.

Weeds	2007 F	2007 U	2007 MFD	2007 AI	2008 F	2008 U	2008 MFD	2008 AI	2009 F	2009 U	2009 MFD	2009 AI
	%		shoots/m^2		%		shoots/m^2		%		shoots/m^2	
Purple nutsedge	85.15	66.14	3.04	154.32	82.50	62.50	3.02	148.02	87.06	60.24	3.47	150.76
Field bindweed	48.51	26.14	0.35	75.00	43.75	22.75	0.20	66.70	42.35	20.47	0.23	63.06
Bermudagrass	39.60	18.02	0.18	57.80	31.25	12.75	0.18	44.18	27.06	11.29	0.24	38.59
Johnsongrass	16.83	8.12	0.10	25.05	12.50	5.25	0.04	17.79	22.35	8.47	0.05	30.87

significant positive correlation coefficients ($P < 0.001$ or $P < 0.05$) over the studied years and sampling sites showing a stable occurrence. Similar results were obtained by Colbach et al. (2000), proving the perennials' spatial stability. Nordmeyer (2009) has also proved the temporal stability of silky windgrass [*Apera spica-venti* (L.) Beauv.] populations between seasons and the consistency of weed spatial occurrence, with the use of Spearman's correlation coefficient. On the other hand, johnsongrass presented significant correlation coefficients ($P < 0.05$) only between 2008 and 2009, indicating a weaker population consistency.

Weed Occurrence and Soil Properties Correlations. The statistically significant Spearman correlation coefficient values are presented in Table 3. Because the soil sampling was conducted in 2007, correlations between weed densities or uniformities and K, Na, Ca, and Mg were not estimated during 2008 through 2009, because these soil properties tend to vary year by year. The positive correlation coefficients between weed densities, uniformities per sampling site, and soil properties ranged from 0.20 to 0.43 in 2007, 0.27 to 0.33 in 2008, and 0.23 to 0.32 in 2009. The respective negative correlation coefficients ranged from −0.20 to −0.38 in 2007, −0.27 to −0.33 in 2008, and from −0.22 to −0.26 in 2009 (Table 3). The highest positive correlation was recorded in 2007 between field bindweed density, uniformity per sampling site, and clay, whereas the highest negative correlation was recorded between field bindweed density and sand in 2007.

Table 2. Density (D) and uniformity (U) Spearman correlation coefficients for all species and sampling years. 2007, 2008, and 2009 are the sampling years. Only statistically significant (P value below 0.05) correlation coefficient values are presented.

		2007 D	2007 U	2008 D	2008 U	2009 D	2009 U
Purple nutsedge							
2007	D						
	U						
2008	D	0.68	0.64				
	U	0.63	0.67				
2009	D	0.23					
	U		0.25		0.28		
Field bindweed							
2007	D						
	U						
2008	D	0.49	0.51				
	U	0.53	0.56				
2009	D	0.41	0.42	0.46	0.48		
	U	0.45	0.46	0.48	0.51		
Bermudagrass							
2007	D						
	U						
2008	D	0.38	0.38				
	U	0.38	0.39				
2009	D	0.32	0.30				
	U	0.33	0.31				
Johnsongrass							
2007	D						
	U						
2008	D						
	U						
2009	D			0.31	0.30		
	U			0.32	0.31		

Field bindweed populations were positively affected by clay during the three studied years, by CEC, organic matter, $CaCO_3$, and pH in 2007 and 2009, and by K and Mg in 2007. Sand was the only soil property that affected field bindweed populations negatively. A previous annual survey at the same region (Kalivas et al. 2010) showed a significant correlation between field bindweed densities and clay content, because the densities of this species were higher in fields with higher clay content. Gaston et al. (2001) conducted a survey in cotton fields, and observed that weed densities were greater in areas where soil texture was finer. The researchers surveyed a large number of species and they indicated a positive correlation between clay content and total weeds, due to more available water content. Additionally, field bindweed has been reported to show a preference to loamy soils (Hanf 1983).

Purple nutsedge populations were negatively correlated with pH, $CaCO_3$, K, and Mg in 2007 and with organic matter and clay in 2008 and 2009, and positively correlated with sand in 2008 and 2009. These correlations prove the demonstrated reverse spatial occurrence of these two species. More specifically, it was shown that in sampling sites where purple nutsedge was characterized by high populations, field bindweed respective populations were low and vice versa. Organic matter had a significant negative influence on purple nutsedge populations during 2008 and 2009, and a positive one on field bindweed populations during 2007 and 2009. Abiotic factors showed that they play a significant role in weed biology. More specifically, soil properties, such as soil texture, may affect weed occurrence in space and time significantly.

Finally, bermudagrass showed no statistically significant correlation, whereas johnsongrass presented only few correlations that were not steady in time. This result is probably due to very low densities of these two species. Similar explanations were provided by Walter et al. (2002) regarding the absence of correlation between catchweed bedstraw (*Galium aparine* L.) and big chickweed (*Cerastium fontanum* Baumg.) and the studied soil variables.

Effect of Climatic Conditions on Weed Occurrence. The compared densities showed no significant difference (*F*-test

Table 3. Spearman's rank correlation coefficients between soil attributes and weeds, for all sampling years. 2007, 2008, and 2009 are the sampling periods.[a]

Weeds	Year		Soil attributes											
			pH	$CaCO_3$	C	Organic mattter	Sand	Clay	Silt	Cation exchange capacity	Na	K	Ca	Mg
			%							meq/100 gr	ppm			
Purple nutsedge	2007	D	−0.20*	−0.20*								−0.26**		
		U	−0.24*	−0.24*				−0.23*	0.27**			−0.22*		−0.27**
	2008	D			−0.33**	−0.32**	0.27*	−0.31**						
		U												
	2009	D				−0.22*	0.28*							
		U				−0.23*	0.27*	−0.26*		−0.24*				
Field bindweed	2007	D	0.26**	0.23*	0.24*	0.23*	−0.38**	0.43**		0.28**		0.32**		0.20*
		U	0.28**	0.24*	0.25*	0.24*	−0.37**	0.43**		0.25*		0.34**		0.22*
	2008	D					−0.27*	0.29**						
		U					−0.30**	0.33**						
	2009	D	0.24*	0.23*	0.23*	0.25*		0.27*		0.30**				
		U	0.26*	0.25*	0.26*	0.29**	−0.25*	0.28*		0.32**				
Johnsongrass	2007	D							0.25*					
		U							0.24*					
	2009	D	−0.27*	−0.29**										
		U	−0.28**	−0.30**										

[a] D, density; U, uniformity.
*,** Statistically significant (P values below 0.001 and 0.05, respectively).

values from 0.003 to 0.218 and significance from 0.956 to 0.642, respectively) within the surveyed years. Furthermore, the densities of each group were compared between the 3 yr and no significant differences were observed (*F*-test values from 0.002 to 0.081 and significance from 0.965 to 0.776, respectively). The fact that climatic conditions did not affect weed occurrence could be attributed to cultivation techniques that may have covered their effect. On the other hand, Patterson (1995) has proved that environmental and especially meteorological effects play an important role on weed occurrence. The results suggest that climatic conditions don't play a key role in weed surveys that are conducted in irrigated crops.

Spatial Analysis. Purple nutsedge and field bindweed were selected for further spatial analysis, because these two species seemed to be the most important according to the studied parameters. Purple nutsedge was highly important in calculating total weed density as it contributed 83%, 88%, and 87% to the total weed densities during the years 2007, 2008, and 2009, respectively. High AI values suggested that the populations of these two species could have been affected by abiotic factors. At the same time the existence of a correlation between a species and abiotic factors (and more specifically with soil properties), was another factor that played a role in this selection. Table 3 shows that bermudagrass and johnsongrass densities and uniformities did not present any statistically significant correlation with abiotic factors that might have affected their growth or distribution.

The weed density spatial outliers are presented in Figure 2 only for purple nutsedge and field bindweed. Two, one, and four spatial outliers were detected for purple nutsedge in the 2007, 2008, and 2009 sampling years, respectively, whereas the respective ones for field bindweed were one, three, and one (Figure 2). The spatial outliers for both perennial weeds were situated in the limits of the study area except for the 2008 purple nutsedge spatial outlier.

Finally, a sampling site situated on the southeastern part of the study area was characterized as an outlier during the whole three study years concerning field bindweed. All the outliers were excluded from further analysis.

Based on skewness values, the studied weed densities did not follow normal distribution (Table 4). Because semivariograms are sensitive to skewed distributions, weed density data were logarithmically transformed after a constant value was added (0.001 for field bindweed, and 0.5 for purple nutsedge), the selection of which was based on normal distribution results. The skewness values range of the transformed data was −0.991 to 0.627. A Kolmogorov-Smirnov test indicated (not shown in Table 4) that all transformed variables were normally distributed.

Eight out of 11 studied soil properties were also logarithmically transformed, because they were not symmetrical. The sand, silt, and CEC descriptive statistics indicated that these properties follow a Gaussian distribution.

The four principal directions experimental variograms (0°, 45°, 90°, 135°) for the densities of the two species during the three study years are presented in Figure 3. All the directional sample variograms (for each variable) exhibit almost the same range and sill indicate the absence of anisotropy. This finding could be justified by the fact that the sampling area is a plain. Additionally, small-scale variations caused by harvest direction were not possible to record, owing to small-size farm holding and the distance between samples.

Therefore, the omnidirectional variograms were calculated. The purple nutsedge density autovariograms were based on 99, 79, and 83 sampling sites for the respective three sampling years. Furthermore, 100, 78, and 84 sampling sites were used for the estimation of the field bindweed density variograms. Soil properties autovariograms were based on analytical data from 590 samples, constituted by 117 weed–soil sampling sites and 473 soil sampling sites. The weed density and soil property autovariograms are presented in Figure 4, whereas significantly correlated cross variograms between soil properties and weeds appear in the same figure.

The weed density and soil property autovariograms showed normal spatial dependence, based on the nugget/sill ratio

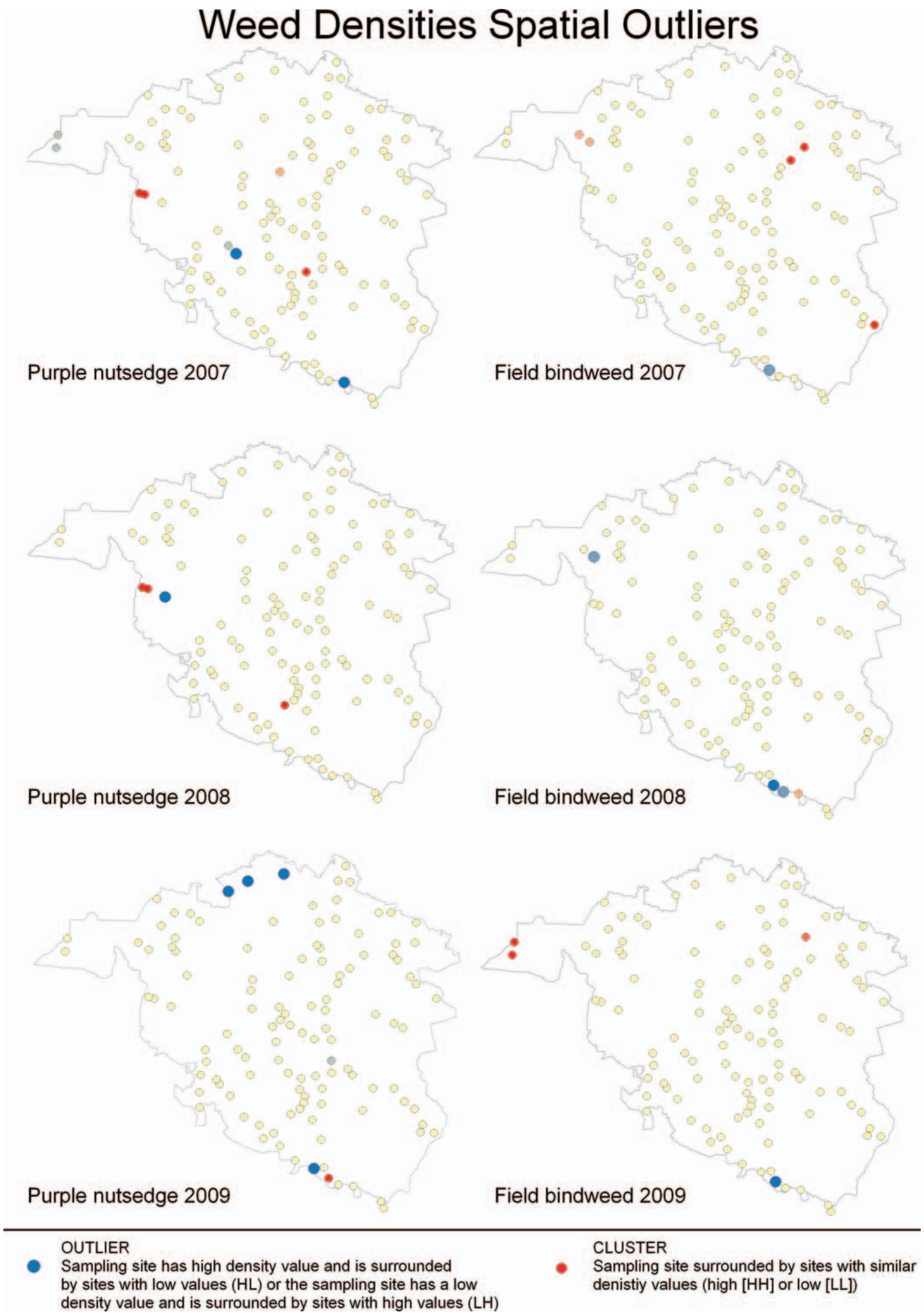

Figure 2. Anselin local Moran's I spatial outliers for field bindweed and purple nutsedge during the three sampling years.

values. The only exception was observed for *C. arvensis* autovariograms during 2007 and 2009, which were characterized by strong spatial dependence. In fact, the difference between sill and nugget shows the spatial distribution magnitude (Isaaks and Srivastava 1989) that could easily be assessed by the nugget/sill ratio. If this ratio is 25% or less the spatial dependence is considered strong, when it is between 25 and 75% the spatial dependence is normal, and, finally, when it is more than 75% the spatial dependence is characterized as weak (Cambardella et al. 1994; Chien et al. 1997). Among the soil properties, clay showed the strongest spatial variability (nugget/sill = 26.45%) with a lag size of 1,400 m and range equal to 8,471 m. The lag size of the weed autovariograms varied from 1,150 to 1,500 m and 1,000 to 1,500 m for soil properties.

The spatial cross correlation between purple nutsedge and clay was negative, and it appeared positive between field bindweed and clay. Generally, positive values of the Spearman correlation coefficients between weeds and soil properties determined positive spatial cross-correlations, whereas negative correlation coefficients are related to negative cross-correlations.

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Table 4. Weed density (weeds m^{-2}) descriptive statistics.

Year	Variable	Sampling sites	Maximum	Mean	SD	Skew	Skew1[a]
2007	Purple nutsedge	99	13.00	2.84	2.750	1.256	−0.293
	Field bindweed	100	3.80	0.33	0.692	3.395	0.294
2008	Purple nutsedge	79	27.16	3.05	4.536	3.488	0.220
	Field bindweed	78	2.32	0.18	0.354	3.530	0.627
2009	Purple nutsedge	83	23.32	3.28	4.581	2.627	−0.991
	Field bindweed	84	4.76	0.20	0.602	5.789	0.627

[a] Skew1, skewness of log-transformed variables after adding a constant value (0.001 for field bindweed, and 0.5 for purple nutsedge).

The co-kriging results based on the theoretical fitted models (Figure 4) were evaluated through the ME, RMSE, and SRMSE values. In all the 23 cross-variograms the mean estimation error decreased, compared to the corresponding kriging results. All SRMSE values diminished compared to those of ordinary kriging. The biggest differences (13.3%) appeared in co-kriging results of field bindweed 2009–clay cross-variograms, followed by field bindweed–2009, with pH (13.0%), organic matter (12.8%), and CEC (12.2%) as covariables. Better improvements in co-kriging SRMSE values would be achieved if the covariable had been measured in thousands of points, just like it was accomplished by other researchers in the past with the use of a digital elevation model. (Jurado-Expósito et al. 2009).

The kriging and co-kriging (using clay as ancillary data) interpolated maps for field bindweed and for each of the 3 yr are presented in Figure 5. Kriging and co-kriging values were transformed back to the original scale in order to create the maps. High densities occurred in the eastern part, along the limits of the survey area, whereas low densities were recorded in the central and southern part of it. In contrast, the spatial distribution results showed that higher densities of purple nutsedge were observed in the center of the study area (the corresponding map is not presented here).

The inverse distance weighting (IDW) interpolation method gave similar results for field bindweed (Kalivas et al. 2010). Overall, when abiotic factors were used to create interpolated weed maps, map precision was improved.

It should be considered that the spatial techniques helped in mapping the most important weeds in cotton, and in achieving crucial conclusions regarding the persistence of the studied weed species. The present study managed to identify threatened regions rather than specific locations by focusing on abiotic-factor variation at a regional scale. It was shown that weed species vary markedly in their spatial distribution, because of different conditions.

Regional mapping provides accurate and up-to-date information on weed locations. It depicts weed distribution and densities that determine changes in infestations over time. Furthermore, regional mapping data can be essential to early and effective detection of current weed growth, which could constitute the basis in deciding about future surveys. Maps like the ones presented in this article could help in identifying areas where direct (accurate application of a broad-spectrum herbicide) or indirect (crop rotation, cultivation technique, etc.) weed management strategies are critical, in order to control the populations of species that seem to exceed a predefined economic threshold. Based on regional weed distribution information,

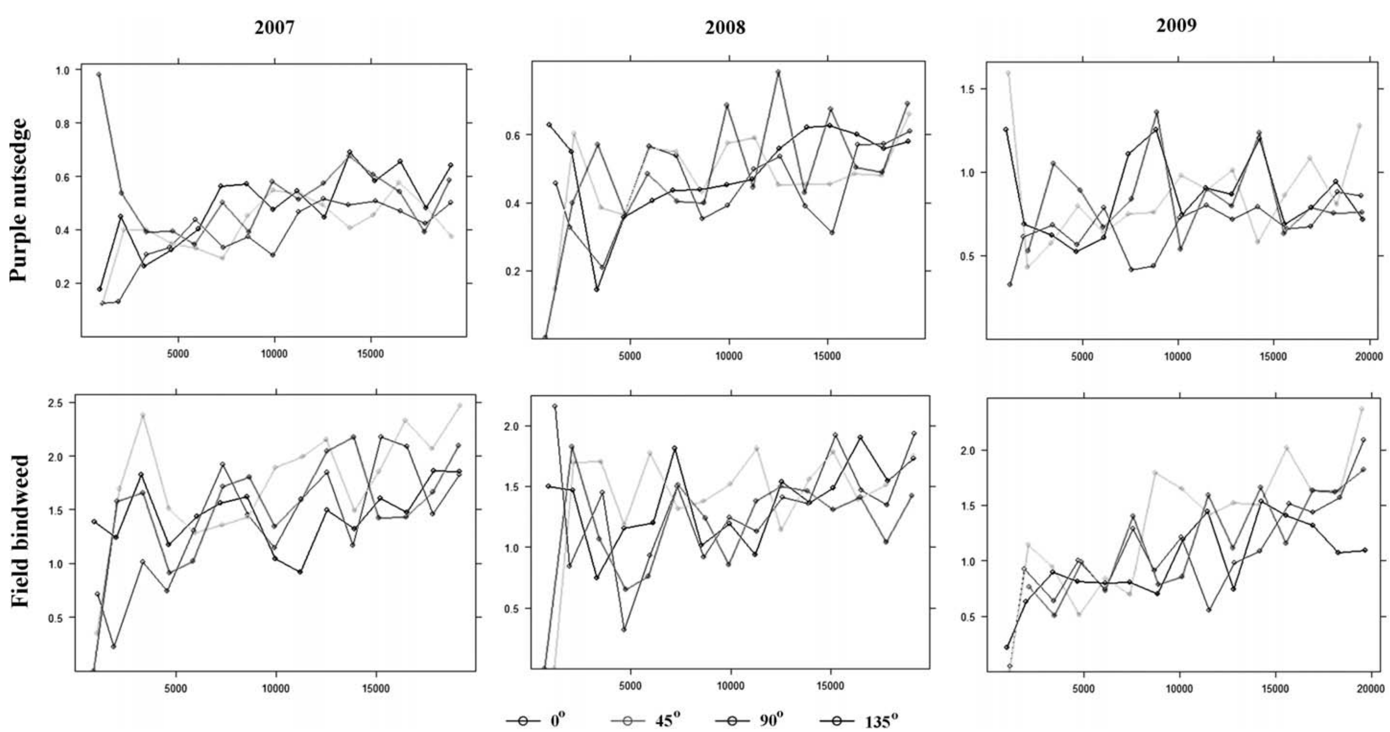

Figure 3. Directional variograms for field bindweed and purple nutsedge during the three sampling years.

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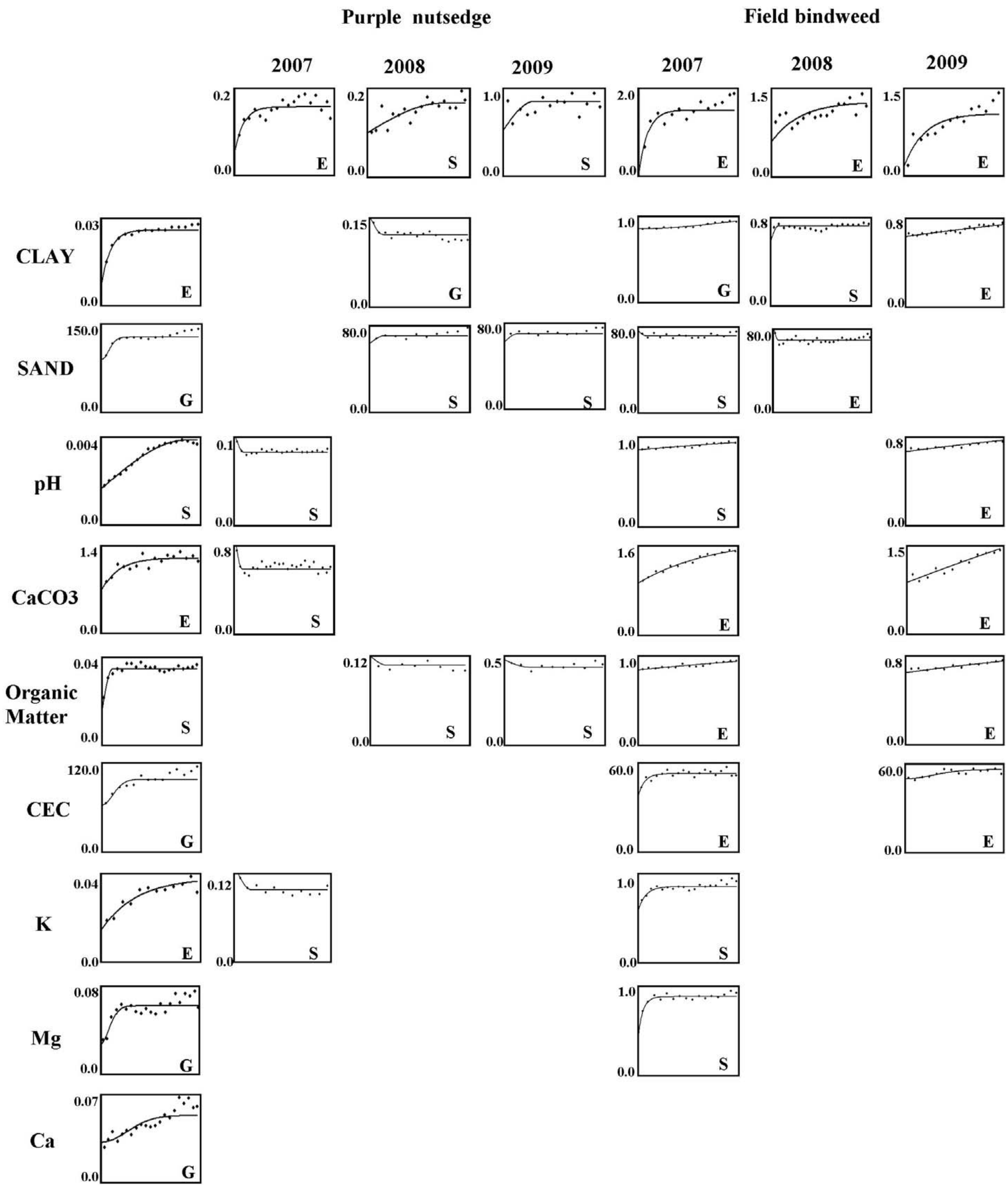

Figure 4. Auto- and cross-semivariograms for all weed species and soil properties. S, E, and G stand for spherical, exponential, and gaussian theoretical fitted models, respectively.

weeds may be categorized into emerging and widespread, which makes the control method development more effective from an agronomic and economical point of view. In particular, the priority for emerging weeds must be to prevent their establishment, eradicating them where possible, and thus halting their spread. On the other hand, the priority for widespread weeds should be based on weed assessment results, especially where sites of high conservation significance are under threat.

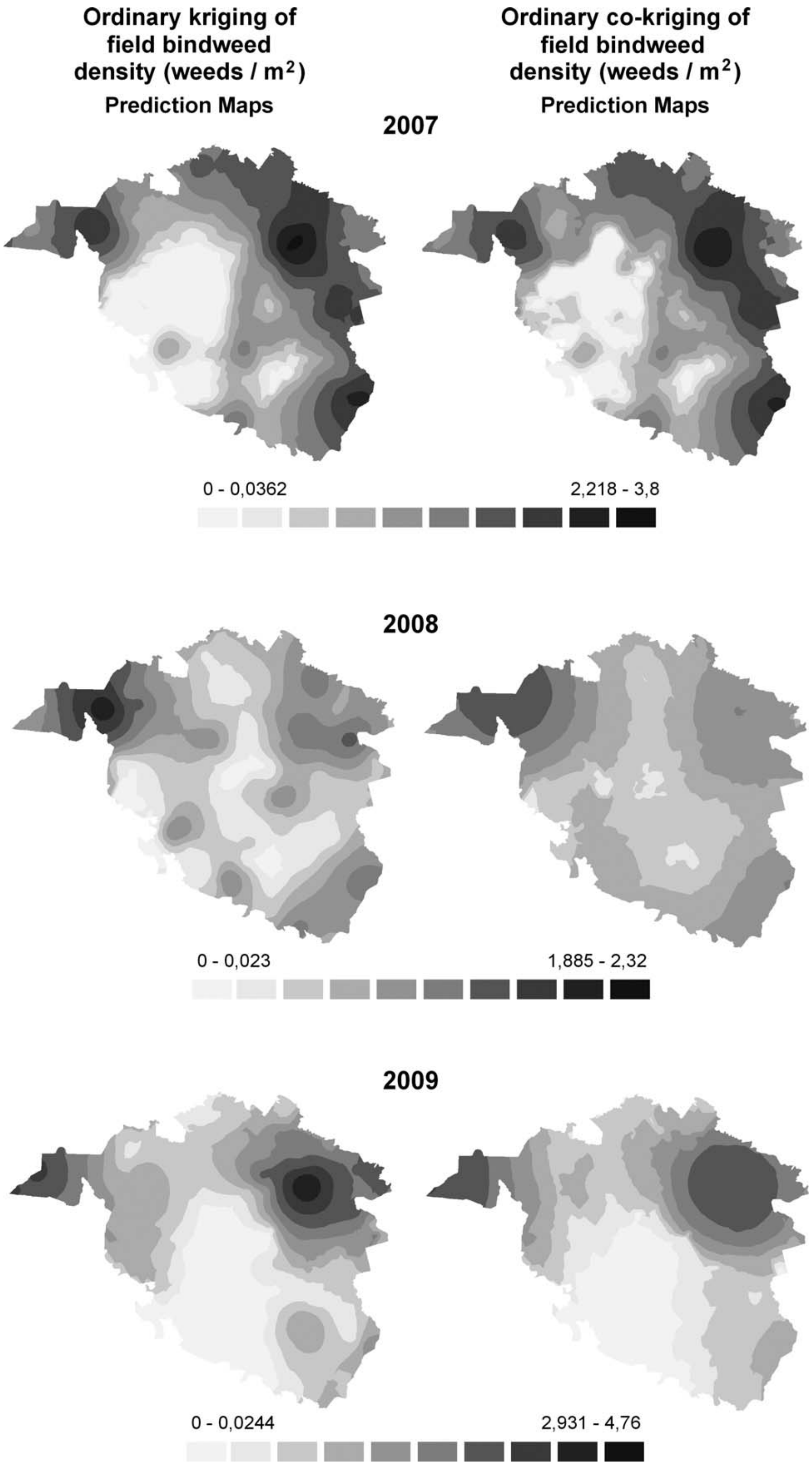

Figure 5. Interpolated maps of field bindweed density with the use of ordinary kriging and co-kriging for the 3 yr.

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Surveying and planning actions will assist agencies to focus on integrated management in areas where biodiversity sustainability is of major importance, and increase farmers' technical skills toward a more holistic evaluation of the problem. The technique described by this study could be used for weeds of other crops or invasive species that threaten an area, and could thus help toward developing management strategies. Large geographic areas are always the limiting factor in weed mapping. Furthermore, conventional weed mapping techniques are expensive, time consuming, and hard to repeat over time.

All in all, the proposed technique could be considered a simple approach that does not require specific technical knowledge on predictive models and can be applied in any region. The regional weed mapping standard can be used to ensure regional consistency, which will assist in determining control site priorities and will provide a basis for monitoring results of control.

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