Spatial Distribution Patterns of Weed Communities in Corn Fields of Central Spain

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The overall objective of this study was to identify common patterns in the spatial distribution of the major weed species present in the corn-growing region of central Spain, exploring the scale dependence of these patterns and the possible associations or dissociations between individual species. Weed density was assessed in 16 commercial fields using digital images acquired in a 9-m by 9-m sampling grid. A set of six species was found in all the fields: black nightshade, common cocklebur, fierce thornapple, johnsongrass, purple nutsedge, and velvetleaf. Spatial analysis by distance indices and inverse distance weighting interpolation methods were performed to create weed distribution maps. The results showed aggregated spatial distribution patterns for all individual species regardless their life cycle, annual or perennial. Some associations and dissociations among species were found in the analysis of interactions. Nevertheless, the spatial patterns of co-occurrence of weed species were field-specific and therefore cannot be considered general patterns of weed co-occurrence. In order to explore the scale dependence of these results, an additional study was conducted in an experimental field located in the same area using a 1.0-m by 0.75-m sampling grid. Although this resolution allowed for a better definition of the positions of the weed patches and weed-free gaps, the results obtained revealed similar patterns to those observed with a coarser sampling resolution.
Nomenclature: Black nightshade, *Solanum nigrum* L. SOLNI; common cocklebur, *Xanthium strumarium* L. XANST; fierce thornapple, *Datura ferox* L. DATFE; johnsongrass, *Sorghum halepense* (L.) Pers. SORHA; purple nutsedge, *Cyperus rotundus* L. CYPRO; velvetleaf, *Abutilon theophrasti* Medik. ABUTH; corn, *Zea mays* L.
Key words: Aggregation indexes, site-specific weed management, species association/dissociation.

The concept of site-specific weed management (SSWM) is based on the assumption that weeds are aggregated in patches. This assumption has been proved for various weed species in different crops and sites (Cardina et al. 1995, 1997; Heijting et al. 2007; Johnson et al. 1996; Mortensen et al. 1993). Within a given field, a variety of species compose the weed community. Each of these species may have different distribution patterns. These patterns could result from agronomic management (e.g., herbicide gaps), environmental heterogeneity, or competitive exclusion or facilitation processes among species, or a combination of these factors (Cardina et al. 1997). The co-occurrence (either aggregation or segregation) among weed species at the field scale has only been studied in a few cases (Borgy et al. 2012; Petit and Fried 2012). Knowledge of the spatial pattern of the weed communities occurring in a field could have a practical value. Considering the spatial pattern

of weeds, and taking into account the selectivity of each active ingredient for each individual species or group of species (e.g., grasses vs. broad-leaved weeds), it could be possible to adjust herbicide treatments to the specific composition at each point of the field (Gutjahr et al. 2012).

Weed species may exhibit different spatial patterns when viewed at different spatial resolutions. In fact, studies conducted with different sampling resolutions have produced different results (Berge et al. 2007; Cousens et al. 2002, 2004; Heijting et al. 2007). This scale dependence may have important practical implications. Optimizing the spatial resolution of weed detection has been the subject of numerous studies (Barroso et al. 2004; Berge et al. 2007; Cousens et al. 2002; Rew et al. 1997). Since a finer sampling resolution involves a significant additional cost (Barroso et al 2004), the degree of discrepancy in spatial distribution patterns between high and low resolutions should be explored. Ultimately, the herbicide savings that could be obtained for a given field will depend on its weed spatial pattern, the weed threshold criteria used in decision making, and the spraying resolution.

Various methods have been used to quantify spatial patterns in ecological data (Perry et al.

2002). Some of these techniques have been developed using global positioning system (GPS) and geographic information system software in order to obtain a continuous map from sampling points. The reliability of maps obtained by kriging, a common interpolation technique, increases with the number of samples used within a given area (Zanin et al. 1998), that is, a finer sampling resolution. Other types of spatial analysis tools are also based on distance indices. Spatial analysis by distance indices (SADIE) uses a simple methodology that allows quantifying the spatial pattern of a variable under study, detecting local "clusters" of the variable, and quantifying the degree of spatial association or dissociation between pairs of variables (Quero 2006). A cluster is referred to as a region of either relatively large counts close to others in a two-dimensional space (i.e., a patch), or of relatively small counts (i.e., a gap) (Perry et al. 1999). This method has previously been used in studies of insect distribution patterns (Winder et al. 2001), the spatial pattern of surface soil properties (e.g., crusts, rock fragments, belowground stone content) (Maestre and Cortina 2002), and the spatial pattern of survival of mastic tree (*Pistacia lentiscus* L.) (a Mediterranean native shrub) seedlings (Maestre et al. 2003). In weed science these methods have been used to compare the spatial pattern of weed distribution in conventional no-tillage and organic systems in spring wheat fields (Pollnac et al. 2008), as well as to analyze the spatial distribution pattern of crenate broomrape (*Orobanche crenata* Forsk.) in crop fields (Oveisi et al. 2010).

The aims of this study were to identify common patterns in the spatial distribution of weeds, verify the absence of a scale effect in the different spatial patterns observed, and explore the possible associations or dissociations between individual species present in the corn-growing region of central Spain. We assessed the spatial patterns of weed communities in 16 intensively managed corn fields using regular 9-m grids, contrasting these patterns with those obtained in an experimental plot using a finer sampling resolution (1.0-m by 0.75-m grid). Our hypothesis was that the aggregation patterns and the co-occurrence of weed species are independent of the agronomic management of the fields and of the sampling resolution used to describe weed spatial distribution. To test this hypothesis, we first analyzed the pattern of aggregation of individual species at both scales using SADIE distance indices and maps showing gaps and patches. We expected annual species to be more evenly distributed than perennial species as the latter are more constrained by dispersal processes. In addition, we determined whether the spatial relationship between pairs of weed species fits an associated or disassociated pattern using SADIE association indices and maps. Finally, we investigated how sampling resolution affects the measured spatial structure of weed vegetation.

Materials and Methods

Study Area and Data Collection. *Farmers' Fields.* Weed density data were collected in 16 commercial fields located in four different farms (four fields at each farm) in the Jarama Valley (Madrid, central Spain). All the farms were located within 30 km of each other (Añover: 39.95°N, 3.77°W; Arganda: 40.33°N, 3.47°W; Morata: 40.22°N, 3.43°W; Villamanrique: 40.06°N, 3.25°W). Corn was grown following similar production practices in all fields (0.75-m interrow area), with similar herbicide programs and irrigation systems (Table 1).

Data collection was performed in May 2011, when corn was at the three- to five-leaf stage and weeds were at the two– to five–true-leaf stage. Sampling was conducted on a rectangular area in the center of each field. Digital images were taken at the intersection of each 9-m by 9-m area, with a sampling quadrat of 0.5 m by 0.75 m placed between crop rows, the longer side of quadrats coinciding with the width of the interrow. The geolocation of each quadrat was obtained with a differential GPS receiver. Each field was a different size, thus the sampling area (ranging between 0.5 and 2 ha) and the number of sampling points (ranging from 132 to 249) were different in each field (Table 1). Weed species were identified and counted in all the digital images obtained from each sampling point across all the fields. Weed densities per quadrat were plotted according to their position within the field. This map, generated from the raw data, was used as the basis for further analysis.

Research Station Field at La Poveda. In order to study the spatial pattern with a finer sampling resolution we conducted an additional experiment on a 41.0-m by 10.5-m plot located within a 4-ha corn field at La Poveda Experimental Field in Arganda, Madrid, Spain (40.31°N, 3.49°W). This location is within the same region as the 16 farmers' fields. Corn had been grown continuously during the previous 9 yr and the agronomic management was conventional to the area (tillage and sprinkler

Table 1. Field location, sampled field size (ha), number of sampling points (sampling quadrats of 0.5 m by 0.75 m) and management practices (herbicide treatments and irrigation system) in the commercial fields studied (9-m by 9-m sampling grid) and the experimental plot La Poveda (1.0-m by 0.75-m sampling grid).

Location	Field	Field size	No. of sampling points	Irrigation system	Herbicide treatments
Villamanrique	1	1.55	215	Sprinkler	PRE: mesotrione 0.12 kg ai ha^{-1} +
Villamanrique	2	1.52	166	Sprinkler	S-metholachlor 1.2 kg ai ha^{-1} (Camix, Syngenta,
Villamanrique	3	0.73	207	Sprinkler	Madrid, Spain, http://www3.syngenta.com/country/es)
Villamanrique	4	0.93	211	Sprinkler	POST: mesotrione 0.12 kg ai ha^{-1} +
					S-metholachlor 1.2 kg ai ha^{-1}
					(Camix, Syngenta, Madrid, Spain)
Morata	5	0.77	181	Sprinkler	A rain just after herbicide
Morata	6	0.98	204	Sprinkler	application, decreasing its effectiveness
Morata	7	0.77	198	Surface	PRE: mesotrione 0.15 kg ai ha^{-1}
Morata	8	0.57	192	Surface	(Callisto, Syngenta, Madrid, Spain)
					POST: nicosulfuron 0.045 kg ai ha^{-1}
					(Elite, Syngenta, Madrid, Spain)
Añover	9	1.68	195	Surface	Data obtained before applying the herbicide, usually:
Añover	10	1.87	235	Surface	PRE: mesotrione 0.12 kg ai ha^{-1} +
Añover	11	1.95	249	Surface	S-metholachlor 1.2 kg ai ha^{-1} (Camix, Syngenta,
Añover	12	1.64	199	Surface	Madrid, Spain)
					POST: nicosulfuron 0.045 kg ai ha^{-1}
					(Elite, Syngenta, Madrid, Spain)
Arganda	13	0.98	217	Sprinkler	PRE: isoxaflutole 0.100 kg ai ha^{-1}
Arganda	14	0.50	167	Sprinkler	(Spade, Bayer Crop Science, Paterna,
Arganda	15	0.44	132	Sprinkler	Valencia, Spain, http://www.bayercropscience.es)
Arganda	16	0.57	157	Sprinkler	POST: thifensulfuron 0.015 kg ha^{-1}
					(Harmony, Dupont, Barcelona, Spain,
					http://www.dupont.es) + rimsulfuron 0.030 kg ha^{-1}
					(Titus, Dupont, Barcelona, Spain)
La Poveda	17	0.043	574	Sprinkler	No herbicide treatment in the year of study

irrigation). Although the field had received herbicide treatments during the previous years, no herbicides were applied in the study year in order to avoid interference with the actual spatial distribution of weed species.

Data collection was performed on digital images acquired on May 2011, with corn plants at the three- to five-leaf stage. A total of 574 digital images were taken at the intersection of each 1.0-m by 0.75-m grid, with a sampling quadrat of 0.5 m by 0.75 m placed between crop rows, the longer side coinciding with the width of the interrow. The geolocation data of the quadrats was provided by a differential GPS receiver. As in the previous case, the density of all the weed species was visually assessed in each image obtained from each sampling point, plotting these data according to their position within the field.

Data Analyses. Various spatial analyses were conducted using the SADIE statistical method (Perry 1998; Perry et al. 1999) in order to describe the spatial patterns of the different weed species. The basis of SADIE for spatially referenced sampling units is to quantify pattern by the total distance that individuals must be moved between sampling units so that the data are as regular as possible. The degree of nonrandomness is quantified by comparing the distance to regularity for the observed data set (D) with distance to regularity for rearrangements of the observed data (E_a). Therefore, the index of aggregation (I_a) is defined as $I_a = D/E_a$, where D is the minimum total distance that individuals in an observed arrangement would need to move to accomplish the same value in each sample unit, and E_a is the arithmetic mean distance to regularity based on several randomizations of the data (Perry 1998). A value of $I_a \leq 1$ suggests the spatial pattern of weed density is random, whereas a value of $I_a > 1$ indicates aggregation of the counts into clusters. The formal randomization test (Perry 1998) of the null hypothesis that the observed counts were arranged randomly within the experimental area was used to calculate the associated probability (P_a) from a total 912,951 permutations in randomizations.

In addition, a clustering index (v) showing the spatial pattern for each weed species in each field was calculated (Perry and Dixon 2002). This index quantifies the contribution of each sampling point to the overall degree of clustering, either as part of a patch (subscript i), or gap (subscript j), or neither.

The clustering index discriminates values as those contributing to patches, $V_i = Y_i Y_o / Y_i Y_c$, and to gapping, $V_j = Y_j Y_o / Y_j Y_c$, with Y_i and Y_j being the average distance from units i and j, weighted by the magnitude of each individual flow; Y_c the expected value of the average flow distance for the observed sampling point c; and Y_o the expected value of the overall average absolute distance of flow for all points and counts in the randomizations (Perry et al. 1999). A sampling point belonging to a patch is indicated by a value of $V_i > 1$, whereas a gap is indicated by points with values of $V_j < -1$ (Perry and Dixon 2002). The usual (and arbitrary) limit for considering values as significant are $V_i = 1.5$ and $V_j = -1.5$.

Furthermore, the possible association/dissociation between pairs of weed species was assessed. SADIE provides an overall spatial association index (X), which indicates the degree of association between two data sets (e.g., two weed species, 1 and 2) with same geographical coordinates. Denoting v_{k1} and v_{k2} the clustering indices of data sets 1 and 2, respectively, the measure of local spatial association (X_k) for unit k is calculated by

$$X_k = \left[n \left(v_{k1} - q_1 \right) \left(v_{k2} - q_2 \right) \right] \Big/ \sqrt{ \sum_k \left(v_{k1} - q_1 \right)^2 \sum_k \left(v_{k2} - q_2 \right)^2 } \qquad (1)$$

where q_1 is the mean of v in species 1, q_2 the mean of v for species 2, n is the number of sampling units (574 in this study) and $k = 1, \ldots, n$. The overall spatial association is the mean of these local values, $X = \Sigma_i X_i / n$; that is, a simple correlation coefficient between the clustering indices of each dataset (Perry and Dixon 2002). A positive value of X indicated a gap or patch matching in the two data sets and, therefore, a positive correlation or association. A negative value of X means that a patch of a data set coincides with a gap of the other data set and, therefore, a negative correlation or dissociation existed. The higher the X value, the greater the association. To estimate the significance of the correlations between X values, SADIE performs a permutation test considering two-tailed significance and a 0.05 significance level (Perry and Dixon 2002; Winder et al. 2001). For each pair of species we tested the null hypothesis that the spatial distribution was random (i.e., no association).

The aggregation and association analyses for each weed species were performed only in those fields showing an average density above 1 seedling plant m^{-2} (Table 2) or where spatial dependence based on semivariogram models was observed (data not shown). Aggregation analysis (i.e., I_a, V_i and V_j) of weed species was performed by SADIEShell v.2.0 free software. Association indices (i.e., X and X_i) were calculated with N_AShell v.1.0 free software (http://home.cogeco.ca/~sadiespatial/index.html). Maps with gaps and patches were constructed with ArcGIS® 10.1 software (ESRI, 380 New York Street, Redlands, CA), in which the inverse distance weighting (IDW) interpolation method with a power coefficient of $p = 2$ was used, based on V_i and V_j values. Only significant patches ($V_i > 1.5$) and gaps ($V_j < -1.5$) were depicted. Similarly, an IDW interpolation method was used to obtain maps representing areas where association or dissociation happen, based on X_i values. Association or dissociation areas were depicted when the X_i value was $X_i > 0.5$ or $X_i < -0.5$ respectively.

Results and Discussion

Weed Species Composition. Although there was a diversity of species throughout the 16 commercial fields, our analysis included only those species that were common across all the locations (farms). The six common species were black nightshade, common cocklebur, fierce thornapple, johnsongrass, purple nutsedge, and velvetleaf, and appeared with different densities in the different fields (Table 2). In Villamanrique fields (1 to 4), all the species were present at very low densities due to the intensive herbicide program used in this farm. In Morata fields (5 to 8), two species (common cocklebur and johnsongrass) prevailed over the remaining weeds. In Añover fields (9 to 12), black nightshade, johnsongrass, and velvetleaf were abundant because herbicides had not yet been applied at the time of sampling. In Arganda fields (13 to 16), fierce thornapple and purple nutsedge were dominant. These results suggest the effect of weed management on the composition of the weed community. For instance, johnsongrass was mainly found in fields 7 to 12, all of them under flood irrigation (Tables 1 and 2); the highest densities of velvetleaf corresponded to fields 9 to 12, where no herbicide was applied during that year.

In the experimental plot assessed in La Poveda, a large number of weed species (common cocklebur, fierce thornapple, johnsongrass, and velvetleaf) were present at high densities (Table 2) due to the long history (9 yr) of continuous corn and due to the fact

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Table 2. Mean number of seedling plant m^{-2} ± standard deviation of velvetleaf (ABUTH), purple nutsedge (CYPRO), fierce thornapple (DATFE), black nightshade (SOLNI), johnsongrass (SORHA), and common cocklebur (XANST) in each farmers' field and research station field in 2011.

Field[a]	ABUTH[b]	CYPRO[c]	DATFE[b]	SOLNI[b]	SORHA[c]	XANST[b]
1	0.0 ± 0.3	0.1 ± 0.7	16.6 ± 15.7	0.0 ± 0.0	3.0 ± 8.0	0.0 ± 0.5
2	0.0 ± 0.4	0.3 ± 1.4	3.7 ± 6.9	0.0 ± 0.4	2.6 ± 4.5	1.2 ± 6.4
3	0.0 ± 0.0	1.0 ± 3.0	14.5 ± 22.3	0.0 ± 0.0	6.3 ± 11.0	11.3 ± 24.5
4	2.8 ± 4.7	0.0 ± 0.0	9.5 ± 13.9	0.1 ± 0.7	4.7 ± 6.3	0.0 ± 0.3
5	2.3 ± 4.0	0.0 ± 0.4	5.0 ± 8.7	1.8 ± 4.9	8.7 ± 14.8	9.6 ± 25.4
6	15.4 ± 24.1	0.3 ± 1.9	8.6 ± 19.2	0.7 ± 2.3	1.7 ± 4.8	8.2 ± 12.0
7	1.1 ± 2.6	0.0 ± 0.4	0.1 ± 0.5	1.5 ± 3.7	18.8 ± 22.4	57.0 ± 47.8
8	3.9 ± 11.1	0.2 ± 2.6	0.2 ± 1.2	0.8 ± 2.8	29.3 ± 25.4	141.2 ± 104.8
9	129.9 ± 94.7	0.4 ± 2.0	0.1 ± 1.4	144.7 ± 88.4	13.8 ± 34.2	0.0 ± 0.4
10	55.1 ± 93.3	0.1 ± 1.2	13.1 ± 27.8	75.9 ± 63.0	14.0 ± 27.0	0.1 ± 0.7
11	39.4 ± 53.2	1.3 ± 5.2	2.8 ± 5.7	65.3 ± 54.6	18.2 ± 24.0	2.9 ± 20.5
12	20.6 ± 30.7	0.4 ± 1.4	9.3 ± 12.0	12.7 ± 13.2	10.0 ± 16.8	5.4 ± 10.3
13	9.3 ± 15.6	8.9 ± 22.0	24.8 ± 23.8	21.0 ± 25.2	8.6 ± 14.6	21.4 ± 29.2
14	0.1 ± 0.7	1.3 ± 4.3	97.0 ± 55.5	3.1 ± 5.2	7.7 ± 17.1	19.0 ± 17.9
15	5.7 ± 14.6	1.9 ± 4.1	4.9 ± 8.3	2.1 ± 5.1	5.9 ± 14.5	2.3 ± 4.4
16	0.0 ± 0.0	7.1 ± 15.3	33.0 ± 42.3	10.6 ± 14.0	10.4 ± 19.9	3.6 ± 6.1
La Poveda	35.0 ± 26.1	1.5 ± 2.6	157.5 ± 52.2	3.8 ± 4.4	12.9 ± 15.7	23.8 ± 18.1

[a] See the reference to the location of each field in Table 1.
[b] Annual species.
[c] Perennial species.

that no herbicide was applied to the sampled area in this year.

Spatial Aggregation Patterns. All weed species showed aggregated patterns in the 16 farmers' fields, with varying degrees of significance according to SADIE analysis (Table 3). Considering only the fields where the aggregation analysis was performed (i.e., those with average density above 1 seedling plant m^{-2} or spatial dependence or both), purple nutsedge was aggregated significantly (P < 0.05) in 100% of the fields. This high aggregation is consistent with the results reported in a previous study (Roham et al. 2014). Perennial species have, generally, more aggregated distribution than annual species (Colbach et al. 2000). In the specific case of purple nutsedge, subterranean tubers produced in the neighborhood of the mother plant are likely to produce clearly defined patches. However, in the case of johnsongrass our results do not confirm this trend as a perennial, but johnsongrass spreads both by rhizomes and seed. Although previous studies showed an aggregated pattern of johnsongrass distribution (Andújar et al. 2011, 2012), in this study johnsongrass showed the lowest values of aggregation and the least number of fields with a significant index of aggregation (64% of the infested fields). Two factors may have been involved in this result. On the one hand, the presence of low densities of johnsongrass over large areas between patches may have limited the reliability of SADIE analysis. On the other hand, although rhizomes are the primary method of johnsongrass reproduction and dispersal, the dispersion by seeds is also significant (Mitskas et al. 2003). In fact, Barroso et al. (2012) showed that natural dissemination of johnsongrass seeds as well as the effect of combine harvesting on this process may have a significant effect to a less aggregated distribution of this species.

Regarding annual weed species, aggregation indices of velvetleaf, fierce thornapple, black nightshade, and common cocklebur were significant in more than 80% of the fields where the aggregation analysis was conducted. Velvetleaf, fierce thornapple, and black nightshade have already been reported to have an aggregated distribution (Calha et al. 2014; Dieleman and Mortensen 1999; Wallinga et al. 2002). Seed shape, size, and dehiscence time influence seed dispersal and, consequently, plant distribution (Aligner and Petit 2012). For instance, common cocklebur has fruits with glandular hairs that attach themselves to animals or other objects that facilitate their dispersal (Weaver and Lechowicz 1982). In species such are fierce thornapple or velvetleaf, with a large proportion of the seeds remaining on the plant at harvest time, dispersal pattern is mainly related to

Table 3. Aggregation index values (I_a) for velvetleaf (ABUTH), purple nutsedge (CYPRO), fierce thornapple (DATFE), black nightshade (SOLNI), johnsongrass (SORHA), and common cocklebur (XANST) in each farmers' field and research station field in 2011. Significant I_a values with a probability level of 95% are marked in bold.

Field[a]	ABUTH[b]	CYPRO[c]	DATFE[b]	SOLNI[b]	SORHA[c]	XANST[b]
1	—[d]	—	**1.37**	—	**2.85**	—
2	—	—	—	—	**1.86**	—
3	—	**2.93**	2.42	—	1.40	**3.63**
4	**4.52**	—	**2.81**	—	**2.89**	—
5	**3.00**	—	1.21	—	0.99	**2.85**
6	**2.17**	—	**1.61**	**1.88**	1.21	**2.82**
7	**3.25**	—	—	**3.27**	—	**3.14**
8	—	—	—	1.10	**1.58**	**4.41**
9	**2.12**	—	—	**3.39**	**2.07**	—
10	**2.14**	—	**2.95**	**4.69**	1.59	—
11	**4.94**	—	**2.08**	**2.69**	**3.12**	—
12	**3.38**	—	**2.76**	**1.72**	**1.62**	**1.78**
13	**7.15**	**2.95**	**3.60**	**2.69**	**3.07**	**4.06**
14	—	**3.13**	**3.66**	—	**2.67**	1.47
15	**4.56**	**1.68**	**2.43**	**2.03**	—	**2.24**
16	—	**1.99**	**2.55**	1.38	**1.38**	1.28
La Poveda	**3.14**	**1.92**	**4.94**	**1.84**	**1.61**	**3.41**

[a] See the reference to the location of each field in Table 1.
[b] Annual species.
[c] Perennial species.
[d] Dashes indicate that the analysis was not performed because the average density was less than 1 seedling plant m^{-2} or no spatial dependence was observed.

the direction of combine operations (Ballaré et al. 1987).

In the experimental plot in La Poveda, with a finer sampling resolution, the clustering maps showed with considerable detail the position of patches and gaps (Figure 1). Velvetleaf and common cocklebur showed well-defined patterns, with relatively large patches at a right and central position and gaps at the left side of the field. These two species had medium to high values for both aggregation index (3.1 to 3.4) and density (23.8 to 35.0 seedling plant m^{-2}). In contrast, the area occupied by patches and gaps of black nightshade was substantially lower, coinciding with a lower aggregation index (1.8); this was associated with the presence of numerous low-density areas for this species (on average, 3.8 seedling plant m^{-2}). The two perennial weeds (purple nutsedge and johnsongrass) presented several small patches distributed throughout the plot and a few clearly defined gaps in the right side of the field. These results were consistent and confirmed those obtained in farmers' fields, but in addition they provided a higher spatial detail. However, some limitations have been detected in the use of SADIE to conduct the spatial analysis. For example, in some species distributed over the entire field (e.g., fierce thornapple), the SADIE aggregation index showed gaps in areas where seedling density was low, but not zero. This is in agreement with previous studies (Li et al. 2012; Xu and Madden 2003).

Considering that the common agricultural practice in the area is to spray a herbicide for controlling all the broad-leaved weeds and a second treatment with a grass herbicide to control johnsongrass, it is of practical interest to assess if the positions of these two groups of species overlap or whether they are partially or totally disjointed. According to our results from the finest sampling-resolution experiment, SSWM would be justified in the case of johnsongrass, with only four or five small patches in the plot. However, if we consider the whole of broad-leaved weeds (Figure 1), the plot area to be sprayed would be much larger, reducing the interest of using SSWM. Although previous studies have shown the possibility of using different herbicides for different weed groups [e.g., broad-leaved species, grass weeds, and catchweed bedstraw (*Galium aparine* L.)] heterogeneously distributed within a field (Gutjahr et al. 2012), the application of the most effective herbicide for each individual species would be technically difficult.

Association/Dissociation between Weed Species. The analysis of interactions between pairs of species provided by SADIE showed variable associations
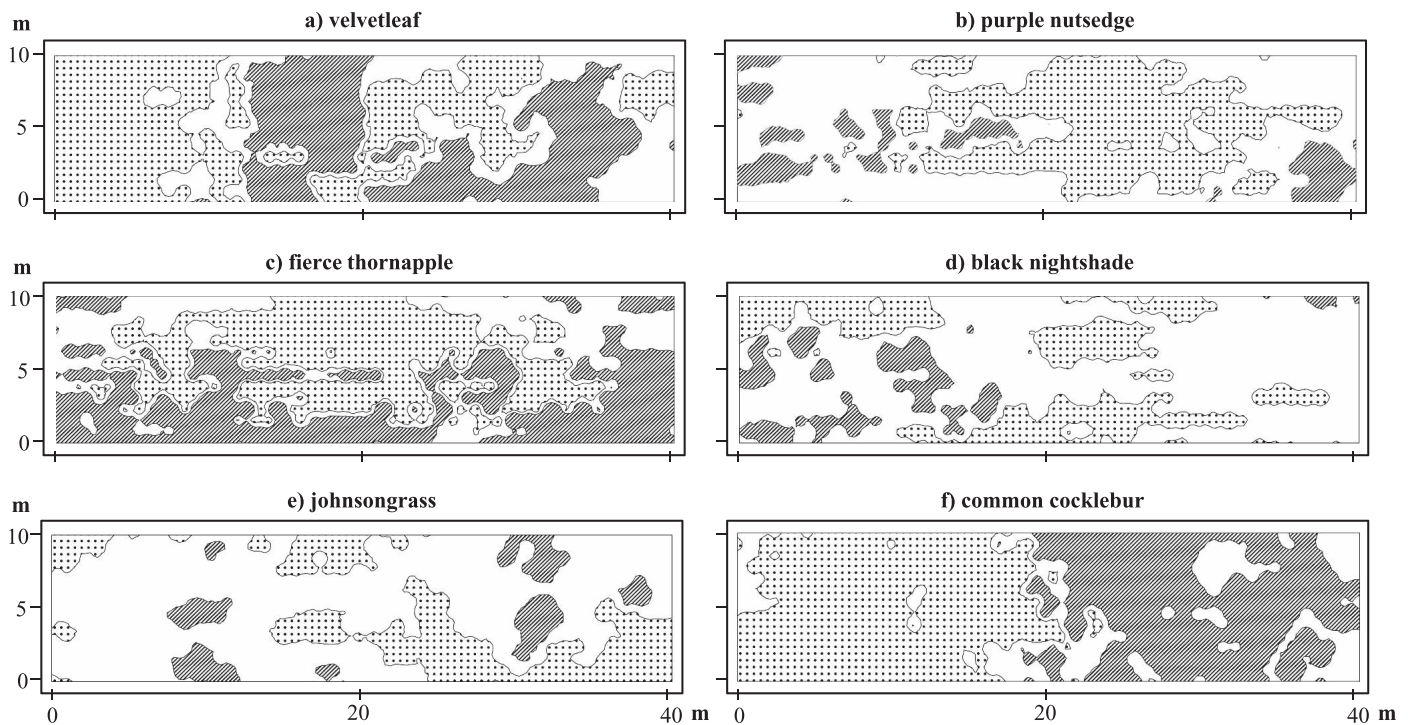
Figure 1. Spatial distribution pattern for (a) velvetleaf, (b) purple nutsedge, (c) fierce thornapple, (d) black nightshade, (e) johnsongrass, and (f) common cocklebur obtained using spatial analysis by distance indices from the finer sampling resolution (1 m by 0.75 m) conducted at La Poveda experimental plot. Patches are represented in a striped pattern when $V_i > 1.5$ and gaps in a spotted pattern when $V_j < -1.5$. Maps are represented in meters.

(both species were present or absent) and dissociations (one of the species was present and the other was not) in the different farmers' fields (Table 4). Since patterns of association and dissociation were never homogeneous between fields, we have only considered those interactions that were significant in at least 50% of the fields where the two species were present. Fierce thornapple was associated with purple nutsedge in 80% of the fields and with black nightshade and common cocklebur in 57 and 50% of the fields, respectively (Table 4). Common cocklebur was associated with purple nutsedge in 60% of the fields. Significant dissociations were observed in 50% of the fields for velvetleaf–johnsongrass and for velvetleaf–common cocklebur. Considering that the proportion of fields with the same type of interaction (either association or dissociation) was generally lower than 60% and since completely different responses were found in different fields, it is not possible to conclude the existence of a nonrandom spatial interaction between species.

The results from the finer sampling resolution study conducted at La Poveda differ slightly from those obtained in farmers' fields. In both studies, fierce thornapple was significantly associated with purple nutsedge (Table 4; Figure 2). This co-occurrence is

not surprising considering the differences in plant geometry and mechanisms of competition of these two species. However, the significant association between fierce thornapple and velvetleaf was only observed in one out of six farmers' fields. In fact, the results from this set of 16 fields suggested that fierce thornapple and velvetleaf were dissociated. According to the results of La Poveda study three pairs of species were significantly dissociated (Table 4). The dissociation between johnsongrass and velvetleaf was quite apparent in the field (Figure 2) and is in agreement with the results from farmers' fields. This type of interaction can be explained by the presence of various interference processes between the two species. Johnsongrass, as a perennial species, has a very rapid growth in the early spring, competing strongly with the small late-emerging velvetleaf seedlings (Dorado et al. 2009). In addition, these two weed species have been reported to produce allelopathic substances that can inhibit the growth of other species (Abdul-Wahab and Rice 1967; Kazinczi et al. 2001). The two other cases of dissociation, purple nutsedge–common cocklebur and black nightshade–common cocklebur, were not in agreement with farmers' fields results. Considering the small size of the plot and its homogeneity in soil properties and agronomic management, it is not likely that these factors were
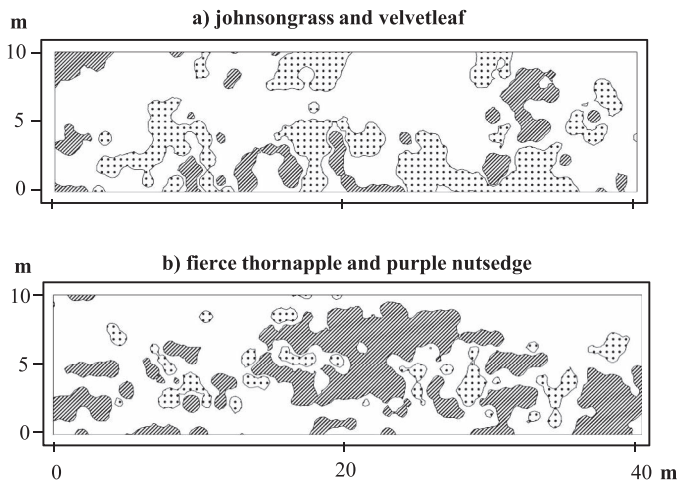
Figure 2. Spatial distribution of association/dissociation between pairs of weed species: (a) johnsongrass vs. velvetleaf; (b) fierce thornapple vs. purple nutsedge, conducted at La Poveda experimental plot. Associations are represented in a striped pattern when $X > 0.5$ and dissociations in a spotted pattern when $X < -0.5$. Maps are represented in meters.

involved in these relationships. Instead, these dissociations could be explained by competition for light. Common cocklebur, with an earlier emergence and a greater leaf surface and plant height than purple nutsedge and black nightshade, was more competitive in the interception of light, therefore shading and inferring in the survival of other weeds (Holt 1995;

Vazin et al. 2010). Purple nutsedge, particularly, has been shown to be very sensitive to shading (Patterson, 1982).

According to Petit and Fried (2012), co-occurrence patterns (i.e., aggregation or segregation) between weeds are not common. In their study, only 21% of the 94 wheat fields sampled showed significant patterns of weed species co-occurrence. This value was lower than those found in our study, especially if we consider that the X index used in our case relates the positions of gaps and patches for two different species whereas the C-score used in Petit and Fried's (2012) study only relates to presence or absence of the two species. Our results support the view that, although patterns of weed co-occurrence may be observed in some fields, these patterns are not general, suggesting that random co-occurrence is widespread. This fact is not surprising considering that most weeds in the corn-growing area of this study are able to produce large amounts of seeds that are dispersed throughout the field, where they survive for long periods in the soil and have a transient and unpredictable expression (Petit and Fried 2012). However, weed species differ in terms of niche breadth and association potential. Fried et al. (2010) ranked a list of weed species along a specialist/generalist gradient based on their niche

Table 4. Overall association index (X) values for each pair of weed species: velvetleaf (ABUTH), purple nutsedge (CYPRO), fierce thornapple (DATFE), black nightshade (SOLNI), johnsongrass (SORHA), and common cocklebur (XANST). Significant values with a probability level of 95% for each value of X are marked in bold. Positive values indicate association, while negative values indicate dissociation. Field 2 has been removed from the table since no association or dissociation was found.

Field[a]	ABUTH[b] DATFE[b]	ABUTH[b] SOLNI[b]	ABUTH[b] SORHA[c]	ABUTH[b] XANST[b]	CYPRO[c] DATFE[b]	CYPRO[c] XANST[b]	DATFE[b] SOLNI[b]	DATFE[b] SORHA[c]	DATFE[b] XANST[b]	SOLNI[b] SORHA[c]	SOLNI[b] XANST[b]	SORHA[c] XANST[b]
1	–[d]	–	–	–	–	–	–	−0.02	–	–	–	–
3	–	–	–	–	**0.28**	−0.09	–	**−0.27**	**0.28**	–	–	0.08
4	−0.08	–	**−0.57**	–	–	–	–	−0.01	–	–	–	–
5	**0.19**	–	−0.04	**−0.31**	–	–	–	0.02	**0.18**	–	–	0.01
6	0.09	**0.30**	−0.09	−0.13	–	–	−0.02	**−0.21**	**0.24**	−0.07	−0.11	**−0.22**
7	–	**0.53**	–	**0.33**	–	–	–	–	–	–	**0.30**	–
8	–	–	–	–	–	–	–	–	–	−0.11	−0.11	**−0.24**
9	–	−0.14	**−0.24**	–	–	–	–	–	–	**−0.22**	–	–
10	−0.03	**−0.16**	**−0.17**	–	–	–	**0.16**	0.02	–	0.10	–	–
11	−0.06	−0.16	**−0.21**	–	–	–	**−0.42**	**0.22**	–	**−0.18**	–	–
12	**−0.27**	−0.06	0.13	**−0.20**	–	–	0.07	0.04	0.08	0.08	**−0.30**	−0.05
13	**−0.18**	**0.17**	**0.30**	**0.22**	0.25	**0.48**	**0.20**	0.06	0.07	**0.33**	0.21	**0.54**
14	–	–	–	–	−0.20	0.12	–	**0.28**	**−0.22**	–	–	**−0.35**
15	**−0.34**	−0.13	–	**−0.34**	**0.40**	**0.27**	**0.63**	–	**0.53**	–	**0.48**	–
16	–	–	–	–	**0.42**	**0.26**	**0.18**	**0.19**	0.05	**0.18**	0.04	0.15
La Poveda	0.04	0.01	**−0.16**	**0.30**	**0.27**	**−0.26**	−0.02	−0.07	0.01	0.09	**−0.19**	−0.09

[a] See the reference to the location of each field in Table 1.
[b] Annual species.
[c] Perennial species.
[d] Dashes indicate that the analysis was not performed because the average density was less than 1 seedling plant m^{-2} in either species tested within the pair.

breadths. The generalist/specialist concept could be appropriate to find community assembly rules (Weiher and Keddy 1999). Using this concept, Petit and Fried (2012) concluded that specialist species tended to be aggregated, whereas generalists and species that had an intermediate degree of habitat specialization tended to be segregated. In our work, three of the six species studied (common cocklebur, fierce thornapple, and johnsongrass) can be considered as specialists and a fourth one (black nightshade) can be considered as intermediate (Fried et al. 2010). Although no information is available on the status of velvetleaf and purple nutsedge, their habitat characteristics makes them good candidates to be considered also as specialists. Consequently, our results, showing intermediate aggregation of most of these species, support the rule that specialists tend to present nonrandom aggregation patterns.

In conclusion, the results of this study showed an aggregate spatial distribution pattern for the main weed species present in corn crops in central Spain. Since weed aggregation is one of the bases for SSWM, our results support the interest of this concept under this type of scenario. However, since the spatial patterns of co-occurrence of weed species were field-specific, each field will have to be managed according to its specific pattern. Finally, the results obtained revealed similar patterns regardless of the scale of sampling resolution.

Acknowledgments

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