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ORIGINAL ARTICLE

Multivariate Analysis of the Agricultural Management Presence of *Sorghum Halepense* (L.) Pers. Relationships in Maize Crops

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Abstract *Sorghum halepense* (L.) Pers. is one of the most troublesome weeds in warm climates. Its control is difficult, and understanding the factors affecting its spreading is crucial. A study was conducted in 47 commercial maize fields, which account for more than 400 ha in the Spanish provinces of Albacete, Badajoz and Madrid, to analyse the distribution of *S. halepense* as a function of various agricultural variables. The results showed significant effects of agricultural management on the presence of this weed. Crop rotation decreased the infestation of *S. halepense*. Furrow irrigation system favored the establishment of large patches with high plant density, while the sprinkler irrigation system favored the presence of isolated plants or small patches. Apparently, moldboard tillage promoted the establishment of large patches. The combination of different variables also had effects on the characteristics of the present infestations, and its management could lead to a better control in maize fields.

Keywords Patch spraying · Weed population dynamics · Mapping

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Multivariate Analyse der räumlichen und zeitlichen Dynamik von *Sorghum halepense* (L.) Pers. Populationen in Maisfeldern

Zusammenfassung *Sorghum halepense* (L.) Pers. ist eines der problematischsten Unkräuter in warmen Klimazonen. Seine Kontrolle ist schwierig. Von entscheidender Bedeutung ist das Verständnis der Faktoren, die seine Verbreitung beeinflussen. In einer Studie in 47 kommerziell bewirtschafteten Maisfeldern, die eine Flächenanteil von mehr als 400 ha in den spanischen Provinzen Albacete, Badajoz und Madrid einnehmen, wurde die räumliche Verteilung der Mohrenhirse (*S. halepense*) als Funktion der verschiedenen landwirtschaftlichen Variablen untersucht. Die Ergebnisse zeigten eine signifikante Wirkung der landwirtschaftlichen Bewirtschaftung bei Anwesenheit dieses Unkrauts. Die Fruchtfolge vermindert den Befall von *S. halepense*. Das Furchenbewässerungssystem begünstigt die Einrichtung von großen Nestern mit hoher Pflanzendichte während das Sprinklerberegnungssystem die Anwesenheit von isolierten Pflanzen oder kleinen Nestern begünstigt. Offenbar fördert Bodenbearbeitung mit dem Abstreichblech die Etablierung von großen Nestern. Die Kombination von verschiedenen Variablen hatte auch Auswirkungen auf die Eigenschaften des vorliegenden Befalls. Das Management des Befalls könnte daher zu einer besseren Kontrolle in Maisfeldern führen.

Schlüsselwörter Teilschlagspezifische Unkrautkontrolle · Unkrautpopulationsdynamik · Unkrautkartierung

Introduction

Intensification of agricultural activities has had a considerable effect on weed patterns. The use of monoculture and herbicide spraying seem to be the main factors. Although, weed behavior and patch expansion are also influenced by different intrinsic characteristics and management factors, such as temperatures, tillage, irrigation, etc. Individual factors are able to provide an understanding of weed patterns. However, they can have a negative or positive influence. For instance, the use of monoculture in maize could reduce the production costs, but this cropping technique would decrease the biodiversity and increase weed problems (Helmers et al. 2001). The monoculture of alfalfa is a similar case; it provides opportunities for nitrogen fixation, soil stabilization, development of soil structure and carbon sequestration (Snapp et al. 2005).

Although a single factor can create a pattern, these management factors or field characteristics can be influenced by secondary factors, making interactions and providing a multifunctional system (Smithet al. 2011). The multiple interactions are often the cause determining weed composition and behavior, and multivariate analysis can be a powerful tool to analyze the combination of a complex number of factors, which can elucidate complex interactions among multiple variables for weed species (Braak 1987). Following this analysis, Dieleman et al. 2000 described a positive combination between herbicide activity and weed presence in maize fields. This combination was affected by the topography and soil texture. In addition, several associations were found indicating the influence of site properties in weed abundance. Within a field, Hausler and Nordmeyer (1995) reported that the visual distribution of *Polygonum amphibium* L. (water smartweed) was similar to the distribution of high soil phosphorus concentration and clay content and low sand content, whereas *Veronica hederifolia* L. distribution was similar to that of sand content. Since weed patches usually have different size, shape and density (Cardina et al. 1995; Johnson et al. 1996; Andújar et al. 2011) understanding the factors causing these patterns could help to the management of these populations.

Vegetation mapping is a good tool to identify the main relationships, as well as to understand their relationships with management factors. This information is helpful to analyze and establish management practices. The characterization of spatial distribution and the factors affecting them would enhance the profitability of the crop by improving the weed management. The possibility of a substantial reduction in herbicide use applying herbicides to patches where weed densities are above a defined threshold would improve the environmental consequences and economic benefits (Williams II et al. 1992; Andújar et al. 2011). The presence and spreading of these patches is highly influenced by management factors. It is common that soil tillage results in clear patch anisotropy, with patches being longer in the tillage direction (Andújar et al. 2012).

Crop rotation is another important factor, because weed species have different requirements that can change with the crop (García and Fernández-Quintanilla 1989). The combination of different factors should be explored to understand the causes and consequences of weed management. This study explored the factors and their interactions in the spatial distribution of *Sorghum halepense* (L.) Pers. in maize fields. This specie is a native of the Mediterranean region, which causes serious problems in some crops such as maize. It is particularly troublesome in southern and eastern Europe, Middle East, India, Australia, South America, and southern United States (Dewar 2009; Holm et al. 1977), causing high yield losses. Damalas and Eleftherohorinos (2001) and Mitskas et al. (2003) reported that maize yields were reduced by 70–88 % because of Johnsongrass interference. This specie is highly influenced by human labour and is difficult to control because of its root system formed by rhizomes which are spread by tillage. A previous study showed that *S. halepense* patches were twice as long in the direction of travel as perpendicular to the direction of tillage. This patches had a tendency to be located in the sections surrounding sprinkler pipes than in the sections located far away from these pipes. In addition the topography showed its influence in the spatial pattern, with a higher infestation in those areas close to river beds and with a higher flooding risk (Andújar et al. 2011). The objective of this work was to assess the interaction between factors and its influence in the spatial dynamics of S. *halepense*.

Materials and Methods

Site Location

The spatial distribution of *S. halepense* was sampled on a large scale, covering wide agronomic and environmental conditions in a large variety of maize fields located in three different provinces: Badajoz (south west), Madrid (center) and Albacete (south east) with over 500 km of separation between them. Forty seven commercial maize fields, with a total area more than 400 ha were evaluated. Due to the similar cropping system used in Spain, all fields had similar characteristics such as a flat topography, low soil fertility, high input levels of fertilizers, and water by irrigation. In Badajoz, maize was generally rotated with various horticultural crops (e.g., tomato, melon), it was furrow-irrigated and received various herbicide treatments, including a post-emergence treatment for control of *S. halepense* with rimsulfuron or nicosulfuron. No inversion tillage was generally used. In Madrid, the use of rotation was quite rare, being the major cropping system maize in monoculture with moldboard tillage practices and either furrow or surface irrigation systems. Herbicide applications were less frequent than in the previous region. In Albacete, maize crops were rotated with onion or winter cereals. The use of specific herbicides against *S. halepense* was not a common practice. All fields were sprinkler irrigated. Further details are given in Andújar et al. (2011).

Weed Assessment

Weed maps were constructed from the combine cabin at harvest time by visual estimation. Software written in visual basic was used for weed mapping. This program was able to join information given by the DGPS with Omnistar differential correction and three possible numeric indicators based on the level of *S. halepense* infestation. The level was selected by an operator based on continuous visual evaluation of *S. halepense* infestation levels from a combine at harvest time. The three categories corresponded to: 0 for areas without *S. halepense* plants, 1 for areas with an estimated density of 1–7 plants m^{-2}, and 2 for areas with more than 7 plants m^{-2}. Finally, a data base that stores the DGPS coordinates and the value selected by the operator was created. This sampling procedures have previously been used in several studies (Barroso et al. 2005; Ruiz et al. 2006; Van Wychen et al. 2002. *S. halepense* maps were generated using ArcInfo 9.3. (1995–2013 ©ESRI Inc., New York Street, Redlands, CA 92373-8100, USA) by kriging interpolation. From the resulting map the percentage of field infested with low and high *S. halepense* infestation levels and the number of isolated plants was calculated. Patches with less than 5 m^2 were considered as isolated plants. The area of each patch was also calculated.

Survey

A survey to the farmers was conducted in order to identify associations among qualitative variables and the abundance and spatial distribution of *S. halepense*. A set of variables were collected through about management and cropping techniques: Rotation (yes/no), irrigation (furrow/sprinkler), moldboard (yes/no) and field size in ha. Some factors such as the application of herbicides for *S. halepense*, tillage practices or crop rotations were used to analyze the patterns of this weed in relation to its abundance and distribution into the fields. Also, qualitative variables concerning the type of irrigation system were analyzed. This dataset was used to explore the relationship between variables and the collaborative effect between them in the *S. halepense* dynamics.

Data Processing

A multivariate analysis was used to explore potential relationships at a site scale. Eleven measured variables were introduced in the multiple regression model. Pearson correlation analysis was assessed to identify pairwise relationships between variables. Data were *Ln* transformed to stabilize variances and pairwise comparisons using t-test were used to separate the means in the analysis of variance. Multivariate analysis was performed using stepwise regressions to determine the influence of management factors in the number, size and shape of patches. Stepwise multiple linear regression fits an observed dependent data set (e. g., Infestation of high density, infestation of low density, patch area, number of isolated plants ha^{-1}, number of patches with less than 50 m^2 ha^{-1}, patches between 50 m^2 and 200 m^2 ha^{-1}, and patches with more than 200 m^2 ha^{-1}) using a linear combination of independent variables (e. g., Rotation (yes/no), irrigation (furrow/sprinkler), moldboard (yes/no) and field size in ha). The result of this statistical method was a number of variables correlated to the dependent variable and a linear equation combining the values of the independent data set with coefficients established by the regression. The following principles assumptions made by standard linear regression models were analyzed: Weak exogeneity, linearity, constant variance, independence of errors and lack of multicollinearity in the predictors. The software SPSS®; 20.0 (SPSS Inc., Chicago, IL, USA) was used for the analysis.

Results and Discussion

The multivariate analysis has shown different models explaining the relationship between management factors and several characteristics of *S. halepense* presence within the fields. From a total of 47 fields, only 38 fields were included in the analysis due to the absence or low percentage of surface infested by *S. halepense* (less than 0.1 %). From the analysis multiple models were created in order to evaluate the interactions between the management factors and the presence of this weed. Although, more than one variable showed its interaction in more than one model, the use of rotation from year to year, resulted significant in almost every model. Thus, in the case of the "low density infestations" (from 1–7 plants m^{-2}), the variable "rotation" resulted significant at $\alpha = 5\,\%$. Equation (1) estimated that the non-use of rotations within the fields produces an infestation with low density of *S. halepense* which affects 11.24 % of the field area; instead of using rotations as cropping technique the infestation decreases to 4.9 %. This effect is clearly visible in Fig. 1, which represents two different fields with use and non-use of rotation. The first map (A) had a lower infestation due to the use of rotation as cropping

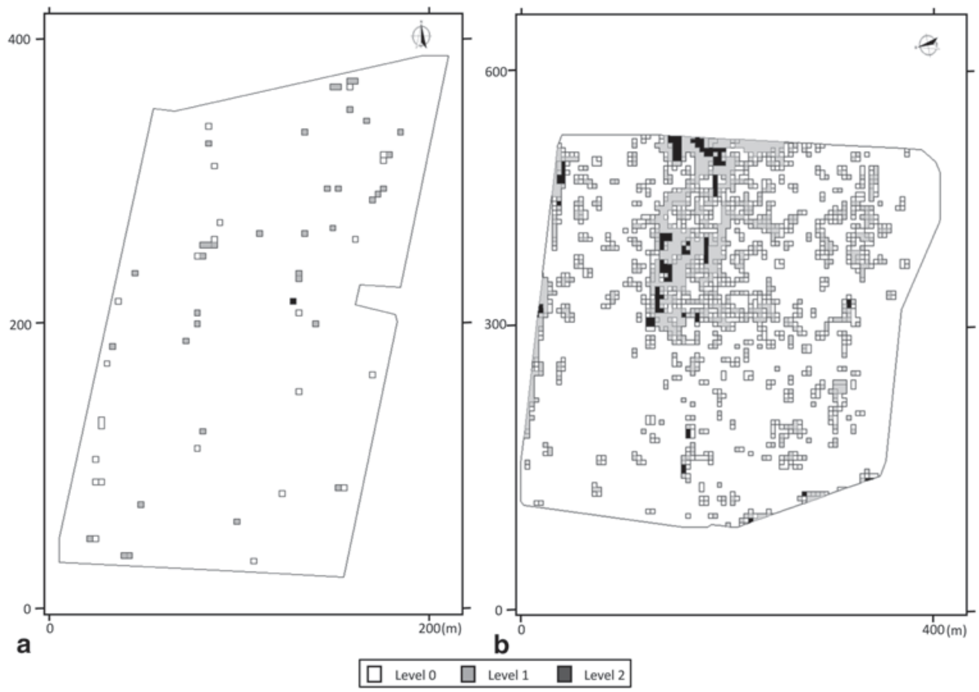

Fig. 1 Sorghum *halepense* (L.) Pers. maps for two fields. (Level 0) for areas without *S. halepense* plants; (level 1) for areas with an estimated density of one to seven plants m^{-2}; and (level 2) for areas with more than seven plants m^{-2}. Map A) corresponds to a field with sprinkler irrigation and use of rotation. Map B) is a field cultivated in monoculture and furrow irrigated

technique. The use of rotations decreased the percentage of low density infestations 56.35 %.

$$\ln(\%\ \textit{infestation of low density}) = 2.420 - 0.829 \times \textit{Rotation} \quad (1)$$

A similar case occurs in most of crops. In rice crops in Asia, the absence of selective herbicides against weeds due to the physical and physiological similarities of weedy rice to cultivated rice, increase weed infestation from year to year. The use of selective herbicides and cultural weed management strategies may help to reduce the problem of weedy rice. These strategies may include the use of clean seeds and machinery, use of stale seedbed practice, thorough land preparation, and the adoption of crop rotation (Singh Chauhan 2013). The use of long term rotations even showed greater effects in weed infestations. A 24 years study showed that crop rotation is one of the main technological steps which contribute to yield increases and weed control with a continuous decrease in the weed pressure along the years when a rotation from year to year was done (Petcu and Ioniţă 1998). The use of different herbicides and tillage change the cropping conditions controlling weeds and decreasing the infestation. In the particular case of Spain, in the most western region, maize field were generally rotated with horticultural crops which received a large amount of herbicides and also the crop cycle was different to maize reducing weed presence next year. The case of Albacete (east) was also affected by rotations, the use of wheat, onions or broccoli in the rotation controlled weed present in the fields. Although these crops differ from the others present in the other two regions, the effect of rotation was the same, lower infestations within the fields.

This variable also showed its influence in the model for the percentage of infestation with high density (more than 7 plants m^{-2}). The variable "rotation" resulted significant at $\alpha = 5\,\%$, whilst "irrigation" was significant at $\alpha = 10\,\%$. Thus, under sprinkler irrigation the use of crop rotation decrease the infestation of *S. halepense* (>7 plants m^{-2}) from 2.5 to 1.2 %. On the other hand, when the irrigation system is based on furrow irrigation, the infestation decreased from 12.4 % to 6.1 when a rotation practice is used, according to equation (2). A reason can be that sprinkler irrigation permits growers to uniformly apply water over large areas, which can allow proper incorporation of some pre-emergent herbicides (Dowler 1995).

The administration of herbicides through furrow irrigation can be challenging. Poor application uniformity and inaccuracies due to difficulties in measuring large quantities of water are challenges associated with applying herbicides through surface irrigation water (Ogg 1986). In addition, when a rotation is used in the system, the "% infestation of high density" decreases 50.8 % when the irrigation system keeps constant. And, when maize is furrow irrigated and the rotation keeps constant, then the "% infestation of high density" increases 85.5 %.

$$\ln(\%\ \textit{infestation of high density}) = 0.896 - 0.711 \times \textit{Rotation} + 0.618 \times \textit{Irrigation} \quad (2)$$

Also, the "number of isolated plants" per ha is conditioned by the same two variables: "Rotation" at a level of significance of $\alpha=5\%$ and "Irrigation" at $\alpha=10\%$. The model estimated a decrement of the number of isolated plants from 14.9 plants ha^{-1} (non-use of rotation) to 9.9 plants ha^{-1} when another crop different from maize is included in the rotation under sprinkler irrigation. In the case of furrow irrigated fields, the number of isolated plants decreased from 4.8 to 3.2 plants ha^{-1} when a crop rotation was used from year to year, equation (3). Thus, the use of rotation when the irrigation system is keeping constant would decrease the number of isolated plants 33.2 %. The stability of *S. halepense* plants is lower when a rotation is used. Large patches remain more stable along the years with a decrease in their area. However isolated plants are easier to control with herbicides or tillage operations. The other way around, when rotation is not used and the irrigation system changes, the furrow irrigation would reduce the number of isolated plants 67.5 %. This effect is exemplified in Fig 1 which shows the effect of rotation and irrigation. The field (A), sprinkler irrigated and with rotations, had a higher number of isolated plants than field (B) which had larger patches and a higher level of infestation.

$$\ln(\%\ isolated\ plants\ ha^{-1}) = 02.701 + 0.403 \times Rotation - 1.123 \times Irrigation \quad (3)$$

"Path size" was also influenced by the "irrigation" system and the "field size". Both variables were significant at $\alpha=5\%$. The equation (4) estimated that for a same field size, the use of furrow irrigation systems would increase 341 % the patch size. This effect could be due to the draft of seed by the irrigation water. Although some weeds propagate vegetative, most develop from seeds. In the case of *S. halepense* the spreading is mostly by rhizomes. However, irrigation also could help the movement of rhizomes in the water. The case of spreading by sprinkling is quite limited due to the use of filters in the water caption and seeds cannot drift in the water throughout the fields like in the case of furrow irrigation. This effect favors the establishment of new foci with isolated plants which can become in large patches during the following years (Kelley and Bruns 1975). For instance, in a field of 5.5 ha the average of patch size increases from 83.14 m^2 to 366.72 m^2. In the case of a field of 6.5 ha the average of patch size increases from 89.56 m^2 to 395.02 m^2, *i.e.*, the increment of 1 ha leads to an increment of 7.71 % in the average patch area when the irrigation is keeping constant.

$$\ln(Path\ \mathrm{size}) = 3.662 + 1.484 \times Irrigation - 0.445 \times \ln(Field\ \mathrm{size}) \quad (4)$$

The patch size was highly influenced by the irrigation system. Patches tend to increase their area faster under this irrigation method. Furrow irrigation does not allow to apply herbicides when the crop is in a high stage of growing. In addition, the draft of seed allows the growing of patches with no control. Although the flooding part of field inhibit the growing of new plants from seed, *S. halepense* propagates vegetative, thus flooding cannot restrict the abundance of this weed. The behavior of number of patches was different from those small patches with less than 50 m^2 to those ones with more than 200 m^2. For intermediate size patch, from 50 m^2 to more than 200 m^2, any of the variables resulted statistically significant. The "number of patches" with less than 50 m^2 ha^{-1} was influenced only by the "irrigation" at $\alpha=5\%$ according to equation (5). For instance, sprinkler irrigation produces an increment in the number of patches per ha from 1.7 patches ha^{-1} (gravity irrigated) to 2.8 patches ha^{-1}. Hence, furrow irrigation systems decreased 1.062 the number of patches ha^{-1}, corresponding to 37.9 %. This effect could be explained due to the presence of larger patches in furrow irrigation fields. Within these fields the growing of large patches integrates the smaller ones, becoming larger and complex in shape. Patches tended to increase their area from year to year when monoculture is used. In this sense a ratio area perimeter^{-2} could be calculated (Andújar et al. 2011). This ratio showed that patches tended to gain in shape complexity, as patch size increased. Similarly, Ruiz et al. (2006) in an approach to the behavior of sterile oat in dry land fields showed a similar pattern, so a similar tendency was observed in the growth type of the two annual and perennial species. This could be attributed to patches grow and incorporate neighboring small patches becoming more irregular and increasing their area.

$$Number\ of\ patches\,(< 50\,\mathrm{m}^2) = 2.802 - 1.062 \times Irrigation \quad (5)$$

Large patches, those with more than 200 m^2, were influenced for three variables: "Irrigation", "moldboard" and "field size", equation (6). In a furrow irrigated field, the number of patches would increase 76 % whether the rest of variables keep constant. In the case of use of moldboard the number of patches would increase 84.59 % when the other variables keep constant. For instance in a 5.5 ha field with no use of moldboard, the number of patches decrease from 1.3 patches ha^{-1} to 0.7 patches ha^{-1} under sprinkler irrigation.

$$\ln[Nr.\ patches\,(> 200\,\mathrm{m}^2)] = -0.711 + 0.566 \times Irrigation + 0.613 \times Moldboard + 0.239 \times \ln(Field\ \mathrm{size}) \quad (6)$$

The effect tillage is clear in the species with vegetative propagation. Andújar et al. (2012) showed that patches spread twice in the direction of tillage helping the growing of patches and the spreading of new foci. Patches expanded gradually into the nearby space almost exclusively in the traffic direction, with small displacements in the two perpendicular directions or backward. The rate of expansion slowed with the time and patch size: small patches tended to expand rapidly initially, but once they reached medium or large sizes, their relative growth decreased gradually. Following, under same conditions in a 6.5 ha field the number of patches decrease from 1.35 patches ha^{-1} to 0.76 patches ha^{-1}. Also, in a 5.5 ha field with use of moldboard and sprinkler irrigation the number of patches would be 1.36 patches ha^{-1}. However, if the field is furrow irrigated the total number of patches would increase to 2.39 patches ha^{-1}. Same conditions in a 6.5 ha field would produce 1.42 patches ha^{-1} and 2.49 patches ha^{-1}, respectively. Consequently, the increment of 1 ha would increment 4.07 % the number of patches with more than 200 m^2. Several can be the implications of agronomic factors. Understanding the causes and consequences of *S. halepense* management could help to better control this weed. Such predictive models would be useful for directing efforts and applying weed control practices in areas where presence can occur.

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