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Spatial and temporal dynamics of *Sorghum halepense* patches in maize crops

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Summary

Patches of *Sorghum halepense* of various sizes and densities were artificially created in a maize field. Spatial and temporal patch expansion was monitored during four years. The results show that patches expanded in the same direction of field traffic, with little or no displacement in all the other directions. Apparently, tillage was the main mechanism for dispersal of *S. halepense* rhizomes with seeds playing a minor role in dispersal. The spatial growth pattern was characterized by a compact spread of the original patch and by the appearance of small patches at various distances from the primary source, which tended to merge with each other and with the original source. This type of pattern indicates an 'infiltration' invasion strategy. The initial patch size significantly influenced their growth rate: small patches grew proportionately faster than larger patches. The initial plant density had a significant influence on the temporal dynamics: low density patches increased up to 130 shoots m^{-2} , the same upper level reached by high density patches. *Sorghum halepense* seems to be an excellent target for Site-Specific Weed Management (SSWM), with compact patches expanding slowly and in a highly predictable way. However, new foci detached from the original source can expand quickly and could invade the whole field in a relatively short time. An early detection and management of small patches can contribute to improve SSWM practices.

Key-words: Weed patch dynamics; site-specific weed management; perennial weeds.

Introduction

Weed populations are irregularly distributed within crop fields. Weed patches vary greatly from field to field, with variable sizes, shapes and densities (Cardina *et al.*, 1997; Dieleman & Mortensen, 1999). Climatic and cropping variation may cause patches to be more evident in some years than in others, making the patches to 'wax and wane' (Nordmeyer, 2009). Although patch edges may vary highly from year to year, the central areas of the patches are more stable spatially (Mortensen & Dieleman, 1998). In general, aggregation and patch stability is higher in perennial species than in annuals due to dispersal is limited to short distances by their vegetative reproduction. Annuals, in contrast, are distributed more randomly due to their capacity for seed dispersal, which provides greater ability to colonize weed-free areas.

In spite of the fact that the aggregated distribution of weeds is the base of site-specific weed management (SSWM), there is little information published on patch expansion and distribution, particularly with perennial weeds. Various studies have shown that *Cirsium arvense* patches were more stable than those of various annual weeds (Colbach *et al.*, 2000; Hamouz *et al.*, 2004). However, little specific information is available for other perennial weeds (Webster *et al.*, 2000; Guglielmini & Satorre, 2003; Jurado-Exposito *et al.*, 2004). This information is essential for understanding their spatial dynamics, which is necessary for planning and conducting SSWM.

Sorghum halepense (L.) Pers. is an extremely widespread species. It is considered one of the most troublesome weeds on the world (Holm *et al.*, 1977) and it is a common weed in maize in various regions of Spain (Andújar *et al.*, 2011). Numerous studies have shown that the interference of *S. halepense* with maize can greatly reduce crop yields (Bendixen, 1986; Mueller *et al.*, 1993; Ghosheh *et al.*, 1996; Vasilakoglou *et al.*, 2005)

The ability of *S. halepense* to colonize new areas, its establishment and its persistence depend on many factors. Combine harvesters have been reported to increase significantly dispersal distances of this species (Ghersa *et al.*, 1993; Barroso *et al.*, 2012). However, the actual role of seeds in population growth is still not clear. Seed predation has been found to contribute largely to population control (Scopel *et al.*, 1988). In seed-propagated plants, the new seedlings are subjected to many mortality factors: pre-planting tillage, pre-emergence and post-emergence herbicides, and inter-row cultivation. In contrast, plants coming from rhizomes are, apparently, much less affected by all these factors. Soil tillage spreads rhizomes and favors *S. halepense* to colonize new areas. In the absence of tillage, this weed spreads as a circular-shaped patch with no preferential direction of growth (Horowitz, 1973). However, a survey conducted in commercial maize fields in Spain (all of them under conventional tillage) showed a differential growth of patches according to tillage direction, with patches being twice as long in the direction of tillage (Andújar *et al.*, 2011).

The objective of this study was to characterize the growth of *S. halepense* patches in a continuous maize field over four growing seasons, analyzing the influence of initial patch size and plant density on the spatial and temporal patch expansion and anisotropy. Knowledge of the dynamics of *S. halepense* patches growing under field conditions is essential to planning effective prevention and control measures in the context of SSWM.

Materials and methods

Site Location and Description

Field experiments were conducted from 2007 to 2010 at La Poveda Research Farm (Arganda del Rey, Madrid, Central Spain), in a 2 ha maize field that was free from *S. halepense* and with low infestation of other weeds. The landscape of the site is an alluvial plain in the Jarama

river basin with a flat topography. Soil has a sandy-loam texture with 39% sand, 47% silt, 14% clay, and 1.4% organic matter, N 0.75 g kg⁻¹, CaCO₃ 34 g kg⁻¹ and pH 8.1.

Maize was planted all four years in mid April with 75-cm row spacing with a population of 80,000 plants ha⁻¹. Fertilizers were applied at planting time (40 kg N, 75 kg P and 75 kg K ha⁻¹) and at the eight-leaf stage (100 kg N ha⁻¹). Pre-emergence herbicide treatment with S-metolachlor + terbutylazine (0.94 + 0.56 kg ai ha⁻¹) was applied in 2007, with isoxaflutol (0.07 kg ai ha⁻¹) in 2008, and with S-metolachlor + mesotrione (1.20 + 0.12 kg ai ha⁻¹) in 2009 and 2010. No specific herbicides were applied in post-emergence (e.g., nicosulfuron) to control *S. halepense* in any case. All the agricultural operations (ploughing, seed drilling, spraying and combine harvesting) were conducted parallel to the longest side of the fields and always in the same direction, in order to assess the effect of traffic direction in the pattern of expansion of *S. halepense* patches. The tillage system used included disking the maize stubble after harvesting, moldboard ploughing during the winter and preplanting tillage with a field cultivator. Sprinkler irrigation was used, providing ample water for crop and weed growth.

Experimental Design

Three separated experiments were established in order to assess the potential of expansion of *S. halepense* as a function of initial patch size and plant density.

In the first two experiments, patches of *S. halepense* were created by transplanting rhizomes collected during the previous winter from a highly infested area in a nearby field. Rhizomes remained buried near the experimental plot until the start of the experiment. Then, rhizomes were prepared for planting by removing the secondary roots and cutting into 2-node pieces to reproduce the fragmentation effect caused by soil tillage and seedbed preparation. Rhizomes pieces containing two buds each were transplanted on 27th March 2007, previously to maize sowing. Both experimental designs were randomized complete block design with

three replications. The first experiment, evaluating the effect of the initial patch size, consisted of patches artificially established with the same weed density (10 shoots m^{-2}) but different patch sizes: 1 m^2 , 10 m^2 and 100 m^2 . The second experiment evaluated the effect of initial *S. halepense* density. In this case, the initial patch size was always 10 m^2 (3.3 m $\times$ 3.3 m) and established densities were 4, 20 and 100 shoots m^{-2} . Each plot was established in a 25 m $\times$ 65 m *S. halepense*-free area in order to assess weed spread in the following three seasons without interfering with other plots. Plots were established at 1/3 of distance from the beginning of its allotted area in the direction of field traffic and in the centre of the field portion in the perpendicular direction (Fig. 1). Initial planting was made by evenly distributing the rhizomes onto the soil surface of the required patches. Shoot emergence was assessed 4 weeks after planting and unsprouted rhizomes were re-planted in order to achieve the established density for each treatment.

A third experiment was conducted in order to evaluate the capability of individual *S. halepense* plants to create and establish permanent patches. Seven rhizome pieces containing two buds each were transplanted on 27th March 2007 in a nearby 12 m $\times$ 56 m strip free of *S. halepense* (Fig. 2). Rhizome pieces were transplanted 8 m from each other along a straight line in the same direction than traffic operations.

Patch Monitoring

In order to assess the expansion of *S. halepense* patches by agricultural operations (primary and secondary tillage, planting, harvesting) and by natural dissemination, patches of the first two experiments were georeferenced during four growing seasons in the maize stage BBCH 16–18, when most of *S. halepense* vegetative shoots were emerged. The perimeter of the patches was defined using a geopositioning system receiver with Omnistar differential correction (DGPS) working in a frequency of 5 Hz. An operator walked around the patch

perimeter, registering points along the patch border. In order to determine population changes in weed density within patches, shoots of *S. halepense* present in every inter-row area were sampled, using a 0.66 m × 0.33 m quadrat that was located at each meter within each row.

Furthermore, in the third experiment evaluating spatial and temporal dynamics of individual *S. halepense* plants, all individual shoots were manually counted and each one was geo-referenced with DGPS coordinates during 2007 and 2008 seasons. Due to the high patch growth in 2009 and 2010 it was not possible to monitor each individual shoot. Therefore, the perimeter of the patches was assessed using a DGPS system as described previously. Spatial data for shoot emergence of *S. halepense* was analyzed over the time, and *S. halepense* maps were created in order to describe the spatial and temporal expansion patterns.

Data Analyses

The geopositioning data were managed using ArcMap® 10.1, creating polygon maps by merging points, integrating the area, perimeter, maximum length in the traffic direction, maximum width perpendicular to traffic direction, and centroids for each patch during the four years. Differences in weed density between treatments were analyzed by the Kruskal-Wallis test.

In order to describe the spatio-temporal evolution of patches, various parameters were assessed. Total patch area was the major descriptor used to assess the expansion of patches into the space. The complexity index (ratio area perimeter⁻²) was used as an estimator of regularity of patch shape (Ruiz *et al.*, 2006; Andújar *et al.*, 2011). The lower the ratio the more complex and irregular was the patch. Patch anisotropy was studied by comparing the projection in the direction of traffic and the projection in the direction perpendicular to traffic. The changes of distance and direction of the patch centroids from one year to the next were calculated following the procedures described by Krohmann *et al.* (2006). The expansion to

weed free areas was studied by assessing the new foci of *S. halepense*, using the previous parameters as well as the distance and angle to their patch of origin.

Results

Patch Size Growth

During the four experimental years, patches expanded gradually into the nearby space. Patch growth was observed almost exclusively in the traffic direction with small displacements in the two perpendicular directions or backward (Fig. 1). In addition, new foci of infestation separated from original patches were found in the direction of traffic.

Initial patch size was the factor with the largest influence in the relative patch growth (Table 1). Patches of 1 m² increased their size more than 17 times during the first year and 137 times at the end of the four year period. Medium size patches (10 m²) grew at a slower rate, expanding their initial area 22 times during the four years. The largest patches (100 m²) increased their sizes 5 times during the four year period. Apparently, 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.

The effect of initial plant density on patch size growth was not significant (Table 1). Patches with 4 plants m⁻² increased their size 5 times during the first year and 31 times after four years. Medium (20 shoots m⁻²) and high (100 shoots m⁻²) density patches showed a similar tendency increasing their size by the fourth year 20 and 42 times, respectively.

Plant Density Growth

Practically all treatments followed the same trend, with plant density increasing exponentially during the growth period reaching a maximum in the fourth year (Fig. 3). Initial patch size did not have any significant effect on population growth (Fig. 3a). In relation to the initial density

of plants, the evolution of *S. halepense* density was somewhat diverse (Fig. 3b). Patches started with 4 and 20 shoots m^{-2} had very similar densities in the four years, reaching 120 to 130 shoots m^{-2} on average at the end of the experiment. In contrast, patches started with 100 shoots m^{-2} showed a decline in density in the second year (down to 25 shoots m^{-2}) followed by a recovery in the two other years. At the end of the experimental period, shoot density was similar than in the two other treatments.

Spatial Patterns

The displacement in distance and direction of the patches was studied by analyzing the movement of the centroids. Centroid displacement was relatively similar in different years and treatments, with values ranging from 1.6 to 8.3 m per year (Table 2). The changes of direction of the patch centroids were nearly parallel to traffic direction with values ranging between -23° and $+25^\circ$. Neither the initial patch size nor initial plant density had significant effects on these displacements.

Patch expansion took place following two different patterns: a) spreading uniformly as a compact patch; and b) generating new foci that, in subsequent years, merged with the original patch. In general, large patches generated new foci more often and at greater distances from the origin than small patches (Table 3). In this experiment, no new foci were detected one year after planting (2008). In 2009, the smallest patches (originally 1 m^2) produced 2 new foci (with an average perimeter of 0.7 m) displaced 13 m from the origin, whereas the largest patches (originally 100 m^2) produced 7 new foci (with a 12.3 m average perimeter) displaced 42 m from the origin. In 2010, the number of new foci decreased, probably due to the fact that patch and foci expansion connected some of the patches/foci. Foci which were not connected with other patches increased their area and perimeter over the time. All the new patches emerged in the traffic direction and none were found outside this

direction. In addition, the change of direction of the new foci centroids respect to the original patch centroids was almost parallel to traffic direction. On the other hand, similar characteristics in the new foci were observed depending on the initial plant density.

Spatial Indexes

The complexity index (relationship between area and squared perimeter) provides information about how compact or regular are patches. In general, patches tended to decrease this ratio with time (Fig. 4). This means that patches became less regular when they grew in size and density. This decline in regularity was particularly evident in the first three years of the experiment, regardless of the initial patch size and plant density.

Evolution in patch anisotropy (relationship between the projections parallel to traffic direction and perpendicular to traffic direction) is shown in Fig. 5. In 2007, because of the squares shape of the recently established patches, the length/width ratio was 1. In the following three years, this ratio increased on average to 2.3, 3.2 and 4.4 times longer than wider in the direction of traffic, respectively. Initial patch size and plant density had no significant influence on the evolution of this index.

Individual Plant Expansion

Although seven plants were established in 2007, only six survived in the following year. The high capacity of these plants to colonize weed free areas is shown in Fig. 2. Patch growth during the initial year (without additional tillage after planting) followed a circular pattern, with no preferential direction of growth for new vegetative shoots (data not shown). The year after planting, the original plants formed small patches with some shoots emerging at distances higher than 3 m from the origin. This expansion continued during 2009, with some patches reaching up to 20 m². These larger patches were formed either by the expansion of

smaller patches either by merging two or more patches. In 2010 a single patch 70 m long and 4 m wide, covering an area of 237 m², occupied practically all the experimental area. Thus, soil tillage resulted in clear patch anisotropy.

A progressive increase in the number of shoots emerged from these individual plants was observed during the first two years (Fig. 6). At the end of the second growing season, the density of *S. halepense* increased up to 22 shoots m⁻² from each individual plant established the first year.

Discussion

Based on the results of this study we can establish some important features of *S. halepense* patch dynamics in a continuous maize cropping. The data collected for 4 years using the contour maps of the patches provided precise spatial information, avoiding spatial interpolation techniques. According with these data, the size of *S. halepense* patches increased annually 2 to 17 times depending on patch size. Although the relative growth of patches was larger in the smaller patches, the actual patch displacement (measured by the displacement of their centroids) was relatively similar for all patch sizes. Obviously, a displacement of 4 m in a 1 m² patch represents a much larger proportional expansion than the same displacement in a 100 m² patch. It is likely that due to the faster expansion of small patches, the relative differences in size will be reduced over time compared to large patches. Thus, small patches may become large patches and then expand more slowly, but this needs confirmation in a long-term study. According to a survey of maize fields infested by this weed, most of the area was concentrated in a few large patches: only 5% of the infested area corresponded to patches smaller than 50 m² (Andújar *et al.*, 2011).

Previous studies had shown that *S. halepense* expands without preferential direction, establishing patches with approximately circular shape (Horowitz, 1973). However, these

results were obtained with plants grown without any soil tillage. In our study, the use of a unique direction for all agricultural operations (including tillage) created a clear spatial pattern with elongated patches in the direction of field traffic and little or no movement in all the other directions. This effect was clearly observed by the small changes of direction of the patch centroids, the evolution of the complexity index and the anisotropy of the patches. These results indicate that tillage is the main mechanism for spatial dispersal of *S. halepense* as was confirmed by the results of the individual plant experiment.

In this study, although the results of the first year were coincident with those of Horowitz (1973), once tillage was started (in the second year after planting), the patches expanded in an anisotropic pattern. Throughout the experimental period, the spatial distribution pattern became increasingly complex with the appearance of new foci. This growth pattern is, apparently, in accordance with the dual strategy of population growth proposed by Lovett Doust (1981). While the main patches tended to grow according to a '*phalanx*' strategy, spreading compact from a central point of establishment, new infestation foci showed a '*guerrilla*' strategy, exhibiting directional dispersal and proliferating far away from the original patches along one or a few axes. Both, compact spread around the primary source and occasional hops to new sites occurred at the same time, with new foci merging among them and with the original source. Due to the fact that growth of small patches is proportionally much faster than spread of the primary source, both processes may contribute to field invasion. This type of growth resembles more the '*infiltration*' pattern proposed by Wilson & Lee (1989). This pattern is probably associated to the existence of two different dispersal mechanisms: short-distance by vegetative growth and medium or long distance by tillage operations. One consequence of this result is that patch spread can be minimized by using no-tillage systems.

Although Ghera *et al.* (1993) attributed the spread of *S. halepense* to both rhizomes and seeds our results suggest that *S. halepense* relies predominantly on vegetative dispersal, with a negligible effect of seed dispersal. *Sorghum halepense* plants observed during the visual assessments of the patches and during population sampling on quadrats were, apparently, vigorous shoots coming from rhizomes. Some small seedlings were detected later in the center of the patches, but they were relatively easy to distinguish from the rhizome shoots. Furthermore, studies conducted to assess the influence of combine harvesting maize on seed dispersal of this weed have shown that seeds can be dispersed forward long distances and backward up to 12 m from the infestation source (Barroso *et al.*, 2012). However, our results show both, that annual patch displacement is relatively small and that the movement of the patches in the backward direction is almost nil. One possible explanation of the small role of seeds in patch displacement would be seed predation (Scopel *et al.*, 1988). However, in our experiment we did not detect any symptoms of seed predation by insects and/or rodents. We attribute the low relevance of seeds in *S. halepense* patch spread to a low seedling survivorship. Although we observed numerous seedlings in early stages of maize crop, most of them were not able to complete their life cycle, probably due to the effect of pre-emergence herbicides and to crop and weed competition. S-metolachlor, one of the pre-emergence herbicides used in the experimental field, is effective in controlling *S. halepense* seedlings before they emerge. Other studies have shown that *S. halepense* vegetative shoots are harder to control and more competitive than young seedlings (Millhollon, 1993; Rosales-Robles *et al.*, 1999a; Mitskas & Eleftherohorinos 2003).

The population dynamics of low density patches (≤ 20 shoots m^{-2}) was characterized by an exponential growth, reaching densities up to 130 shoots m^{-2} in a 4-year period. In contrast, in patches with high plant density (100 shoots m^{-2}) we observed an initial population decrease followed by a recovery to levels close to the other treatments. Apparently, *S. halepense* in

maize fields has a carrying capacity close to 130 shoots m^{-2} . Although Horowitz (1973) reported that one single plant produced 100 shoots m^{-2} in the first year and up to 165 shoots m^{-2} after two years, that study was conducted in the absence of crop competition. Maize competes strongly with *S. halepense* and limits its potential density. Population densities recorded in other studies conducted in maize fields heavily infested by this weed show population densities ranging from 40 to 60 shoots m^{-2} (Eleftherohorinos & Kotoula-Syka, 1995; Rosales-Robles *et al.*, 1999b).

The results obtained in this study have several important implications for SSWM of *S. halepense*. Previous studies have shown that the economic feasibility of using SSWM systems is conditioned by the frequency of re-mapping (Barroso *et al.*, 2004; Van Wychen *et al.*, 2002). Our results indicate that *S. halepense* patches are generally very compact and they expand slowly in a highly predictable way (in the same direction of field traffic). Consequently, a map obtained at a given time could be used in the decision making process later in the same season or in the following season. The information provided by our study can be used in spatial models designed to predict patch location at different time periods. This would be very desirable in terms of improving the feasibility of SSWM systems for this weed. Nevertheless, due to the fact that new foci can expand rapidly, new small patches are a potential hazard if they are not managed adequately. Therefore, it is required to devise action plans to account with this fact. One possible option is to reduce as much as possible weed detection and herbicide application resolution in order to spray not only the large patches but also the small foci. This 'small pixel' option will also provide the potential to lower the total amount of herbicide used (Wallinga *et al.*, 1998). However, this improved control and higher herbicide savings has to be balanced by the extra engineering costs. Another option is to spray the standard rate of herbicides to the large compact patches and apply reduced rates of the same products to the remaining field area. This 'variable rate' option would probably result in

higher amounts of herbicides used. Furthermore, some recent research suggests that low herbicide rates may promote herbicide resistance (Manalil *et al.*, 2011).

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Table 1. Relative growth of *Sorghum halepense* patches in different experimental years referred to the year of planting (2007).

Factor studied	2007 / 2008		2007 / 2009		2007 / 2010	
	Growth	SD*	Growth	SD	Growth	SD
Initial patch size (m ²)						
1	17.3	10.5	30.0	19.3	137.3	101.6
10	5.7	1.1	8.6	0.9	22.3	1.5
100	2.3	0.4	3.5	0.8	5.4	3.7
Significance (95%)	0.05		0.05		0.03	
Initial plant density (shoots m ⁻²)						
4	5.3	1.0	10.3	2.2	31.1	13.7
20	4.9	3.7	8.7	3.4	20.1	20.1
100	8.3	2.5	12.0	1.1	42.6	11.8
Significance (95%)	0.15		0.59		0.43	

* Standard deviations of three patches.

Table 2. Average distance (m) between centroids and change of direction (degrees) of the patch centroids in different experimental years referred to the year of planting (2007). In parentheses is shown the standard deviation for the three patches.

Factor studied	2007 / 2008		2007 / 2009		2007 / 2010	
	Distance	Shift direction	Distance	Shift direction	Distance	Shift direction
Initial patch size (m ²)						
1	2.9 (0.9)	-22.4° (12.8)	3.0 (1.2)	24.8° (22.0)	4.9 (4.0)	-4.9 (42.1)
10	2.9 (2.0)	-15.3° (28.5)	1.6 (1.3)	9.0° (47.8)	7.0 (5.1)	-14.9 (29.0)
100	4.1 (2.9)	-21.6° (24.9)	3.8 (4.3)	-1.9° (39.4)	8.3 (7.2)	-13.7 (28.4)
Significance (95%)	ns	ns	ns	ns	ns	ns
Initial plant density (shoots m ⁻²)						
4	2.7 (1.9)	-23.2° (24.8)	3.4 (2.4)	-8.1° (34.5)	4.7 (3.9)	-16.2° (29.9)
20	6.1 (1.8)	-20.9° (15.4)	4.2 (3.6)	15.6° (18.4)	2.4 (-)	12.9° (-)
100	5.9 (1.7)	-10.8° (6.5)	4.7 (2.7)	15.0° (4.6)	6.4 (-)	4.6° (-)
Significance (95%)	ns	ns	ns	ns	ns	ns

Table 3. Description of new foci of *Sorghum halepense* in the three years following planting based on the initial patch size and the initial plant density. The descriptors include the number of new foci, distance to their patch of origin (m), area (m²), perimeter (m) and change of direction of the foci centroids to their patch of origin (angle degrees). In parentheses is shown the standard deviation for three patches of origin.

Factor studied		New Foci	Distance	Area	Perimeter	Angle
Initial patch size (m ²)						
2008	1	0	-	-	-	-
	10	0	-	-	-	-
	100	0	-	-	-	-
2009	1	2	13.0 (3.7)	<0.1 (<0.1)	0.7 (0.2)	<0.1 (<0.1)
	10	3	37.2 (7.5)	0.4 (0.6)	2.1 (2.4)	-1.3 (2.3)
	100	7	41.8 (12.9)	8.1 (7.6)	12.3 (9.3)	0.6 (5.6)
2010	1	2	35.6 (10.7)	5.9 (8.1)	9.3 (10.8)	-1.5 (2.1)
	10	2	49.8 (12.9)	22.0 (2.6)	24.2 (2.3)	3.5 (2.1)
	100	3	55.0 (8.3)	10.4 (2.3)	15.7 (1.2)	-0.7 (2.1)
Initial plant density (shoots m ⁻²)						
2008	4	0	-	-	-	-
	20	0	-	-	-	-
	100	1	54.1 (-)	10.1 (-)	13.8 (-)	-3.0 (-)
2009	4	6	40.5 (14.8)	1.4 (3.3)	2.93 (5.2)	1.2 (2.5)

	20	3	38.2 (10.1)	0.0 (0.0)	0.08 (0.0)	-3.3 (1.2)
	100	6	40.0 (19.5)	12.7 (15.3)	15.5 (15.3)	-0.2 (0.8)
2010	4	4	48.4 (10.7)	15.7 (15.7)	16.6 (12.1)	-0.3 (1.5)
	20	2	40.4 (41.3)	71.7 (28.9)	38.5 (22.2)	<0.1 (<0.1)
	100	1	56.8 (-)	5.2 (-)	21.2 (-)	-1.0 (-)

Figure caption

Fig. 1. a) *Sorghum halepense* patch growth as a function of its initial size. Black quadrats of different sizes (1, 10 and 100 m²) are the initial patches in 2007 and dotted areas correspond to patch location in every year. b) *Sorghum halepense* patch growth as a function of initial plant density. Quadrats with different colors (light gray: 4 plants m⁻²; gray: 20 plants m⁻²; and black: 100 plants m⁻²) represent the initial patches in 2007 and dotted areas correspond to patch location in every year. Arrows show the tillage direction.

Fig. 2. Growth of *Sorghum halepense* patches in four successive years started from six individual plants. Arrows show the tillage direction.

Fig. 3. Plant density evolution in four successive years for: a) patches with the same initial density (20 plants m⁻²) and different initial patch sizes; and b) patches with the same initial size (10 m²) and different initial plant densities.

Fig. 4. Average complexity index (ratio area perimeter⁻²) evolution in four successive years for: a) patches with the same initial density (20 plants m⁻²) and different initial patch size; and b) patches with the same initial size (10 m²) and different initial plant densities.

Fig. 5. Average anisotropy (ratio between the projection in the direction of traffic and the projection in the direction perpendicular to traffic) evolution in four successive years for: a) patches with the same initial density (20 plants m⁻²) and different initial patch size; and b) patches with the same initial size (10 m²) and different initial plant densities.

Fig. 6. Average increase in the density of *S. halepense* (shoots m⁻²) during the first and second year after planting a single rhizome piece at each site.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6