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Weed Management—Techniques

Reliability of a Visual Recognition System for Detection of Johnsongrass (*Sorghum halepense*) in Corn

Dionisio Andújar, Ángela Ribeiro, Cesar Fernández-Quintanilla, and José Dorado*

The feasibility of visual detection of weeds for map-based patch spraying systems needs to be assessed for use in large-scale cropping systems. The main objective of this research was to evaluate the reliability and profitability of using maps of Johnsongrass patches constructed at harvest to predict spatial distribution of weeds during the next cropping season. Johnsongrass patches visually were assessed from the cabin of a combine harvester in three corn fields and were compared with maps obtained in the subsequent year prior to postemergence herbicide application. There was a good correlation (71% on average) between the position of Johnsongrass patches on the two maps (fall vs. spring). The highest correlation (82%) was obtained with relatively large infestations, whereas the lowest (58%) was obtained when the infested area was smaller. Although the relative positions of the patches remained almost unchanged from 1 yr to the next, the infested area increased in all fields during the 4-yr experimental period. According to our estimates, using a strategy based on spraying full rates of herbicides to patches recorded in the map generated in the previous fall resulted in higher net returns than spraying the whole field, either at full or half rate. This site-specific strategy resulted in an average 65% reduction in the volume of herbicide applied to control this weed.

Nomenclature: Johnsongrass, *Sorghum halepense* (L.) Pers. SORHA; corn, *Zea mays* L.

Key words: Weed maps, visual estimation, patchy weed distribution, patch spraying.

La viabilidad de la detección visual de malezas para su tratamiento localizado en base a mapas debe ser evaluada de cara a su aplicación en sistemas de cultivo a gran escala. El objetivo principal de esta investigación fue evaluar la fiabilidad y rentabilidad del uso de mapas de rodales de *Sorghum halepense* elaborados durante la recolección en otoño para predecir la distribución espacial de la maleza en la siguiente campaña de cultivo. Los rodales de *S. halepense* fueron localizados de forma visual desde la cabina de una cosechadora en tres campos de maíz, y su posición se comparó con la de los mapas obtenidos la primavera siguiente, antes del tratamiento de post-emergencia. Los resultados mostraron una buena correlación (71% en promedio) de la ubicación de los rodales de la maleza entre los dos mapas (otoño vs. primavera). La mayor correlación (82%) se observó con infestaciones relativamente grandes, mientras que la menor (58%) se obtuvo cuando el área infestada era más pequeña. Aunque las posiciones relativas de los rodales se mantuvieron constantes de un año al otro, el área infestada se incrementó en todos los campos durante los cuatro años del período experimental. Según nuestras estimaciones, la estrategia basada en aplicar una dosis completa de herbicida a los rodales localizados el otoño del año anterior produjo un beneficio neto mayor que la aplicación de herbicida sobre todo el campo, ya sea a dosis completa o a mitad de dosis. Esta estrategia de tratamiento localizado resultó en una reducción media del 65% respecto al volumen de herbicida aplicado en toda la superficie para el control de esta maleza.

Johnsongrass is one of the most important weed species infesting corn fields in North and South America and in southern Europe (Holm et al. 1977) and can greatly reduce corn yields. Bendixen (1986), in North America, reported yield losses up to 100% in a continuous corn system with high Johnsongrass densities. Studies conducted in Greece, under similar conditions to those present in Spain, showed that corn yields were reduced 83% and 62% with season-long interference by Johnsongrass from rhizomes and from seeds, respectively (Mitskas et al. 2003).

The life cycle of Johnsongrass is conducive to its survival in a wide range of environmental conditions. Growth begins from the apical and axillary nodes as well as the primary rhizomes as the temperature increases in the spring. Seedlings emerge later and grow slower than rhizome sprouts (Warwick and Black 1983). Although hundreds of seeds are produced on each panicle, sexual reproduction is not as important as

asexual reproduction in the life cycle of this species. A single Johnsongrass plant can produce 60 to 90 m of rhizomes in 1 mo (McWhorter 1981). These extensively creeping rhizomes, which regenerate easily when cut into small pieces, are capable of producing highly competitive plants or can remain dormant in a wide range of environmental conditions. Johnsongrass plants that originate from rhizomes are not affected by most of the pre-emergence herbicides used in corn fields. A postemergence herbicide treatment is generally necessary for control but will increase production costs.

Previous studies conducted in corn crops in Spain have indicated a highly aggregated distribution pattern of this species (Andújar et al. 2011). Each of the Johnsongrass patches is generally compact with clearly defined borders. These patches easily can be detected at harvest time because Johnsongrass remains green, but maize plants take on a yellowish color. These features make Johnsongrass an ideal target for site-specific weed management.

There are two major approaches for site-specific weed management: (1) creating a map of weed locations and then controlling an automatic sprayer with the map; and (2)

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detecting and spraying weeds in one operation. Although real-time automatic weed detection and spraying is the focus of considerable research, until now the major approach used has been spraying based on previously constructed maps (Christensen et al. 2009).

The use of map-based patch spraying depends on the availability of reliable data on the spatial distribution of weeds within the fields. Although a wide range of weed detection techniques have been developed over the last 10 yr, none of them have reached a wide acceptance. Aerial-based remote sensing can be applied successfully to detect weed patches only when they are relatively large, dense, and uniform, and have unique spectral characteristics (Brown and Noble 2005). A major disadvantage of aerial detection from aircraft or satellites is that images can be difficult to acquire on demand. Ground-based detection using visual evaluations, optoelectronic sensors, or digital cameras, shows more promise for the spatial treatment of small patches (e.g., adjusting the spraying with a nozzle or boom section) and/or when weed size and density are low (Burgos-Artiz et al. 2009; Christensen et al. 2009; Gerhards and Oebel 2006). However, most of these systems are technologically complex and expensive.

Weed mapping systems using human observation constitute a simple and reliable alternative. Generally, weed detection is based on the fact that flowering structures of weeds penetrate the crop canopy and can be discriminated easily from the crop. Rew et al. (1997) tested a semi-automated system that relied on visual recognition of spikes of various grass weeds in cereal crops from a high-clearance vehicle traveling over the crop tramlines at harvest time. Numerous researchers have used the same approach to map wild oats (*Avena fatua* L. and *A. sterilis* L.) from the cabin of combine harvesters (Andújar et al. 2011; Barroso et al. 2005; Colliver et al. 1996; Luschei et al. 2001; Ruiz et al. 2006a,b; Van Wychen et al. 2002).

Two critical issues arise regarding visual weed mapping at harvest time. The first is that the cost associated with weed assessment (Barroso et al. 2005) should be proportional to the economic benefits derived from patch spraying (Forcella 1993). The second issue is the predictive power of these maps. If weed patches are stable between seasons, harvest maps could be used to plan herbicide treatments the following season. If they are not, then the predictive value of these maps might be minimal. Although patch stability depends on the species, some of the key target species for patch treatment, such as common sunflower or cleavers, have been shown to have relatively stable patches (Gerhards et al. 1997; Hamouz et al. 2004; Zhang and Hamill 1998). Although rhizomatous species such as Johnsongrass are expected to be relatively stable in their location, plant densities can change depending on the management practices and environmental conditions present during the growing season.

The objective of this research was to assess the reliability of using maps of Johnsongrass patches constructed at harvest to predict the location of patches in the following cropping season. Furthermore, the long-term stability of these patches was studied in order to determine the temporal limit of these predictions. Economic and environmental factors were considered to evaluate the potential application of this detection system.

Materials and Methods

Experimental Conditions. The study was conducted from 2005 to 2009 at La Poveda Research Farm (Arganda del Rey, Madrid, Central Spain), in three fields naturally infested with Johnsongrass. The landscape of the site is an alluvial plain in the Jarama River basin with a flat topography. Soils in the three fields have 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. Mean daily temperature and annual precipitation during the last 10 yr were 13.5 C and 460 mm, respectively.

Corn was planted all 3 yr in mid-April with 75-cm row spacing and a population of 90,000 plants ha⁻¹. Field A (2.5 ha) was infested heavily with Johnsongrass, fierce thornapple (*Datura ferox* L.) and cocklebur (*Xanthium strumarium* L.), with very sparse weed-free areas. In contrast, large portions of Field B (8.3 ha) and Field C (3.4 ha) were almost free of weeds other than Johnsongrass. From 2005 to 2007, a pre-emergence herbicide treatment with atrazine (0.96 kg ai ha⁻¹) plus S-metolachlor (0.96 kg ai ha⁻¹) was applied. From 2008, these two herbicides were substituted by isoxaflutol (100 g ai ha⁻¹). Postemergent treatments with nicosulfuron (60 g ai ha⁻¹) were applied at the four- to six-leaf stage of corn in 2005. From 2006 a postemergence treatment with rimsulfuron (60 g ai ha⁻¹) was applied for the control of Johnsongrass and with thifensulfuron (10 g ai ha⁻¹) for the control of broad-leaved weeds using 200 L ha⁻¹ of water. Weather conditions during herbicide treatments were adequate, with no wind and warm temperatures. Thereafter, temperatures remained relatively high during the entire growing season with no stress symptoms present. 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). All of the agricultural operations (plowing, seed drilling, spraying, and combine harvesting) were conducted parallel to the longest side of the fields. The tillage system used included disking the corn stubble in the fall, moldboard plowing during the winter, and one or more preplanting tillage with a field cultivator. Although all these practices favor rhizome displacement, their effects might have been altered by the variable directions of tillage. Sprinkler irrigation was used, with an average of 12 irrigations during 3 mo with a total contribution of 800 L m⁻². This provided an ample supply of water for crop and weed growth.

Weed Assessment. Johnsongrass patches in Field A were assessed at harvest time during 3 consecutive yr (October 2005, 2006, and 2007) and prior to postemergence herbicide application in the 3 subsequent yr (May 2006, 2007, and 2008). In Field B, fall assessments were conducted in October 2006, 2007, and 2008 and spring assessments in May 2007, 2008, and 2009. In Field C, assessments were carried out in October 2007 and 2008 at harvest time and in May 2008 and 2009 in the spring.

In the fall, presence of Johnsongrass was visually assessed by an observer located in the combine harvester cabin. Johnsongrass plants were easy to identify because they were still green at harvest while corn plants were dry and yellowish. In order to minimize errors, the evaluator remained the same

for all observations and was previously trained in identifying Johnsongrass patches and in the use of the hardware/software. Johnsongrass patches were relatively homogeneous, and were defined as an area with more than one panicle m^{-2} . Densities below that value were considered scattered plants. This threshold was arbitrarily selected based on the fact that this area is relatively easy to recognize and remember. Data was recorded using a tablet personal computer¹ with a specific software² designed and developed for this application, and a differential geopositioning system (DGPS) receiver³ giving submetric precision. The computer program combined the geoposition provided by the DGPS and the numeric indicator selected for each position (0: absence; 1: presence). Georeferenced points were taken at intervals of 1 sec, corresponding to the DGPS frequency, i.e., 1 to 1.2 m (assuming a maximum speed of 4.5 km h^{-1} for the combine) of separation between neighboring points within the same row and 4.5 m corresponding to the combine swath width (6 corn rows).

In the spring, at the four-leaf stage of corn, most Johnsongrass plants clearly were visible due to the smaller size of corn plants and to their presence in the wide interrow area. A georeferenced database was generated by an observer equipped with a tablet PC and a DGPS system, using a continuous visual assessment procedure similar to that described previously. The database was created by walking along parallel transects every 6 corn rows (4.5 m). Georeferenced positions of each assessment were recorded with the same equipment (placed in the backpack of the observer) used at harvest, and using the same numeric indicator to discriminate the absence (less than one plant m^{-2}) and presence (more than one plant m^{-2}) of Johnsongrass. Because the speed at which the observer walked was similar to the speed of the combine harvester, the fall and spring maps had a similar resolution.

Data Processing and Analysis. Data management and spatial data analysis were carried out using ArcInfo® Geostatistical Analyst.⁴ Preprocessing of data in fall maps was performed in order to remove part of the points with coincident coordinates after projection (two indicator values at the same point) by preserving those with the highest indicator values. This occurred mostly at the beginning/end of the rows and in zones where the combine harvester had to cope with obstacles.

Fall and spring databases were compared to test the similarity of spatial distribution. Observations recorded in fall were interpolated by kriging in order to have comparable continuous estimates with matching points from the spring maps. Due to the binary structure of the data (0/1), indicator kriging was used. Exponential and spherical models were used to fit the semivariograms to the data. The interpolated map obtained at harvest was overlaid on the original map of points obtained in the following season resulting in a database with information from both fall and spring. This database stored the georeferenced points of the spring map with the respective value of presence/absence and the associated information for the same coordinate in the interpolated fall map. Cross tables (SPSS 15.0)⁵ were used to analyze the relationship between both categorical databases. In the “fall database,” original values were transformed to a two-category scale according to their probability (0 for $P < 0.5$; 1 for $P \geq 0.5$), whereas the

“spring database” consisted of weed presence/absence (0/1) values. In addition, 3- and 5-m buffers were added to the fall maps before creating interpolated maps; kriging then was performed using the above-indicated procedure.

Economic Analysis. The potential economic benefits of patch spraying based on weed distribution maps was assessed by using equation [1], which is adapted to corn from the equation proposed by Ruiz et al. (2006b) for wild oats:

$$NT = Y \left[1 - \frac{Y_{50}}{100} \cdot \frac{A_{50t}}{100} - \frac{Y_l}{100} \cdot \frac{Ant}{100} \right] P - \left[C_m + C_t + H(D_1 \cdot \frac{A}{100} + D_2 \cdot \frac{A_{50}}{100}) + C_{cm} \right] \quad [1]$$

where NT is the net return per hectare; Y is the corn yield on Johnsongrass-free areas; Y_{50} is the percentage of yield loss at half-rate herbicide in infested areas; Y_l is the percentage of yield loss at nontreated infested areas; A is the percentage of the field treated at full-rate; A_{50t} is the percentage of infested surface treated at half-rate; A_{50} is the percentage of surface treated at half-rate; A_{nt} is the nontreated infested area; P is the price of corn; C_m (only considered in site-specific treatments) is the cost of mapping the field using a 4.5 m swath combine harvester, which includes the cost of the mapping equipment (DGPS, tablet PC, and software) and the cost of the scout person; C_t is the treatment cost with a sprayer with independently controlled sections; C_{cm} is the remaining costs involved in crop production (e.g., seeding, fertilization, tillage, irrigation, pre-emergence herbicide); H is postemergence herbicide cost at full-rate application; and D_1 and D_2 are the applied rates (1 and 0.5).

Parameter values used for simulation were: $Y = 12,000 \text{ kg ha}^{-1}$; $P = \$0.23 \text{ kg}^{-1}$; $Y_{50} = 7\%$; $Y_l = 16\%$ (Barroso, personal communication); $C_m = \$12.7 \text{ ha}^{-1}$ (Ruiz et al. 2006a); $C_t = \$9.3 \text{ ha}^{-1}$ at 3.46 ha h^{-1} work capacity (Barroso et al. 2004); $C_t = \$24 \text{ ha}^{-1}$ for site-specific spraying of patches and $C_t = \$29.6 \text{ ha}^{-1}$ for a differential-rate spraying (Gerhards and Sökefeld 2003); $C_{cm} = \$1,270 \text{ ha}^{-1}$; $H = \$127 \text{ ha}^{-1}$. Actual values for patch densities ranged from 1 to 50 plants m^{-2} , but because individual values were not recorded, Y_l and Y_{50} values were estimated, based on our experimental data for a density of 5 plants m^{-2} (Barroso, unpublished results).

Six herbicide application strategies were simulated: (1) no herbicide; (2) overall full-rate application (standard practice); (3) overall half-rate application; (4) full-rate application to patches recorded in the map generated in the previous fall; (5) half-rate application to patches detected in the previous fall; and (6) full-rate application to patches recorded in the map and half-rate at the rest of the field. Treatment maps were generated using a 6 m by 6 m grid, which corresponded to the 6-m width of a section of the sprayer. Due to sampling errors and the displacement of patches from 1 yr to the next, we also have included the economic impact of adding a 3-m buffer to the patches in the three site-specific strategies (numbers 4 to 6).

In order to assess the potential benefits of herbicide applications based on maps from previous years, we calculated

Table 1. Proportions of the fields infested by Johnsongrass in the fall and spring of various years, and percentages of agreement between the position of Johnsongrass in the two sets of data. Comparisons included also adding 3- and 5-m buffers to the data from the fall in order to take into consideration sampling errors and patch displacement.

	Fall vs. Spring		Fall + 3 m vs. Spring		Fall + 5 m vs. Spring	
	Infestation	Agreement	Infestation	Agreement	Infestation	Agreement
	% surface	%	% surface	%	% surface	%
Field A						
October 2005	26.4	74.9	39.4	85.2	53.0	91.4
May 2006	22.6		22.6		22.6	
October 2006	40.2	82.0	58.6	91.5	77.4	97.1
May 2007	27.8		27.8		27.8	
October 2007	40.5	82.3	49.0	85.2	72.4	96.8
May 2008	28.1		28.1		28.1	
Field B						
October 2006	19.1	57.9	28.9	72.1	34.3	78.6
May 2007	11.2		11.2		11.2	
October 2007	44.9	69.8	53.2	76.9	72.4	91.5
May 2008	48.8		48.8		48.8	
October 2008	51.8	68.1	68.5	83.5	85.2	95.5
May 2009	60.4		60.4		60.4	
Field C						
October 2007	21.8	72.6	25.0	73.8	43.0	90.1
May 2008	20.0		20.0		20.0	
October 2008	33.5	59.5	49.0	75.4	68.1	92.1
May 2009	38.2		38.2		38.2	
Average		70.9		80.4		91.6

the net returns of the site-specific strategies in different years based on data from 1, 2, or 3 yr. The potential herbicide reduction derived from the different simulated site-specific strategies was calculated based on relation to an overall treatment at full dose.

Results and Discussion

Fall vs. Spring Maps. Visual assessment of Johnsongrass patches carried out from the combine in autumn were relatively simple and yielded a high volume of georeferenced data. A total of 225,717 observations with presence/absence of Johnsongrass were recorded. The proportion of the fields infested by this weed ranged from 19.1% to 51.8%, with an average of 34.8%. Similarly, spring assessments showed infestation levels from 11.2% to 60.4%, with an average of 32.1% (Table 1).

The percentage of agreement between the position of Johnsongrass patches on the two maps (fall vs. spring) was on average 71% (Table 1). The highest agreement (82%) was obtained in two cases with relatively large infestation levels (40% in fall), whereas the lowest agreement (58%) was obtained when the infested area was smallest (19% in fall). In general, the largest differences between the two maps were found in zones of recent patch expansion or with new patches.

Adding 3 m and 5 m buffers to the patches detected at harvest substantially increased the area considered to be infested. The average increases in area were 11.7% and 28.4% for the 3 and 5 m buffers, respectively (Table 1). As expected, adding these “insurance” zones increased the agreement between infested areas in fall and spring to 80.4% and 91.6%

when using 3 and 5 m buffers, respectively. The implementation of buffer zones around the weed patches has been recommended to encompass movements on weed populations and possible mapping errors (Rew et al. 1997). However, using buffers lead to a substantial increase in the sprayed area (Barroso et al. 2004).

Although our study only considered the use of harvest maps to make prescription maps for postemergence herbicide applications, it also is possible to use harvest maps for planning preplanting treatments. Because a proportion of Johnsongrass population can emerge prior to seeding, emerged patches could be destroyed site-specifically with a nonselective herbicide. The potential of pre-emergence patch spraying is minimal due to the very low control of this species by most of the pre-emergence herbicides available in the Spanish market.

Temporal Stability of Patches. Although the relative positions of the original patches remained almost unchanged from 1 yr to the next, the area infested by Johnsongrass increased in all the fields during the experimental period (Table 1), due to the expansion of existing patches and to new patches created by the dispersion of rhizomes by tillage. In field A, the proportion of the field infested in the fall of the first year was about 26%, increasing to over 40% in the next 2 yr. In field B, an initial infestation of about 19% increased to an area above 45% over the next 2 yr. In field C, the area infested increased from about 22% to 33% in 1 yr. Although this expansion might be surprising, considering that the fields were treated with specific herbicides for Johnsongrass control, other studies conducted in the same site and under similar conditions have indicated that control levels obtained with these herbicides frequently were below

Table 2. Percentages of agreement between the position of Johnsongrass patches in the fall and their respective position in the spring 2 and 3 yr later.

	Fall vs. Spring	Fall + 3 m vs. Spring	Fall + 5 m vs. Spring
Agreement (%)			
Comparison after 2 yr			
Field A			
October 2005 vs. May 2007	48.9	62.9	74.8
October 2006 vs. May 2008	69.5	79.1	89.9
Field B			
October 2006 vs. May 2008	46.0	49.1	68.1
October 2007 vs. May 2009	59.8	82.7	95.3
Field C			
October 2007 vs. May 2009	40.8	47.7	74.3
Average	53.0	64.3	80.5
Comparison after 3 yr			
Field A			
October 2005 vs. May 2008	41.5	54.9	68.1
Field B			
October 2006 vs. May 2009	23.9	34.9	64.8
Average	32.7	44.9	66.5

80% (Barroso, personal communication). Weed escapes from these treatments are able to perpetuate or even to expand Johnsongrass infestations, particularly under a continuous corn regime. Although this cropping system clearly is undesirable from the point of view of Johnsongrass management, economic reasons make this the prevailing cropping system in irrigated lands of Central Spain. A survey conducted in three corn-growing regions of Spain showed that the percentage of field area infested by Johnsongrass was four to eight times higher in Central Spain than in other regions where corn was rotated with other crops (Andújar et al. 2011).

The degree of agreement between the position of the patches found in the fall and the position of these patches in the spring 2 yr later decreased to 53%. Moreover, the degree of agreement with the positions 3 yr later (comparison made only in the fields A and B) was only 33% (Table 2). By adding 3 m buffers to the original patches it was possible to increase the percentages of agreement in the position of patches up to 64% and 45% for 2- and 3-yr periods, respectively. Adding 5 m buffers increased these percentages up to 81 and 67% for 2 and 3 yr, respectively (Table 2).

Due to the rhizomatous expansion of this weed, patch growth is relatively predictable. Previous studies have shown that patch growth takes place in the direction of tillage, with little displacement in the opposite direction and both sides (Andújar, unpublished data). Although abundant seed production was observed in the infested area, a very low number of Johnsongrass seedlings were detected inside the patches, and practically no seedlings were found outside these areas. Studies carried out in Argentina show that although

sexual and asexual reproductions occur simultaneously, and in spite of the large annual inputs of seeds, the soil seed bank is maintained at low levels due to heavy predation (Scopel et al. 1988). This could explain the predominant clonal growth of Johnsongrass populations. In addition, emerged seedlings are less competitive with the crop and are more sensitive to most herbicides. Apparently, the only significant role played by seeds may be the long-range dispersal caused by combine harvesters (Ghersa et al. 1993).

Economic Analysis. According to our estimates, the highest net returns could be obtained by spraying full rates of herbicides to patches recorded in the map generated in the previous fall, which improved net returns 1.4% over the no spray treatment (Table 3). Previous studies suggested that this strategy was more profitable on fields with lower infestation levels (Barroso et al. 2004; Luschei et al. 2001) and with higher patchiness (Oriade et al. 1996). Spraying the full- or half-rate over the entire field area resulted in slightly lower returns. Spraying the full herbicide rate on infested areas and half rates in the rest of the field resulted in the lowest net returns. Adding a 3-m buffer to the infested area detected the previous fall increased the net returns, reaching levels similar to the most profitable strategy (Table 3). Adding a 5 m buffer did not result in any significant improvement (data not shown). Although the economic differences among strategies were not significant, the herbicide reduction potential of site-specific strategies could lead to increased interest in these techniques in three different scenarios: (1) if one of the farmer's objectives is to reduce herbicide residues in food; (2) if herbicide prices increase; or (3) if government regulations promote a reduction in the usage of agricultural pesticides.

The economic feasibility of planning herbicide treatments based on weed maps is conditioned by patch stability. If location and density of weed patches remains consistent over time, maps from one year could be used to plan herbicide application in subsequent years. Our simulation showed that using maps obtained in the fall to predict the position of Johnsongrass patches 2 or 3 yr later resulted in a decrease of economic benefits compared with the strategy based on maps obtained the previous year. In the specific case of patch spraying the full rate of herbicide, net returns obtained by using maps generated 2 and 3 yr in advance were reduced by 2.2% (\$29 ha⁻¹) and 4.6% (\$62 ha⁻¹), respectively (Table 3). This is consistent with a study by Colbach et al. (2000) who, working with an annual grass, concluded that although data from one season could be used to predict forward into the following season, longer predictions were too inaccurate.

Herbicide Volume Reduction. Spraying full rates of herbicides to Johnsongrass patches mapped during the previous fall resulted in an average 65% reduction in the volume of herbicide applied to control this weed (Table 4). This reduction was even larger (83%) when the patches were sprayed with half rates of herbicides. Using a low-risk strategy based on applying full rates to the detected patches and half rates to the rest of the field resulted only in a 33% of herbicide volume reduction. Using a 3-m buffer around the detected

Table 3. Estimated net returns (\$ ha⁻¹) according to Equation 1 for different herbicide strategies to control Johnsongrass based on the map generated the previous year, the same areas plus a 3-m buffer, and these infested areas defined in the map generated 2 and 3 yr in advance. Estimated net returns are shown as a percentage of the no-spray treatment.

Herbicide strategy based on:	Estimated net returns								Average
	Field A			Field B			Field C		
	2006	2007	2008	2007	2008	2009	2008	2009	
No spray (\$ ha⁻¹)	1,390	1,367	1,366	1,440	1,275	1,223	1,402	1,321	1,348
Overall, 1× rate (%)	97.4	99.0	99.1	94.0	106.2	110.7	110.7	102.5	100.4
Overall, 0.5× rate (%)	98.8	99.7	99.8	96.9	103.8	106.3	106.0	101.7	100.5
<i>Map of the previous year</i>									
Site-specific, 1× rate (%)	100.3	101.0	101.0	97.8	104.4	106.5	101.0	101.5	101.4
Site-specific, 0.5× rate (%)	99.2	99.6	99.6	97.8	101.5	102.7	99.2	99.9	99.8
Site-specific, 1×–0.5× rate (%)	97.6	98.7	98.7	94.7	104.1	107.4	97.6	100.9	99.7
<i>Map of previous year + 3 m buffer</i>									
Site-specific, 1× rate (%)	99.8	100.0	100.3	97.3	104.3	107.6	99.8	101.7	101.2
Site-specific, 0.5× rate (%)	98.9	99.1	99.2	97.5	101.3	103.2	99.2	99.9	99.6
Site-specific, 1×–0.5× rate (%)	97.3	98.2	98.5	94.4	104.2	108.0	97.3	101.0	99.6
<i>Map of 2 yr earlier</i>									
Site-specific, 1× rate (%)	-	99.3	99.9	-	103.0	105.2	-	100.4	97.8
Site-specific, 1× rate + 3m buffer (%)	-	99.3	99.1	-	103.5	109.5	-	100.9	99.4
<i>Map of 3 yr earlier</i>									
Site-specific, 1× rate (%)	-	-	98.6	-	-	100.2	-	-	95.4
Site-specific, 1× rate + 3m buffer (%)	-	-	98.6	-	-	101.6	-	-	96.1

patches increased the area to be treated and significantly reduced the herbicide reduction obtained with the three site-specific strategies (Table 4).

Although the largest herbicide reductions were obtained with site-specific application at half-rates of herbicides, this strategy involves considerable risks. Various authors have shown that low rates of herbicides can increase the risk of control failure under adverse environmental conditions and under high weed densities (Belles et al. 2000; Zhang et al. 2000). Furthermore, in patch-spraying systems, there is a higher chance of reinfestation from isolated plants present outside the patches (or not detected) and, consequently, not treated in the previous year.

Herbicide volume reduction differed substantially between fields and between years in the same field. Our simulation showed that spraying patches with the full rate of herbicide in field B resulted in 81% herbicide reduction in 2007 (with

19% of the field infested) and only 48% in 2009 (with 52% of the field infested). In general, the highest reductions were obtained in field C, with the lowest levels of infestation (average 29%), whereas the lowest reductions were obtained in field B, with the highest levels of infestation (average 39%). Thus, herbicide reductions were inversely proportional to the infested area in the field.

Previous studies have reported herbicide reductions resulting from patch spraying higher than 75% in corn crops infested with grass weeds (Gerhards and Christensen 2003; Timmermann et al. 2003). In winter cereals, reported reductions reached up to 74% when herbicide rates were adjusted to the densities of wild oats present in different zones of the fields (Ruiz et al. 2006a). All these results indicate the possibility of obtaining an environmental benefit by using site-specific weed management technologies, which can contribute significantly to preserve environmental quality by minimizing the use of herbicides.

Table 4. Estimated herbicide volume reduction (%) for the three site-specific herbicide application strategies to control Johnsongrass. In the simulations, the treatments were applied to the infested areas defined in the map generated the previous year only, or to the same areas plus a 3 m buffer.

Herbicide strategy based on:	Estimated herbicide volume reduction (%)								Average
	Field A			Field B			Field C		
	2006	2007	2008	2007	2008	2009	2008	2009	
<i>Map of the previous year</i>									
Site-specific, 1× rate	74	60	60	81	55	48	78	67	65
Site-specific, 0.5× rate	87	80	80	90	78	74	89	83	83
Site-specific, 1×–0.5× rate	37	30	30	40	28	24	39	33	33
<i>Map of previous year + 3 m buffer</i>									
Site-specific, 1× rate	61	41	51	71	47	31	75	51	54
Site-specific, 0.5× rate	80	71	75	86	73	66	87	76	77
Site-specific, 1×–0.5× rate	30	21	25	36	23	26	27	26	27

Sources of Materials

- ¹ Tablet computer, Stylistic 2300, Fujitsu Personal System, Santa Clara, CA.
- ² Software, Real-time system for acquiring georeferenced visual assessments. System developed at Instituto de Automática Industrial (now Centro de Automática y Robótica), Spain.
- ³ Differential geopositioning system receiver, Hemisphere Crescent R130 DGPS with Omnistar differential correction, Hemisphere GPS Inc. Calgary, AB.
- ⁴ ArcInfo® 9.2, ESRI, Redlands, CA.
- ⁵ SPSS 15.0 (Statistical Product and Service Solutions), SPSS, Chicago, IL.

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