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Response of *Sorghum halepense* demographic processes to plant density and rimsulfuron dose in maize

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Summary

In spatially heterogeneous weed infestations, variable dose technologies could be used to minimise herbicide use; high doses could be applied to reduce high-density patches and low doses to maintain weed populations in low-density portions of a field. To assess the potential short- and long-term effects of variable herbicide dose and site-specific management, the major weed demographic processes were described and parameterised in this study. Various doses of rimsulfuron (from 0 to 12.5 g a.i. ha^{-1}) were applied to different densities of *Sorghum halepense* (0–100 plants m^{-2}). Contrary to similar studies with other weed species, higher herbicide efficacy was not observed at low densities, suggesting that the same rimsulfuron dose should be applied regardless of the *S. halepense* density. The highest percentage of control was obtained with the full rimsulfuron dose. However, it did not guarantee a decrease of the infestation in the following season in the field areas where the initial *S. halepense* density was lower than 60 plants m^{-2}. Reduced doses of rimsulfuron to control *S. halepense* cannot be recommended based on our results.

Keywords: Johnsongrass, *Zea mays*, weed density, rimsulfuron, percentage control.

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Introduction

Sorghum halepense (L.) Pers. is one of the most common and troublesome perennial weeds in crop production areas of Mediterranean, tropical and subtropical climates (Holm *et al*., 1977). In continuous maize systems, *S. halepense* has been reported to reduce crop yields up to 100% through competition for light and other resources (Bendixen, 1986). Rapid growth from underground rhizomes, extensive production of rhizomes and prolific seed production contribute to rapid population growth, making *S. halepense* difficult to control (Ghosheh *et al*., 1996; Andújar *et al*., 2012).

In Spain, the selective control of *S. halepense* in maize crops is based on the use of three specific sulfonylureas: nicosulfuron, foramsulfuron and rimsulfuron. These three products, applied at the recommended doses, have been reported to result in adequate control of this species with no damage to the crop in several other countries (Eleftherohorinos &

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Kotoula-Syka, 1995; Damalas & Eleftherohorinos, 2001; Baghestani *et al*., 2007; Kir & Dogan, 2009). However, due to economic and environmental objectives, reduction in herbicide use is a desirable target in crop production. Variable herbicide dose and site-specific applications are two possible tactics to achieve increased economic returns and reduce environmental effects (Andújar *et al*., 2013).

Numerous authors have shown that, under certain conditions, reducing herbicide doses may result in acceptable weed control and minimum yield losses for different weeds in maize (Pannacci & Covarelli, 2009; Liebman *et al*., 2008; Nadeem *et al*., 2008; Dogan *et al*., 2005; Hamill *et al*., 2004). In the specific case of *S. halepense*, various studies have shown excellent weed control without yield losses with reduced doses of rimsulfuron, primisulfuron, nicosulfuron, fluazifop-P, foramsulfuron and clethodim (Rosales-Robles *et al*., 1999; Kir & Dogan, 2009; Eleftherohorinos & Kotoula-Syka, 1995; Nosratti *et al*., 2007).

In spatially heterogeneous weed infestations, variable dose technologies can be used to accomplish the same economic and environmental objectives, adjusting the herbicide dose to the spatial variability of weed density (Christensen *et al*., 2003; Gerhards & Oebel, 2006). This concept is based on the assumption that, in low-density areas, a low herbicide dose will often be sufficient to reduce weed growth to such an extent that they will have no effect on crop yield. In areas with high weed density, full doses may be appropriate because overlapping weed canopy and reduced spray interception can reduce efficacy (Dieleman *et al*., 1999). Low and spatially variable doses may result in residual populations and represent a risk of large weed populations in following seasons. Dicke and Kühbauch (2006) observed that site-specific herbicide application resulted in increased density of weeds in continuous maize over a period of 6 years. There is limited knowledge on the long-term effect of variable dose applications on weed populations. In order to develop predictive weed population models, it is necessary to quantify the demographic responses to low and spatially variable dose applications of herbicides.

Although the influence of weed density and herbicide dose on various demographic processes has been studied in a few cases (Wille *et al*., 1998; Dieleman *et al*., 1999; Belles *et al*., 2000; Bussan *et al*., 2000, 2001), the long-term response is poorly understood. In the specific case of *S. halepense*, the dense canopy established by high densities of this plant and the presence of rhizomes (that are minimally affected by most herbicides) make controlling this weed particularly difficult to predict, even at low densities and with high herbicide doses. We recognise the additional concern of selecting for resistance with low herbicide doses (Neve & Powles, 2005), but chose to assume that selection pressure for resistance is approximately constant by varying dose with weed density. A better understanding of the influence of *S. halepense* density dependence on survivorship and reproduction (both sexual and asexual) and their interaction with management is required to determine the feasibility of using variable dose herbicide applications.

The objectives of this research were to determine the response of different *S. halepense* densities to rimsulfuron herbicide at full and reduced doses. Specifically, we assessed the herbicide impact on different demographic parameters (plant survival, seed production, biomass production and rhizome bud production), and effects on the next generation of *S. halepense*. Maize yield in relation to *S. halepense* density and rimsulfuron dose was also evaluated. These goals are proposed as a step towards a more complete understanding of *S. halepense* population dynamics under site-specific patch spraying techniques over short- and long-term periods.

Materials and methods

Experimental site and design

The study was conducted in 2009 and 2010 at La Poveda Research Station, 25 km east of Madrid (Central Spain – 40°18′N, 3°29′W, 618 m elevation). Previous 30-year average annual rainfall was 350 mm, mainly distributed in the autumn and spring. Consequently, summer crops are grown under irrigation. The experimental field was located on a flat alluvial plain in the Jarama River Basin on a sandy loam soil (39% sand, 47% silt, 14% clay) with 1.4% organic matter and a pH of 7.9. In both years, the experiments were established in two nearby *S. halepense*-free areas. Maize (cv. Helen, FAO 700 class hybrid) was sown with 0.75 m row spacing with a target population of 80 000 plants ha^{-1}. Maize was sown on 13 April and 7 April in 2009 and 2010 respectively. The maize field had been in continuous maize cropping since 2006. The experimental design was a split-plot design with three blocks. Each block was formed by main plots (13.5 m × 2.5 m) for the different herbicide doses (0, 0.25, 0.5 and 1X). Rimsulfuron (Titus®, DuPont Iberica S.L., 250 g a.i. kg^{-1}), a selective herbicide for the control of *S. halepense* in maize, was used. The full dose (1X = 12.5 g a.i. ha^{-1}) was the recommended dose on the product label. A vegetable oil adjuvant (Codacide®, Cheminova Agro S.A.) was added at 2.5 L ha^{-1} to improve the herbicide efficacy. Each of the main plots had five subplots which were sown with different densities of *S. halepense* (0, 5, 20, 50 and 100 pieces of rhizome m^{-2}). The subplots were 2.5 m long (in the direction of the crop row) and 1.5 m wide (perpendicular to the crop rows), that is including three rows of maize, and were randomly distributed inside each main plot. Likewise, each main plot was randomly distributed inside each block. The space between subplots was 1.5 m and the space between main plots and blocks of 2.5 m. The rhizomes (i.e. bud pieces containing two nodes) used for manual seeding of the subplots were collected the previous fall of each season in a nearby *S. halepense*-infested field and maintained under natural conditions (i.e. buried in the soil) during the 5 months prior to the experiment. The seedbed was prepared with a single pass of a disc harrow at the end of March, followed by a cultivator with roller at the beginning of April in both years. The crop was sown with a pneumatic seeder of four lines (PL Junior 4, Kuhn-Nodet®) just after the seeding of *S. halepense*. Herbicide treatments were applied when the crop was at the five-leaf stage in 2009 and the three- to four-leaf stage in 2010, using a plot sprayer with a 3 m wide boom and a volume of 200 L ha^{-1}, on 22 May and 18 May in 2009 and 2010 respectively. Broad-leaved weeds in the subplots were manually removed throughout the season. The plots were fertilised at the end of March with 500 kg ha^{-1} of 8-15-15 (N-P-K), and at the beginning of June with 240 kg ha^{-1} of urea (46%) in both years. Tillage after harvest of 2009 consisted of a single pass of a disc harrow on 29 November and a single pass of a mouldboard plough on 18 December.

Weed and crop monitoring

Plants of *S. halepense* (all of them coming from rhizome sprouts) were counted and marked with a coloured wire ring 1–2 days before the herbicide application. Sampling was conducted over the entire subplot (3.75 m^2) planted at 5 pieces of rhizomes m^{-2}, in one interrow space, that is half subplot (1.875 m^2) in subplots planted at 20 pieces of rhizomes m^{-2}, and in one permanent established rectangular frame of 1 m × 0.5 m per subplot for densities of 50 and 100 pieces of rhizomes m^{-2}. *Sorghum halepense* plants were evaluated 3 weeks after herbicide treatment (WAT). At this time, plant survival was estimated and the new emerged plants were ringed in the same colour in 2009 and in a different colour in 2010. At the end of each season, 1 day before maize harvest, plant survival, plant biomass, panicle production, seed production and rhizome production of *S. halepense* were measured. Plant survival, plant biomass and panicle production were estimated in the same areas described above. Seed production was evaluated from ten panicles selected randomly from each subplot. Rhizome production was estimated by digging a quadrat area of 0.5 × 0.5 m and 0.3 m depth in each subplot. The crop assessment consisted of measuring maize yield and the weight of 1000 grains per subplot at harvest time. Maize yield was collected manually from the central maize row of each subplot. Maize grain as well as *S. halepense* plant biomass and rhizome were dried in an oven at 70°C for 48 h for dry weight determination. In 2010, before drying the rhizomes, ten random rhizome samples from every subplot were used to evaluate the effect of *S. halepense* density and rimsulfuron dose on the internode length and the thickness of rhizomes (two diameters, the largest and the smallest) were measured. The population of *S. halepense* (plants m^{-2} and biomass m^{-2}) was also measured in the spring of the following season (12 May 2010 and 28 April 2011) using two rectangular frames of 0.66 m × 0.33 m in each subplot.

Statistical analysis

Statistical analyses were performed using the R software (R Development Core Team, 2014). Generalised linear models were used to determine whether year, weed density and rimsulfuron dose influenced significantly different *S. halepense* demographic processes (*S. halepense* survivorship, seed production, biomass production, rhizome production and *S. halepense* density in the following season) and maize yield. Nonlinear regressions were used to assess the effect of *S. halepense* density and rimsulfuron dose on the different demographic processes and maize yield.

Sorghum halepense survival

The relationship between *S. halepense* density 3 weeks after treatment ($N_{3\mathrm{WAT}}$) and at the end of the season (N_{end}) as a function of initial *S. halepense* density (N_i) and rimsulfuron dose (R) was characterised with an exponential function similar to the one described by Lindquist *et al.* (1995), but replacing one parameter with a dose–response curve (Seefeldt *et al.*, 1995; Streibig *et al.*, 1993) and adding a term to account for the year effect when it was significant (Eqns 1 and 2):

$$N_{3\mathrm{WAT}} = N_i * \left[P_m \frac{\exp(-fN_i)}{(1+\exp(b(\log(R)-\log(r50))))}\right] + \mathrm{gYear} \quad (1)$$

$$N_{\mathrm{end}} = N_i * \left[P_m \frac{\exp(-fN_i)}{(1+\exp(b(\log(R)-\log(r50))))}\right] \quad (2)$$

where $N_{3\mathrm{WAT}}$ was the *S. halepense* density 3 weeks after treatment (plants m^{-2}), N_{end} was the *S. halepense* density at the end of the season (plants m^{-2}), N_i was the initial *S. halepense* density (plants m^{-2}), P_m fitted the maximum value of the response variable (N_{3WAT} or N_{end}) from N_i, R was the rimsulfuron dose in g a.i. ha^{-1}, $r50$ was the rimsulfuron dose that caused an inhibition of 50% in the response variable (N_{3WAT} or N_{end}), b was the slope of the curve at $r50$, and f was the rate of decay as *S. halepense* density increased. Year was a binary variable (0 for 2009 and 1 for 2010) added to the equation when the response variable was significant with the year and g was an intercept adjustment accounting for the year effect.

Sorghum halepense seeds, rhizomes and biomass production

The relationship between *S. halepense* density at the end of the season and herbicide dose with respect to seeds per plant, biomass per plant (g) and rhizomes per plant (g) was explored with a variant of Cousens' model (Cousens, 1985), plus a term to account for the year effect when it was significant (Eqns 3 & 4). Rhizome buds per plant was explored with Cousens' model plus a term to account for the year effect (Eqn 5):

$$S_{pp}/B_{pp} = S_{ppmax}/B_{ppmax}\left(1 - \frac{i * N_{end}}{1 + i * N_{end} * \exp(b(\log(R) - \log(r50)))}\right) \quad (3)$$

$$R_{pp} = R_{ppmax}\left(1 - \frac{i * N_{end}}{1 + i * N_{end} * \exp(b(\log(R) - \log(r50)))}\right) + g\text{Year} \quad (4)$$

$$R_{budspp} = R_{budsppmax}\left(1 - \frac{i * N_{end}}{\left(1 + \frac{i * N_{end}}{a}\right)}\right) + g\text{Year} \quad (5)$$

where S_{pp}, B_{pp}, R_{pp} and R_{budspp} were the corresponding dependent variables (seeds per plant, biomass per plant (dry weight per plant), rhizomes per plant (dry weight per plant) or buds of rhizome per plant), S_{ppmax}, B_{ppmax}, R_{ppmax} and $R_{budsppmax}$ were the maximum values of the respective dependent variables, N_{end} was the *S. halepense* density at the end of the season, i accounted for the density effect when density is low, a accounted for the density effect when density approached infinity, and R, b, $r50$, g and Year were the same as in Eqns (1) and (2).

Crop yield

The relationship between *S. halepense* density at the end of the season and herbicide dose with respect to maize yield was explored with an equation similar to Eqn (4) (Eqn (6)):

$$Y = Y_{max}\left(1 - \frac{i * N_{end}}{1 + i * N_{end} * \exp(b(\log(R) - \log(r50)))}\right) + g\text{Year} \quad (6)$$

where Y was the maize yield (kg ha^{-1}), Y_{max} was the maximum value of yield (kg ha^{-1}), and i, N_{end}, b, R, $r50$, g and Year were the same as in previous equations.

Sorghum halepense plant density the following season

Finally, the relationship between *S. halepense* density at the end of the growing season and rimsulfuron dose with respect *S. halepense* plants the following season was described by Eqn (7):

$$N_{i+1} = N_{end} * \left[P_m \frac{\exp(-fN_{end})}{(1 + \exp(b(\log(R) - \log(r50))))}\right] + g\text{Year} \quad (7)$$

where N_{i+1} was the *S. halepense* plants the following season, and N_{end}, P_m, f, b, R, $r50$, g and Year were described previously.

Results

Sorghum halepense survival

The emergence of *S. halepense* plants from the pieces of rhizomes planted was variable, depending on the planting density. Whereas the proportion of emergence for all treatments was 27.3% in the lowest density (5 pieces of rhizome m^{-2} (10 rhizome buds m^{-2})), it was 52.1% in the highest density (100 pieces of rhizome m^{-2} (200 rhizome buds m^{-2})) (Table 1). Variation in *S. halepense* plant density 3WAT was characterised well with initial density, herbicide dose and year. The density 3WAT decreased linearly with respect to the initial density when rimsulfuron dose increased (the parameter f of the exponential term in the equation was not significant, Table 2). The negative g parameter indicated a higher herbicide efficacy in 2010. Variation in *S. halepense* density at the end of the season was accounted for with the initial density and rimsulfuron dose, but not with year. The density at the end of the growing season decreased when rimsulfuron dose and/or initial density increased (Fig. 1). According to Eqn (2), with the full herbicide dose, *S. halepense* density decreased 38.4% and 44% with an initial density of 5 and 100 plants m^{-2} respectively. Values higher than 1 in the parameter P_m indicated that there were new emergences of *S. halepense* plants following herbicide treatment

Table 1 Plant emergence, survivorship and mortality of *Sorghum halepense* in subplots with different planting densities in the absence of herbicide treatments (R = 0X). Standard deviations are indicated in parentheses

Average data of both years (2009 and 2010)

Planting density per m^2		Plants emerged per m^2		Plant emergence (%)	Plants survived per m^2	Plant mortality (%)
Pieces of rhizome	Buds	1st cohort	2nd cohort	1st cohort	1st + 2nd cohort	1st + 2nd cohort
5	10	2.84 (±1.14)	0.9 (±0.65)	28.4	3.28 (±1.54)	12.3
20	40	10.18 (±5.31)	1.42 (±0.73)	25.45	11.51 (±5.60)	0.8
50	100	55.35 (±10.5)	6.67 (±4.50)	55.35	50.73 (±16.63)	18.2
100	200	111.75 (±24.4)	12 (±3.79)	55.87	101.58 (±26.51)	17.9

Average data of 2010

Planting density per m^2		Plants emerged per m^2		Plant survived per m^2		Plant mortality (%)	
Pieces of rhizome	Buds	1st cohort	2nd cohort	1st cohort	2nd cohort	1st cohort	2nd cohort
5	10	3.64 (±0.67)	1.07 (±0.96)	3.64 (±0.67)	0.71 (±0.62)	0	33.6
20	40	14.49 (±3.70)	1.78 (±0.82)	14.33 (±3.50)	1.60 (±0.53)	1.1	10.1
50	100	63.9 (±3.50)	3.33 (±2.31)	62.53 (±4.12)	2.67 (±3.01)	2.1	19.8
100	200	116.7 (±6.32)	10.67 (±5.03)	103.95 (±3.94)	8.0 (±5.29)	10.9	25.0

Table 2 Parameters of *Sorghum halepense* density 3 weeks after treatment (N_{3WAT}) and at the end of the growing season (N_{end}), as influenced by rimsulfuron dose, initial *S. halepense* density and year effect, according to Eqns (1) and (2) (equations are indicated in the Materials and Methods section)

Parameters	P_m	b	log($r50$)	f	g
	N_{3WAT}				
Estimates	0.957	7.30	1.35	−0.002	−1.36
Standard error	0.031	3.51	0.119	0.002	0.800
P-values	<0.001	0.041	<0.001	0.413	0.092
	N_{end}				
Estimates	1.100	2.1	1.22	0.001	–
Standard error	0.214	0.993	0.139	0.0003	–
P-values	<0.001	0.037	<0.001	0.002	–

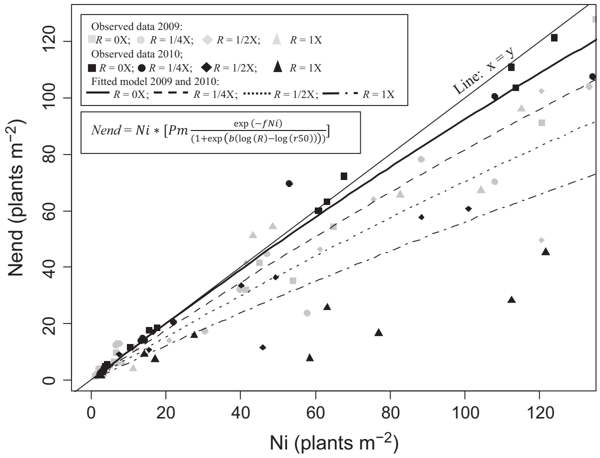

Fig. 1 Influence of initial *Sorghum halepense* density (N_i) and rimsulfuron doses (R) on *S. halepense* density at the end of the season (N_{end}). Parameters of the equation (Eq. 2) are presented in Table 1.

(Table 2). The second cohort, plants that emerged between herbicide treatment and 3WAT, added significantly to the initial densities when the initial density was low, but not when the initial density was high (data are not shown). The maximum emergence rate for the second cohort was approximately 30%, compared with the first cohort. The mortality of the plants emerging later in the season was higher than the mortality of plants emerging earlier, even though both mortality rates were influenced by the density present. The lowest mortality rate at the end of the season, which occurred at low *S. halepense* initial densities (5 pieces of rhizomes m^{-2}), was 0% for the first cohort versus 33.6% for the second cohort (Table 1).

Sorghum halepense seeds, rhizomes and biomass production

Seeds per plant (sexual reproduction) and biomass per plant were significantly reduced with increasing rimsulfuron dose and/or *S. halepense* density at the end of the season (Fig. 2A). There was no year effect with these relationships (Table 3). According to Eqn (3), seeds produced per plant were 2638 at a density of 1 plant m^{-2}, and 975 (a 63.0% decrease) at 100 plants m^{-2} with no herbicide applied. The half herbicide dose reduced the seed produced per plant by 10.5% and 81.3% for 1 and 100 plants m^{-2}, respectively, and the full dose by 14.5% and 100% respectively.

Rhizome biomass produced per plant (vegetative reproduction) was reduced with increasing *S. halepense* density at the end of the season and/or herbicide dose. This relationship also had a significant year effect (Fig. 2B, Table 3). Rhizome buds per plant were

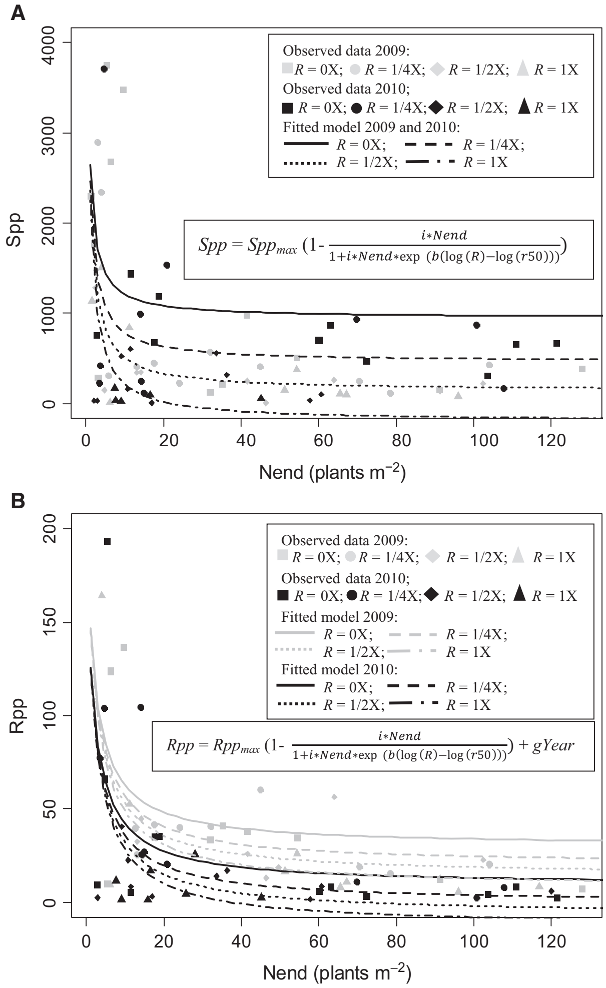

Fig. 2 Influence of *S. halepense* density at the end of the season (N_{end}) and rimsulfuron dose (R) in: (A) seeds per plant (S_{pp}) and (B) rhizomes per plant (R_{pp}) (dry weight (g)). Parameters are presented in Table 3.

reduced with increasing *S. halepense* density at the end of the season, and there was a year effect, but no herbicide dose response (Table 3). Rhizome thickness increased with decreasing *S. halepense* densities and decreased with increasing rimsulfuron dose. The rhizome internode length maintained an average of 0.027 m (±0.014 SD) for different densities and herbicide doses. In 2010, surviving plants produced fewer rhizomes (in number of buds and weight) than in 2009 (Table 3, Fig. 2). Increasing *S. halepense* plant density affected the number of buds and biomass of rhizomes more than seed production. According to Eqns (4) and (5), without herbicide treatment, increasing density from 1 plant m^{-2} to 100 plants m^{-2} decreased buds and biomass of rhizomes 87.4% and 77.3% respectively. However, seed production decreased 63% in the same density range (parameters b and i in the response of S_{pp} were smaller and bigger, respectively, than in R_{pp} or R_{budspp} (Table 3)).

Sorghum halepense plant density the following season

The densities of *S. halepense* plants emerged 1 year after the various treatments were applied decreased with increasing rimsulfuron dose, with a significant year effect. There were higher densities in the season following 2010 than in the season following 2009. In relation to previous density, low and moderate densities of *S. halepense* at the end of the initial season (i.e. 1 to 40 plants m^{-2}) increased sharply in the following year, but high or very high densities at the end of the initial season decreased relatively depending on the herbicide dose applied (Fig. 3). The intersection of the line $x = y$ with the fitted models in Fig. 3 shows (on the X axis) the density at the end of the first season where the relative density started to decrease in the following year. In 2009, without herbicide treatment, it happened beyond 120 plants m^{-2}, and with full herbicide dose, it happened beyond 75 plants m^{-2}.

Crop yield

Maize yield was reduced with increasing *S. halepense* plant density and decreasing herbicide dose (Fig. 4). There was a significant year effect: yields were higher in 2009 than in 2010. According to Eqn (6), there was a 54.3%, 9.5% and 2.1% yield loss with 100, 5 and 1 plants m^{-2}, respectively, in comparison with the *S. halepense*-free yield. The full herbicide dose had a yield increase of 102.2%, 116.0%, 141.7% and 170.7% in comparison with no herbicide treatments for the densities 5, 20, 50 and 100 plants m^{-2} respectively. Even though the yield increased with all herbicide doses, the herbicide did not avoid certain yield losses. With full herbicide dose, these losses ranged from 7.6% (with densities of 5 plants m^{-2}) to 22% (with densities of 100 plants m^{-2}). The dry weight of 1000 maize grains did not decline with increasing initial *S. halepense* density and rimsulfuron dose in either year. Differences in yield might be due to ear size or number of grain per year, rather than to the formation/maturation of the maize grain.

Discussion

Previous studies, conducted with various herbicides and weeds, reported higher herbicide efficacy on lower weed densities (Burrill & Appleby, 1978; Winkle *et al.*, 1981; Wille *et al.*, 1998). This response was not observed for the combination of *S. halepense* and rimsulfuron. In order to understand this response, it is convenient to consider the partial effects on the various demographic processes. Although plant survival

Table 3 Parameters of seeds per plant (S_{pp}), biomass per plant (B_{pp}), rhizomes per plant (R_{pp}) and buds of rhizomes per plant (R_{budspp}) of *Sorghum halepense* as influenced by rimsulfuron dose, *S. halepense* density at the end of the season and year (in the case of rhizome production), according to Eqns (3), (4) and (5). $S_{ppmax}/B_{ppmax}/R_{ppmax}/R_{budsppmax}$ were the maximum *S. halepense* seeds per plant, biomass per plant, weight of rhizomes per plant and buds of rhizomes per plant observed in the study. *i, b,* log(*r50*), *a* and *g* are the estimated parameters of Eqns (3), (4) and (5) (equations are indicated in the Material and Methods section).

Parameters	$S_{ppmax}/B_{ppmax}/R_{ppmax}/R_{budsppmax}$	*i*	*b*	log(*r50*)	*a*	*g*
	S_{pp}					
Estimates	5257	1.27	−0.214	0.929	–	–
Standard Errors		0.375	0.058	0.163		
P-values		0.002	<0.001	<0.001		
	B_{pp}					
Estimates	196.9	2.215	−0.210	1.077	–	–
Standard Errors		0.611	0.042	0.139		
P-values		<0.001	<0.001	<0.001		
	R_{pp}					
Estimates	193.1	0.338	−0.116	1.448	–	−20.84
Standard Errors		0.086	0.067	0.587		7.594
P-values		<0.001	0.088	0.016		0.008
	R_{budspp}					
Estimates	173.6	0.303	–	–	0.891	−21.4
Standard Errors		0.079			0.037	7.17
P-values		<0.001			<0.001	0.004

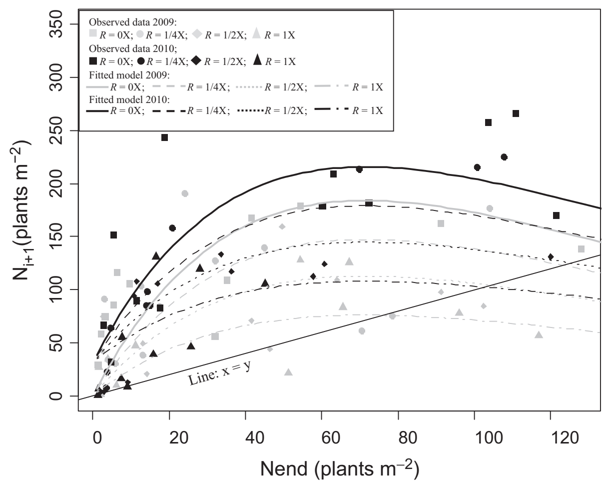

Fig. 3 Effect of previous *Sorghum halepense* density (N_{end}) and rimsulfuron herbicide (*R*) on *S. halepense* density the following season (N_{i+1}). The effect was represented through Eqn (7): $N_{i+1} = N_{end} * \left[7.82(\pm1.80)\frac{\exp(-0.014(\pm0.001)N_{end})}{(1+\exp(2.43(\pm1.23)(\log(R)-0.881(\pm0.186))))}\right]$ $+31.8(\pm7.84)$Year. Parameter standard errors are indicated in parentheses. All parameters were significant ($P < 0.001$) with the exception of parameter *b* ($P = 0.052$).

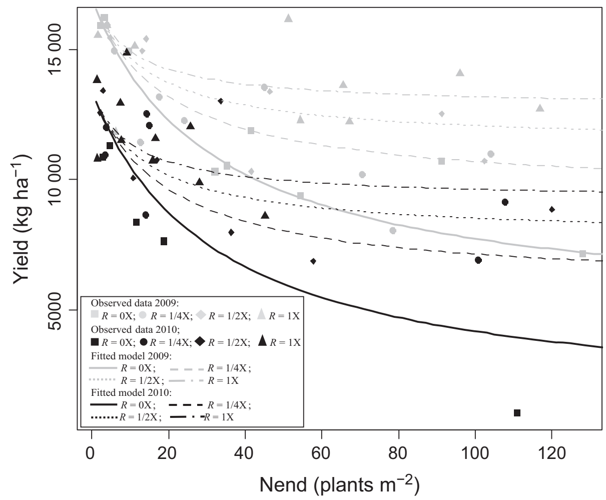

Fig. 4 Effect of *S. halepense* density (N_{end}) and rimsulfuron dose (*R*) on maize yield (*Y*). The effect was represented with Eqn (6): $Y = 16,889 * \left[1 - \frac{0.022(\pm0.005)*N_{end}}{(1+0.022*N_{end}*\exp(0.984(\pm0.170)(\log(R)+0.333(\pm0.178))))}\right]$ $-3554(\pm347.4)$Year. Parameter standard errors are indicated in parentheses. All parameters were significant ($P < 0.001$) except the parameter log(*r50*) ($P = 0.066$).

measured 3WAT decreased with increasing rimsulfuron doses, this response was not influenced by weed density. This linear response with weed density was also found by Dieleman *et al.* in 1999 working with *Abutilon theophrasti* Medik. and *Helianthus annuus* L. However, other authors (Winkle *et al.*, 1981; Pannell, 1990) found a decreased herbicide efficacy with increasing weed densities. They attributed this effect to the decreased absorption/interception of herbicide per plant as plant population increased. *Sorghum halepense* canopy architecture is erect and, consequently, it is likely that the interception mechanism is not acting in this weed. In addition, at the time of herbicide application, *S. halepense* vegetative shoots were all of similar size and overlapping between leaves was low, even at the highest densities. However, the subsequent new germinations (cohorts) and mortality of *S. halepense* plants was dependent on their density, resulting in a curvilinear herbicide response.

At the end of the season, the relative effect of rimsulfuron on seeds produced per plant, biomass per plant and rhizome biomass per plant was greater at higher *S. halepense* densities than at lower densities. We offer four possible explanations for these results: (i) high intraspecific weed competition at high densities resulted in weaker plants with less ability to recover from the rimsulfuron treatment; (ii) a higher emergence of the second cohort (plants that emerged 3 WAT) at low densities (these plants escaped herbicide treatment); (iii) higher release and accumulation of allelochemicals produced by *S. halepense* in the high-density plots in addition to the herbicide effect (Stef *et al.*, 2013; Rout *et al.*, 2013); and (iv) erect canopy architecture of *S. halepense* does not limit post-emergence herbicide contact with the plants at high densities.

Biomass per plant, seeds per plant and rhizome biomass per plant were the three demographic processes more strongly impacted by rimsulfuron dose, while number of buds produced on rhizomes and plant density at the end of the season was less responsive. Similarly, Damalas and Eleftherohorinos (2001) found that fresh weight of *S. halepense* 30 days after rimsulfuron treatment was more affected than stem number. Although rimsulfuron always increased maize yield in comparison with the non-treated plots (132.6% averaged over the four *S. halepense* densities), even the full rimsulfuron dose did not prevent yield losses (16.3% in comparison with no infestation). This is in agreement with previous studies (Baghestani *et al.*, 2007).

In spite of the application of rimsulfuron, populations of *S. halepense* increased in the following year in practically all cases. The only exception was when the full dose of rimsulfuron was applied on high *S. halepense* densities and soil was tilled (disc harrow plus mouldboard plough) during the following winter. These operations could have cut rhizomes into smaller pieces and encouraged their dehydration (McWhorter, 1972). In addition, seedbed preparation could have killed emerged *S. halepense* plants before seeding (Rasmussen, 2004). The poor efficacy of rimsulfuron to control the *S. halepense* population might have also been due to an increase in herbicide resistance in this species to sulfonylurea herbicides, as it was recently observed in the Catalonia region (north-east of Spain) (pers. comm. J Barroso). However, when we initiated this study, farmers in our region did not suspect *S. halepense* to be rimsulfuron resistant. There are few cases cited to date for *S. halep*ense resistant to rimsulfuron, with one reported in México in 2009 (Heap, 2015).

Rimsulfuron treatments reduced maize yield losses and affected all *S. halepense* demographic processes. However, these treatments did not prevent the growth of this species in the following season. Although the use of reduced rimsulfuron doses led to more unfavourable results, it would be necessary to make an economic evaluation to assess the profitability of these doses. According to our results, variable dose technologies should not be used in spatially heterogeneous *S. halepense* infestations to minimise rimsulfuron use. The equations developed in this work to predict yield and infestation in the current and following season represent valuable knowledge to be included in simulation models of population dynamics to inform long-term management of *S. halepense*.

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