Spanish Journal of Agricultural Research
14(3), e1005, 9 pages (2016)
eISSN: 2171-9292
http://dx.doi.org/10.5424/sjar/2016143-9436
Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA)

RESEARCH ARTICLE

OPEN ACCESS

Optimization of foramsulfuron doses for post-emergence weed control in maize (*Zea mays* L.)

Euro Pannacci

University of Perugia, Department of Agricultural, Food and Environmental Sciences, Perugia, 06121 Italy.

Abstract

Four field experiments were carried out from 2011 to 2014 in order to evaluate the effects of foramsulfuron, applied at the recommended (60.8 g a.i./ha) and reduced doses (1/3 and 2/3), on the efficacy against several of the most important weeds in maize. For each "year-weed" combination, dose-response curves were applied to estimate the dose of foramsulfuron required to obtain 90% and 95% weed control (ED_{90} and ED_{95}). Foramsulfuron phytotoxicity on maize and crop yield were assessed. Foramsulfuron at 1/3 of the recommended dose (20.3 g a.i./ha) provided 95% efficacy against redroot pigweed (*Amaranthus retroflexus* L.), green foxtail (*Setaria viridis* (L.) Beauv.), wild mustard (*Sinapis arvensis* L.) and black nightshade (*Solanum nigrum* L.). Velvetleaf (*Abutilon theophrasti* Medik.), common lambsquarters (*Chenopodium album* L.) and barnyardgrass (*Echinochloa crus-galli* (L.) Beauv.) were satisfactorily controlled (95% weed efficacy) with ED_{95} ranged from 20 to 50 g/ha of foramsulfuron (about from 1/3 to 5/6 of the recommended dose) depending on growth stage. The recommended dose was effective against pale smartweed (*Polygonum lapathifolium* L.) at 2-4 true leaves (12-14 BBCH scale), but this dose did not kill plants larger than 2-4 true leaves. The ranking among weed species based on their susceptibility to foramsulfuron was: redroot pigweed = green foxtail = wild mustard = black nightshade > velvetleaf = common lambsquarters = barnyardgrass > pale smartweed. Dose of foramsulfuron can be reduced below recommended dose depending on weed species and growth stage. Foramsulfuron showed a good crop selectivity and had no negative effect on maize yield.

Additional key words: dose-response curves; environmental sustainability; herbicide dose optimization; herbicide field trials; integrated weed management.

Abbreviations used: ED (effective dose); MDRE (minimum dose requirement for a satisfactory efficacy); WAT (weeks after treatments).

Author's contributions: Conceived and designed the experiments, performed the experiments, analysed the data, contributed reagents/materials/analysis tools and wrote the paper: EP.

Citation: Pannacci, E. (2016). Optimization of foramsulfuron doses for post-emergence weed control in maize (*Zea mays* L.). Spanish Journal of Agricultural Research, Volume 14, Issue 3, e1005. http://dx.doi.org/10.5424/sjar/2016143-9436.

Received: 08 Feb 2015. **Accepted**: 11 Jul 2016.

Funding: The author received no specific funding for this work.

Competing interests: The author has declared that no competing interests exist.

Correspondence should be addressed to Euro Pannacci: euro.pannacci@unipg.it.

Introduction

Maize (*Zea mays* L.) is one of the most widely planted crop in the world and its production is increasing globally. Weed control has a major effect on the success of maize growth, because the competition ability of maize is relative low at early crop growth stages (Ghanizadeh *et al.,* 2014). Weed control in maize largely depends on chemical methods. High input of herbicides results in environmental pollution, risks of residues carry-over and the development of weed resistance (Pannacci *et al.,* 2006; Zhang *et al.,* 2013). An effective way to reduce the side effects of the herbicides, according to the Integrated Weed Management System (IWMS), is to apply the lowest dose needed for biologically effective weed control (Swanton & Weise, 1991; Kudsk & Streibig, 2003; Blackshaw *et al.,* 2006), although low doses can increase risk of polygenic resistance (Neve & Powles, 2005; Busi *et al.,* 2011). Furthermore, several studies have demonstrated satisfactory weed control and acceptable crop yields, when herbicides are used at lower than normally recommended doses (Devlin *et al.,* 1991; Zhang *et al.,* 2000; Barros *et al.,* 2009; Pannacci & Covarelli, 2009). Application doses of post-emergence herbicides can be, indeed, substantially reduced if the "minimum dose requirement for a satisfactory efficacy" (MDRE) is known with respect to the most common "herbicide-weed species" combinations (Dogan & Boz, 2005; Kudsk 2008; Pannacci *et al.,* 2010). Furthermore, the knowledge of MDRE is one of the main factors in the implementation of the Decision Support Systems for Integrated Weed Management (Rydahl, 2004; Sønderskov *et al.,* 2015), with the aim to decrease the dependence on herbicides that has become a distinct objective within the EU with the directive 2009/128/EC. The determination of MDRE requires dose-response studies for each "herbicide-weed species" under various environmental conditions (Kudsk & Kristensen, 1992; Pannacci & Covarelli, 2009).

Among post-emergence herbicides in maize, foramsulfuron is a sulfonylurea that exerts its herbicidal activity by inhibiting acetolactate synthase also known as acetohydroxy acid synthase and provides control of grass, perennial and some broadleaved weeds with a good selectivity to the maize (Bunting *et al.,* 2004a, 2005). Furthermore, foramsulfuron can be applied in mixture with other herbicides increasing the control of some important key weeds, without risks of carry-over problems also in rotational vegetable crops (Bunting *et al.,* 2005; Soltani *et al.,* 2005).

In the past, several data were obtained on the efficacy of foramsulfuron used alone and in mixture with other herbicides against some problematic weeds (Bunting *et al.,* 2004b; Nurse *et al.,* 2007; McCullough *et al.,* 2012), but few information is available about MDRE in the Mediterranean area conditions (Kir & Doğan, 2009). The objective of this study was to determine dose-response curves for foramsulfuron against several of the most important weeds in maize, and extrapolate the MDRE. Indeed, dose-response curve model applied in field herbicide efficacy trials was an important tool to estimate biologically meaningful parameters and to express weed control ability in terms of biological equivalent doses. Finally, the knowledge of MDRE for each "foramsulfuron-weed species" will allow to get the final goal to reduce foramsulfuron rates without losses of effectiveness against weeds.

Material and methods

Experimental site and design

Four field experiments in maize were carried out in 2011, 2012, 2013 and 2014 in central Italy (Experimental Station of Papiano, 42°57'N, 12°22'E, 165 m a.s.l.) on two adjacent fields (one in 2011 and 2012 and the other one in 2013 and 2014), with similar characteristics in terms of weed species, agronomic practices and soil composition (clay-loam soil, 25% sand, 30% clay and 45% silt, pH 8.2, 0.9% organic matter). The main agronomic practices are shown in Table 1. The trials were carried out in accordance with recommended management practices, as concerns soil tillage and seedbed preparation (Bonciarelli & Bonciarelli, 2001) adopting low input in terms of irrigation and fertilization. Maize hybrids were 'DKC4490' (FAO class 300, Dekalb, Monsanto Co.) in 2011 and 2012, 'DKC4316' (FAO class 300, Dekalb, Monsanto Co.) in 2013 and 2014. In all the four experiments, foramsulfuron (Equip, 22.5 g a.i./L + 22.5 g of isoxadifen-ethyl/L, Bayer CropScience Italy, maximum recommended dose: 60.75 g a.i./ha) was applied at the 5-6 leaves stage [15-16 BBCH scale (Meier, 2001)] of maize. The growth stage of broadleaved weeds ranged from 2-4 to 6-8 true leaves stage (from 12-14 to 16-18 BBCH) and grass weeds ranged from first tiller visible to 3-4 tiller visible stage (from 21 to 23-24 BBCH), depending on species and years (Table 2). Foramsulfuron was sprayed at three doses (20.3, 40.5 and 60.8 g a.i./ha, corresponding to 1/3, 2/3, and the entire of the maximum recommended herbicide dose, respectively) using a backpack plot sprayer fitted with four flat fan nozzles (Albuz APG 110 – Yellow) and calibrated to deliver 300 L/ha spray liquid at 200 kPa. One untreated plot and one weed-free plot per block were added as controls. The experimental design was a randomized block with four replicates in separate blocks, randomised treatments within blocks and plot size of 17.5 m^2 (2.5 m width). Each plot was established from five rows, three central rows for meas-

Table 1. Agronomic practices performed in the herbicide field trials in maize crop.

	2011	2012	2013	2014
Preceding crop	Corn	Corn	Corn	Corn
Sowing date	28 April	30 April	15 May	16 May
Corn cultivar	DKC4490	DKC4490	DKC4316	DKC4316
Density (plants/m^2)	7	7	7	7
Spacing between rows (m)	0.50	0.50	0.50	0.50
Fertilization (kg/ha)	150 N; 75 P_2O_5	150 N; 75 P_2O_5	150 N; 75 P_2O_5	150 N; 75 P_2O_5
Irrigation (m^3/ha)	1600	1550	1550	1200
Crop emergence date	08 May	10 May	25 May	23 May
Herbicides treatments date	03 June	30 May	21 June	10 June
Crop harvest	13 Sept.	11 Sept.	26 Sept.	30 Sept.

Table 2. Weed species occurring in the untreated control of the four herbicide field trials in maize crop: weed growth stages was referred at the treatment time; weed ground cover was evaluated 4 weeks after treatments (WAT).

Weed species	Common name	Weed growth stage at the treatments time (BBCH scale)				Weed ground cover (%) (4 WAT)			
		2011	2012	2013	2014	2011	2012	2013	2014
Abutilon theophrasti	Velvetleaf	12-14	14	-	14-16	6	10	-	13
Amaranthus retroflexus	Redroot pigweed	12	12	16	16	18	19	44	8
Chenopodium album	Common lambsquarters	12-14	12-14	16-18	-	9	11	6	-
Echinochloa crus-galli	Barnyardgrass	21	21	23-24	23-24	21	41	88	94
Polygonum lapathifolium	Pale smartweed	12-14	12-14	16-18	16-18	9	39	45	59
Setaria viridis	Green foxtail	-	21-22	-	-	-	7	-	-
Sinapis arvensis	Wild mustard	-	-	16-18	-	-	-	34	-
Solanum nigrum	Black nightshade	12	12	-	14-16	7	11	-	5
Total						70	138	217	179

urements and two border rows on the perimeter of each plot to reduce potential border effects.

In each trial, the efficacy of foramsulfuron towards each weed species was visually assessed on ground cover, 4 weeks after treatments (WAT), on a scale from 0 (no weed control in comparison with the untreated control) to 100 (total weed control). Phytotoxicity to the crop was evaluated visually, 2 WAT, on a 0-10 scale (0: no visible injury; 10: plant death). At harvest, the maize grain yield (adjusted to 15.5% of moisture content) was determined by hand-harvesting the central part of each plot (9 m^2).

Meteorological data (daily maximum and minimum temperature and rainfall) were collected from a nearby weather station. The average decade of daily values were calculated and compared with multi-annual average values (from 1921) (Fig. 1). The times and quantity (mm) of irrigations were reported (Fig. 1).

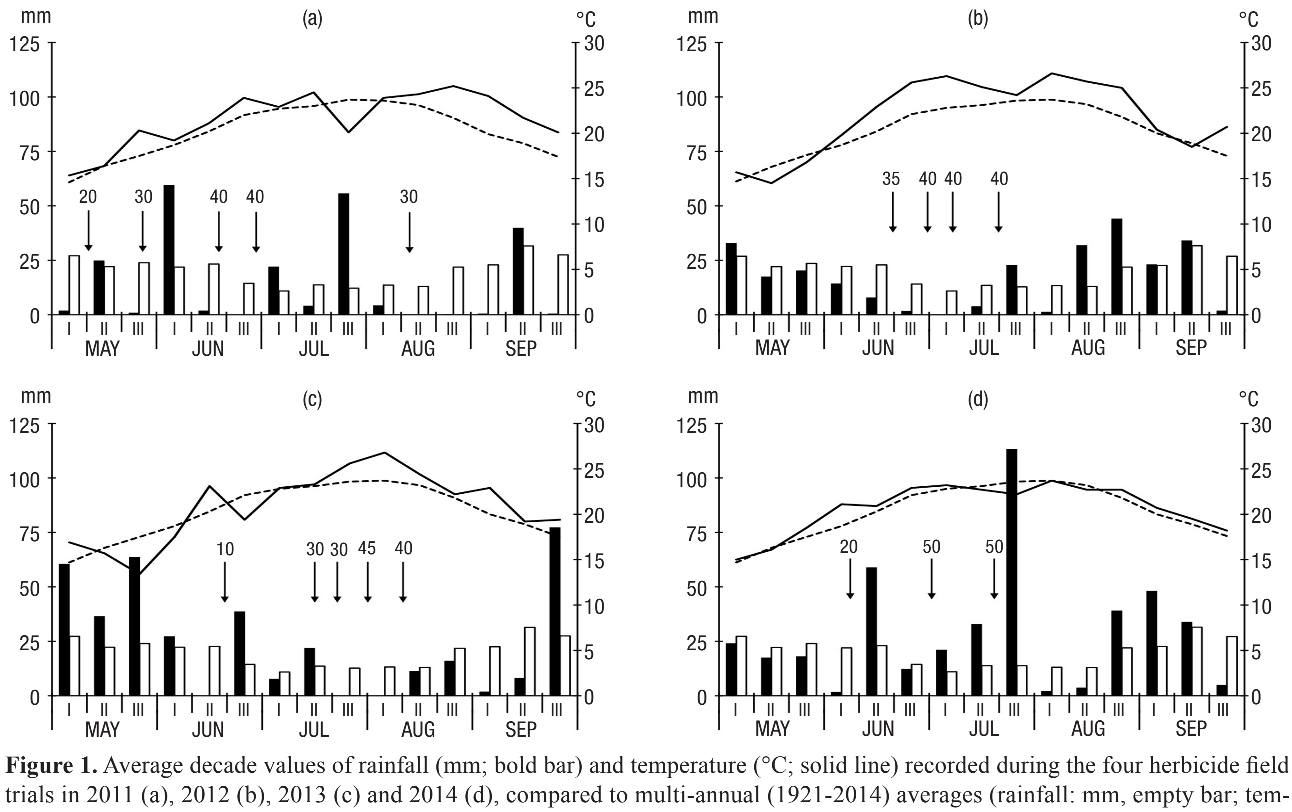

Figure 1. Average decade values of rainfall (mm; bold bar) and temperature (°C; solid line) recorded during the four herbicide field trials in 2011 (a), 2012 (b), 2013 (c) and 2014 (d), compared to multi-annual (1921-2014) averages (rainfall: mm, empty bar; temperature: °C, sketched line). The arrows show the times and the quantities (number is the mm of water) of the irrigations.

Statistical analysis

For each "year-weed" combination, data of herbicide efficacy was subjected to a non-linear regression analysis using the following logistic dose-response model (Streibig *et al.,* 1993):

$$Y = \frac{100}{1+\exp\left\{-b\left[\log(x)-\log(ED_{50})\right]\right\}} \quad [1]$$

where Y is the percentage efficacy of the herbicide, x is the dose of herbicide, b is the slope of the curve around the inflection point, $ED50$ is the dose required to give 50% weed control.

The ED_{50} parameter can be replaced by any ED level, so the selected model was used to estimate the dose of foramsulfuron required to obtain 90% and 95% weed control against each species, defined as MDRE (ED_{90} and ED_{95} values) (Copping *et al.,* 1990; Seefeldt *et al.,* 1995; Pannacci & Covarelli, 2009). When the upper asymptote did not reach 100%, it was included as a parameter in the model fitting (Streibig *et al.,* 1993).

The logistic dose-response model was directly fitted to the experimental data, by using the EXCEL® Add-in macro BIOASSAY97 (Onofri & Pannacci, 2014). The goodness-of-fit was assessed by graphical analyses of residuals and F-test for lack-of-fit (Ritz & Streibig, 2005).

Data of phytotoxicity of maize were correlated to the three foramsulfuron doses in order to asses Pearson's r correlation coefficient (Kozak *et al.,* 2012). Pearson's r correlation coefficient was performed by using EXCEL® function.

Data of phytotoxicity and crop yield were subjected to analyses of variance and means were separated using Fisher's protected LSD at p = 0.05 level. The analyses of variance were performed with the EXCEL® Add-in macro DSAASTAT (Onofri & Pannacci, 2014). Analysis of phytotoxicity data did not include untreated and weed-free plots, but these plots were included in grain yield data analysis.

Results

ED levels for weed control

The four experiments were characterised by a different weed flora composition each year (Table 2). However, some weed species were ubiquitous and common in the four years, such as redroot pigweed, barnyardgrass and pale smartweed. Total weed ground cover was higher in 2013 and 2014 than in 2011 and 2012 (Table 2). Other sporadic weeds, not considered due to their ground cover values lower than 2%, were *Portulaca oleracea* L. in 2011, 2012 and 2013 and *Xanthium strumarium* L. in 2014.

Dose response curves for foramsulfuron against eight weed species showed always a good fit to experimental data (Fig. 2). ED_{90} and ED_{95} values for foramsulfuron and b values are reported in Table 3.

Velvetleaf was present in three field experiments and ED values for foramsulfuron were very similar in the three years (see Fig. 2 and Table 3). In more detail, this weed could be satisfactorily controlled (with an efficacy of 90% or 95%) using doses of foramsulfuron from 22.8 to 29.4 g a.i/ha; these doses correspond to 38-48% of the maximum labelled dose (60.75 g a.i./ha).

Redroot pigweed was present in all the field experiments all years and, also in this case, ED values appeared to be comparable across years (Fig. 2 and Table 3). In particular, foramsulfuron showed a high efficacy against redroot pigweed, with ED_{95} values ranging from 11.7 to 19.7 g a.i/ha depending of years.

Common lambsquarters showed EDs comparable in 2011 and 2012 with values ranging from 20.7 to 24.6 g a.i/ha, while in 2013 ED values were two times higher such as 40.1 and 52.6 g a.i/ha for ED_{90} and ED_{95} respectively (Table 3).

Barnyardgrass and pale smartweed were collected in all field experiments and their EDs showed a similar trend as for common lambsquarters, with lower values in 2011 and 2012 than in 2013 and 2014. In particular, in 2011 and 2012, barnyardgrass was satisfactorily controlled (with an efficacy of 90% or 95%) using doses of foramsulfuron ranging from 15.4. to 20.7 g a.i/ha; while in 2013 and 2014 ED values increased from 27.0 to 48.1 g a.i/ha (Fig. 2 and Table 3). Similarly, pale smartweed was satisfactorily controlled with doses of foramsulfuron from 47% to 71% of the maximum labelled dose in 2011 and 2012; while in 2013 and 2014 this weed was not satisfactorily controlled, regardless of application dose, indicating a high tolerance to foramsulfuron (Table 3).

Wild mustard, green foxtail and black nightshade were only represented in one or two experiments. All these weed species showed low ED levels and thus high susceptibility to foramsulfuron (Table 3).

Phytotoxicity to the crop and crop yield

Phytotoxicity data showed that foramsulfuron could be considered safe to the crop with maize injury that appeared to be significantly correlated to

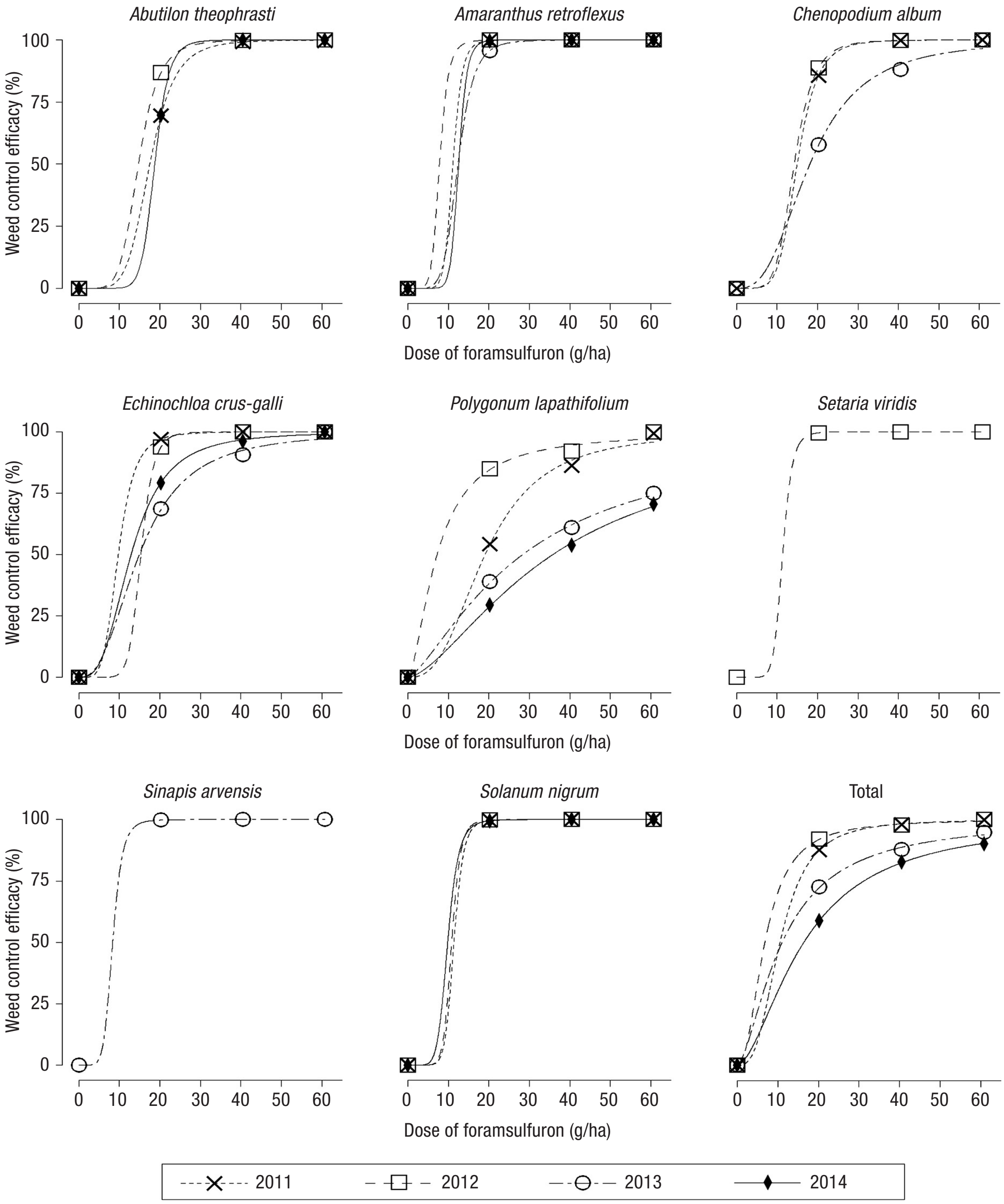

Figure 2. Dose-response curves for foramsulfuron against weed species in four herbicide field trials in maize (2011, 2012, 2013 and 2014). Symbols show observed weed control data, lines show fitted curves according to Model [1].

the doses of herbicide (Pearson's *r* correlation coefficient = 0.925, 0.924, 0.993 and 0.997, respectively in 2011, 2012, 2013 and 2014) although with low phytotoxicity values and symptoms (Table 4). Indeed, phytotoxicity symptoms, *i.e.* leaves slightly crinkled and distorted, were always transitory and dissipated within 3-4 WAT.

In general, crop yield in weed-free plots were at the same level in 2011, 2012 and 2013, while in 2014 was lower than in the previous years (Table 4).

The crop yield differences among untreated control and the increased foramsulfuron doses were lower in 2011 and 2012 than in 2013 and 2014 (Table 4), although the untreated controls showed a significant lower crop yield than the other treatments in all years, except in 2011. In particular, the highest losses in the untreated plots were observed in 2013 and 2014 with a yield reduction, compared to the weed-free control of 91% and 81% respectively; while in 2011 and 2012 the yield losses were of 38% and 33%, respectively (Table 4).

Table 3. Regression parameters (*i.e.* b, ED_{90} and ED_{95}) for the relationship between the dose of foramsulfuron and its efficacy against weed species in 2011, 2012, 2013 and 2014. ED_{90} and ED_{95} were assumed as "minimum doses requirement for satisfactory efficacy, MDRE". Standard errors are in parentheses.

Year and weed species	b	ED_{90} (g/ha)	ED_{95} (g/ha)
2011			
Abutilon theophrasti	5.67 *(0.38)*	25.8 *(0.4)*	29.4 *(0.7)*
Amaranthus retroflexus	9.77 *(1.03)*	13.9 *(0.6)*	15.0 *(0.4)*
Chenopodium album	5.94 *(0.09)*	21.7 *(0.02)*	24.6 *(0.1)*
Echinochloa crus-galli	4.73 *(0.15)*	15.4 *(0.1)*	18.1 *(0.1)*
Polygonum lapathifolium	2.71 *(0.40)*	43.0 *(4.3)*	56.6 *(7.8)*
Solanum nigrum	9.64 *(1.04)*	14.3 *(0.6)*	15.4 *(0.4)*
Total	2.99 *(0.25)*	21.9 *(0.2)*	28.2 *(0.8)*
2012			
Abutilon theophrasti	6.57 *(0.07)*	22.8 *(0.03)*	25.6 *(0.1)*
Amaranthus retroflexus	7.26 *(0.99)*	10.6 *(0.9)*	11.7 *(0.9)*
Chenopodium album	5.86 *(0.10)*	20.7 *(0.01)*	23.6 *(0.1)*
Echinochloa crus-galli	9.71 *(1.02)*	19.2 *(0.1)*	20.7 *(0.05)*
Polygonum lapathifolium	1.77 *(0.58)*	28.6 *(3.4)*	43.6 *(10.1)*
Setaria viridis	9.60 *(1.04)*	14.3 *(0.5)*	15.5 *(0.5)*
Solanum nigrum	9.90 *(1.01)*	13.5 *(0.6)*	14.6 *(0.5)*
Total	2.37 *(0.40)*	19.2 *(0.6)*	26.4 *(1.3)*
2013			
Amaranthus retroflexus	6.30 *(0.08)*	17.5 *(0.03)*	19.7 *(0.01)*
Chenopodium album	2.76 *(0.42)*	40.1 *(3.9)*	52.6 *(7.2)*
Echinochloa crus-galli	2.51 *(0.44)*	35.7 *(3.4)*	48.1 *(6.9)*
Polygonum lapathifolium	1.39 *(0.06)*	> 61	> 61
Sinapis arvensis	6.98 *(1.01)*	11.4 *(1.0)*	12.7 *(0.9)*
Total	1.59 *(0.12)*	44.0 *(2.3)*	> 61
2014			
Abutilon theophrasti	10.67 *(1.02)*	23.0 *(0.3)*	24.7 *(0.5)*
Amaranthus retroflexus	12.03 *(1.45)*	15.0 *(0.4)*	16.0 *(0.3)*
Echinochloa crus-galli	2.97 *(0.33)*	27.0 *(0.9)*	34.7 *(2.0)*
Polygonum lapathifolium	1.57 *(0.07)*	> 61	> 61
Solanum nigrum	7.32 *(1.02)*	13.3 *(0.8)*	14.7 *(0.7)*
Total	1.71 *(0.02)*	59.1 *(0.5)*	> 61

However, reduced doses of foramsulfuron (20.3 and 40.5 g a.i./ha) gave crop yield levels not significantly different to that of weed-free plots in all the experiments, except in 2013 (Table 4).

Discussion

The four field experiments showed that weed susceptibility against foramsulfuron can be quantified by dose-response curves, and that weeds can be classified with respect to their susceptibility via ED_{90} and ED_{95} values. The ranking among weed species based on their sensitivity to foramsulfuron was: redroot pigweed = green foxtail = wild mustard = black nightshade > velvetleaf = common lambsquarters = barnyardgrass > pale smartweed. Baghestani *et al.* (2007) evaluated the efficacy of reduced rates of foramsulfuron in Iran and reported a lower susceptibility of velvetleaf and redroot pigweed to foramsulfuron than that obtained in this study, while similar results were obtained for barnyardgrass. On the contrary, Kir & Doğan (2009) found similar results to this research in terms of sensitivity of redroot pigweed to foramsulfuron. In this study the lower efficacy of foramsulfuron against barnyardgrass in 2013 and 2014 than in 2011 and 2012 was probably due to the bigger growth stage of plants at treatment time in 2013 and 2014 (3-4 tiller visible) than in 2011 and 2012 (first tiller visible) (Table 2). Indeed, in 2011 and 2012 the early sowing of maize at the end of April reduced the total weed flora, and due to low temperatures, barnyardgrass plants grew more slowly than in 2013 and 2014. It is well known that annual weed species are generally more susceptible to herbicides at early growth stages (Kudsk, 2008). Similarly, growth stage at application could explain the lower efficacy of

Table 4. Effects of different doses of foramsulfuron on crop injury and crop yield.

Dose of foramsulfuron (g/ha)	Phytotoxicity (scale 0-10) (2 WAT)				Crop yield (t/ha)			
	2011	2012	2013	2014	2011	2012	2013	2014
0	0.0	0.0	0.0	0.0	7.55	9.13	1.10	1.88
20.3	0.0	0.3	0.1	0.1	9.77	12.26	6.48	6.25
40.5	0.1	0.4	0.4	0.4	11.08	12.74	7.33	7.43
60.8	0.9	0.5	0.8	0.9	11.82	12.80	7.41	7.74
Weed-free control	0.0	0.0	0.0	0.0	12.24	13.56	12.34	9.70
LSD (p = 0.05)	*0.32*	*n.s.*	*n.s.*	*0.29*	*2.63*	*1.58*	*2.69*	*2.11*

WAT: weeks after treatments.

foramsulfuron against pale smartweed in 2013 and 2014 (pale smartweed plants at 6-8 true leaves at treatment time) than in 2011 and 2012 (pale smartweed plants at 2-4 true leaves at treatment time), and against common lambsquarters in 2013 (6-8 leaves at treatment time) than in 2011 and 2012 (2-4 true leaves at treatment time) (Table 2). Furthermore, in 2013 and 2014 the weather conditions, like water stress and high temperatures at the treatment time (21 June 2013 and 10 June 2014, see Figs. 1c and 1d, respectively) were more unfavourable to foliar-herbicides applications than in 2011 and 2012, especially against difficult-to-wet weed species, like barnyardgrass and common lambsquarters (Kudsk & Mathiassen 2004; Pannacci *et al.,* 2010). This may be due to reduced herbicide availability caused by rapid drying of droplets to solid deposits in warm conditions (Ramsey *et al.,* 2005). Furthermore, plants grown under high temperature, low humidity and soil water deficit tend to have leaves with thicker cuticles, more epicuticular wax and pubescence than unstressed plants, and this might retard interception, retention and penetration of the herbicide (Lundkvist, 1997). Indeed, common lambsquarters is characterised by very waxy leaves decreasing spray retention and uptake under hot and dry conditions (Steckel *et al.,* 1997).

This study showed that foramsulfuron, also at reduced doses, is an effective herbicide to control several weed species (*i.e.* redroot pigweed, black nightshade, common lambsquarters and barnyardgrass) characterized by high competitiveness to the crop (Zanin *et al.,* 1994; Pannacci & Tei, 2014), high seedbank densities (Graziani *et al.,* 2012) and low susceptibility to several pre-emergence herbicides (*i.e.* velvetleaf). The use of herbicides at reduced doses seems to be possible; however, a limit could be the presence of non-susceptible weeds, *i.e. Fallopia convolvulus* (L.) Holub, *Polygonum aviculare* L., *Chenopodium polyspermum* L. and *Stellaria media* (L.) Vill. for foramsulfuron (Tracchi *et al.,* 2002), that may frustrate the overall effectiveness of weed control (Pannacci & Covarelli, 2009). In such cases a good strategy is to use two or more active ingredients in mixture (*i.e.* sulcotrione or dicamba for foramsulfuron) in order to enlarge the spectrum of controlled weeds, and also avoiding the increase of herbicide resistant weeds (Green & Streibig, 1993; Pannacci *et al.,* 2007; Beckie & Reboud, 2009).

Foramsulfuron may be considered fairly safe to the crop, thanks to phytotoxicity symptoms always low and transitory as confirmed also by Tracchi *et al.* (2002), Nurse *et al.* (2007) and Zaremohazabieh & Ghadiri (2011) in other studies.

In general, lower crop yield in weed-free plots in 2014 than previous years can probably be due to the very high rainfall (113 mm in three consecutive days in the last decade of July) and low temperature (the daily average temperature decreased during the last decade of July until to 19 °C in these three days of rain) at flowering time (see end of July, Fig. 1d), that have affected pollination and growth of maize temporarily, reducing the potential yield of crop. The crop yield differences among untreated control and the increased foramsulfuron doses lower in 2011 and 2012 than in 2013 and 2014 were due to the high total weed control obtained also at low doses of foramsulfuron; indeed, the lower total weed pressure and younger growth stages at the treatment time increased their susceptibility to foramsulfuron (see Fig. 2). Otherwise, in 2013 and 2014, the low efficacy of foramsulfuron against barnyardgrass and pale smartweed (Fig. 2), together with their high ground covers, reduced crop yields values with no significant differences among the three doses (Table 4). This indicates that barnyardgrass and pale smartweed plants escaping the treatment were very competitive, resulting in high yield losses in the most infested plots. Similar yield losses in maize were obtained by Pannacci & Tei (2014) and by Pannacci & Onofri (2016), in the same area with similar weed infestations.

The results presented in this paper (*i.e.* ED_{90} and ED_{95} values) have shown that the post-emergence application dose of foramsulfuron can be reduced below recommended labelled rate depending on weed species and growth stage. In particular, foramsulfuron at 1/4 of the maximum labelled dose (≈ 20.3 g a.i./ha) provided 95% efficacy on redroot pigweed, green foxtail, wild mustard and black nightshade. The same efficacy was obtained against velvetleaf, common lambsquarters and barnyardgrass at 25-35 g/ha of foramsulfuron, corresponding to half of the maximum labelled dose. These results showed that foramsulfuron is an effective post-emergence herbicide to control the above mentioned weed species that are key weeds in maize and characterized by high competitiveness towards this crop. The MDRE's estimated in this study for foramsulfuron to optimize chemical weed control in maize, especially ED_{95} values, can be implemented in Decision Support Systems (Kudsk, 2008). Finally, foramsulfuron showed a good selectivity to the crop, without negative effects to crop yield.

Acknowledgments

The author would like to acknowledge Solvejg K. Mathiassen (Senior Researcher at the Department of Agroecology - Crop Health, Aarhus University, Denmark) for helpful suggestions.

References

Baghestani MA, Zand E, Soufizadeh S, Eskandari A, PourAzar R, Veysi M, Nassirzadeh N, 2007. Efficacy evaluation of some dual purpose herbicides to control weeds in maize (Zea mays L.). Crop Prot 26: 936-942. http://dx.doi.org/10.1016/j.cropro.2006.08.013.

Barros JFC, Basch G, Freixial R, de Carvalho M, 2009. Effect of reduced doses of mesosulfuron + iodosulfuron to control weeds in no-till wheat under Mediterranean conditions. Span J Agric Res 7 (4): 905-912. http://dx.doi.org/10.5424/sjar/2009074-1104.

Beckie HJ, Reboud X, 2009. Selecting for weed resistance: herbicide rotation and mixture. Weed Tech 23: 363-370. http://dx.doi.org/10.1614/WT-09-008.1.

Blackshaw RE, O'Donovan JT, Harker KN, Clayton GW, Stougaard RN, 2006. Reduced herbicide doses in field crops: A review. Weed Biol Manag 6: 10-17. http://dx.doi.org/10.1111/j.1445-6664.2006.00190.x.

Bonciarelli F, Bonciarelli U (eds), 2001. Coltivazioni Erbacee. Edagricole – Edizioni Agricole, Bologna, Italy. 492 pp.

Bunting JA, Sprague CL, Riechers DE, 2004a. Physiological basis for tolerance of corn hybrids to foramsulfuron. Weed Sci 52: 711-717. http://dx.doi.org/10.1614/WS-04-008R.

Bunting JA, Sprague CL, Riechers DE, 2004b. Absorption and activity of foramsulfuron in giant foxtail (Setaria faberi) and woolly cupgrass (Eriochloa villosa) with various adjuvants. Weed Sci 52: 513-517. http://dx.doi.org/10.1614/WS-03-135R.

Bunting JA, Sprague CL, Riechers DE, 2005. Incorporating foramsulfuron into annual weed control systems for corn. Weed Techn 19: 160-167. http://dx.doi.org/10.1614/WT-04-063R1.

Busi R, Vila-Aiub MM, Powles SB, 2011. Genetic control of a cytochrome P450 metabolism-based herbicide resistance mechanism in Lolium rigidum. Heredity 106: 817–824. http://dx.doi.org/10.1038/hdy.2010.124.

Copping LG, Hewitt HG, Rowe RR, 1990. Evaluation of a new herbicide. In: Weed control handbook: principles, VIII ed.; Hance RJ, Holly K, (eds.). pp: 261-299. Blackwell Sci Publ, Oxford.

Devlin DL, Long JH, Maddux LD, 1991. Using reduced rates of postemergence herbicides in soybean (Glycine max). Weed Techn 5: 834-840.

Dogan MN, Boz Ö, 2005. The concept of reduced herbicide rates for the control of johnsongrass (Sorghum halepense (L.) Pers.) in cotton during the critical period for weed control. J Plant Dis Protect 112: 71-79.

Ghanizadeh H, Lorzadeh S, Ariannia N, 2014. Effect of weed interference on Zea mays: Growth analysis. Weed Biol Manag 14: 133-137. http://dx.doi.org/10.1111/wbm.12041.

Graziani F, Onofri A, Pannacci E, Tei F, Guiducci M, 2012. Size and composition of weed seedbank in long-term organic and conventional low-input cropping systems. Eur J Agron 39: 52-61. http://dx.doi.org/10.1016/j.eja.2012.01.008.

Green JM, Streibig JC, 1993. Herbicide mixtures. In: Herbicide bioassay; Streibig JC, Kudsk P (eds.). pp: 117-135. CRC Press, Boca Raton, FL, USA.

Kir K, Doğan MN, 2009. Weed control in maize (Zea mays L.) with effective minimum rates of foramsulfuron. Turk J Agric For 33: 601-610.

Kozak M, Krzanowski W, Tartanus M, 2012. Use of the correlation coefficient in agricultural sciences: problems, pitfalls and how to deal with them. An Acad Bras Ciênc 84: 1147-1156.

Kudsk P, 2008. Optimising herbicide dose: a straightforward approach to reduce the risk of side effects of herbicides. Environmentalist 28: 49-55. http://dx.doi.org/10.1007/s10669-007-9041-8.

Kudsk P, Kristensen J, 1992. Effect of environmental factors on herbicide performance. Proc 1st Int Weed Control Congress, Melbourne, Australia, Vol. 1, pp: 173-186.

Kudsk P, Streibig JC, 2003. Herbicides – a two-edged sword. Weed Res 43: 90-102. http://dx.doi.org/10.1046/j.1365-3180.2003.00328.x.

Kudsk P, Mathiassen SK, 2004. Adjuvant effects on the rainfastness of iodosulfuron-methyl + mesosulfuron formulations. Proc 7th Int Symp on Adjuvants for Agrochemicals, 8-12 November 2004, Cape Town, South Africa, pp: 159-164.

Lundkvist A, 1997. Predicting optimal application time for herbicides from estimated growth rate of weeds. Agric Sys 54: 223-242. http://dx.doi.org/10.1016/S0308-521X(96)00086-8.

McCullough PE, de Barreda DG, Raymer P, 2012. Nicosulfuron use with foramsulfuron and sulfentrazone for late summer goosegrass (Eleusine indica) control in bermudagrass and seashore paspalum. Weed Techn 26: 376-381. http://dx.doi.org/10.1614/WT-D-11-00153.1.

Meier U, 2001. Growth stages of mono-and dicotyledonous plants. BBCH Monograph, 2nd Edition. Federal Biological Research Centre for Agriculture and Forestry. https://www.politicheagricole.it/flex/AppData/WebLive/Agrometeo/MIEPFY800/BBCHengl2001.pdf.

Neve P, Powles S, 2005. High survival frequencies at low herbicide use rates in populations of Lolium rigidum result in rapid evolution of herbicide resistance Heredity 95: 485–492. http://dx.doi.org/10.1038/sj.hdy.6800751.

Nurse RE, Hamill AS, Swanton CJ, Tardif FJ, Sikkema PH, 2007. Weed control and yield response to foramsulfuron in corn. Weed Techn 21: 453-458. http://dx.doi.org/10.1614/WT-06-071.1.

Onofri A, Pannacci E, 2014. Spreadsheet tools for biometry classes in crop science programmes. Commun Biom Crop Sci 9: 3-13.

Pannacci E, Covarelli G, 2009. Efficacy of mesotrione used at reduced doses for post-emergence weed control in maize (Zea mays L.). Crop Prot 28: 57-61. http://dx.doi.org/10.1016/j.cropro.2008.08.011.

Pannacci E, Tei F, 2014. Effects of mechanical and chemical methods on weed control, weed seed rain and crop yield in maize, sunflower and soyabean. Crop Prot 64: 51-59. http://dx.doi.org/10.1016/j.cropro.2014.06.001.

Pannacci E, Onofri A, 2016. Alternatives to terbuthylazine for chemical weed control in maize. Commun Biom Crop Sci 11: 51-63.

Pannacci E, Onofri A, Covarelli G, 2006. Biological activity, availability and duration of phytotoxicity for imazamox in four different soils of central Italy. Weed Res 46: 243-250. http://dx.doi.org/10.1111/j.1365-3180.2006.00503.x.

Pannacci E, Graziani F, Covarelli G, 2007. Use of herbicide mixtures for pre and post-emergence weed control in sunflower (Helianthus annuus). Crop Prot 26: 1150-1157. http://dx.doi.org/10.1016/j.cropro.2006.10.008.

Pannacci E, Mathiassen SK, Kudsk P, 2010. The effect of adjuvants on the rainfastness and performance of tribenuron-methyl on broadleaf weeds. Weed Biol Manag 10: 126-131. http://dx.doi.org/10.1111/j.1445-6664.2010.00376.x.

Ramsey RJL, Stephenson GR, Hall JC, 2005. A review of the effects of humidity, humectants, and surfactant composition on the absorption and efficacy of highly water-soluble herbicides. Pestic Biochem Phys 82: 162–175. http://dx.doi.org/10.1016/j.pestbp.2005.02.005.

Ritz C, Streibig JC, 2005. Bioassay analysis using R. J Stat Softw 12: 1-22. http://dx.doi.org/10.18637/jss.v012.i05.

Rydahl P, 2004. A Danish decision support system for integrated management of weeds. Aspects Appl Biol 72: 43-53.

Seefeldt SS, Jensen JE, Furst EP, 1995. Log-logistic analysis of dose-response relationships. Weed Tech 9: 218-227.

Soltani N, Sikkema PH, Robinson DE, 2005. Effect of foramsulfuron and isoxaflutole residues on rotational vegetable crops. HortScience 40: 620-622.

Sønderskov M, Fritzsche R, de Mol F, Gerowitt B, Goltermann S, Kierzek R, Krawczyk R, Bøjer OM, Rydahl P, 2015. DSSHerbicide: Weed control in winter wheat with a decision support system in three South Baltic regions - Field experimental results. Crop Prot 76: 15-23. http://dx.doi.org/10.1016/j.cropro.2015.06.009.

Steckel GJ, Wax LM, Simmons FW, Phillips WH II, 1997. Glufosinate efficacy on annual weeds is influenced by rate and growth stage. Weed Tech 11: 484-488.

Streibig JC, Rudemo M, Jensen JE (1993) Dose-response curves and statistical models. In: Herbicide bioassay; Streibig JC, Kudsk P (eds.). pp: 29-55. CRC Press, Boca Raton, FL, USA.

Swanton CJ, Weise SF, 1991. Integrated weed management: the rationale and approach. Weed Tech 5: 657-663.

Tracchi G, Ballasso G, Magli G, Marchi A, 2002. Foramsulfuron: a new post emergence sulfonylurea for the control of grasses and broadleaf weeds in corn. Proc Giornate Fitopatologiche 2002, Baselga di Pinè, Trento, Italy, pp: 165-170.

Zanin G, Berti A, Sattin M, 1994. Estimation of economic thresholds for weed control in maize in northern Italy. Proc 5th Eur Weed Res Soc, Mediterr Symp, Perugia, Italy, pp: 51-58.

Zaremohazabieh S, Ghadiri H, 2011. Effects of rimsulfuron, foramsulfuron and conventional herbicides on weed control and maize yield at three planting dates. J Biol Environ Sci 5: 47-56.

Zhang J, Weaver SE, Hamill AS, 2000. Risks and reliability of using herbicides at below-labeled doses. Weed Techn 14: 106-115. http://dx.doi.org/10.1614/0890-037X(2000)014[0106:RAROUH]2.0.CO;2.

Zhang J, Zheng L, Jäck O, Yan D, Zhang Z, Gerhards R, Ni H, 2013. Efficacy of four post-emergence herbicides applied at reduced doses on weeds in summer maize (Zea mays L.) fields in North China Plain. Crop Prot 52: 26-32. http://dx.doi.org/10.1016/j.cropro.2013.05.001.