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Efficacy and Selectivity of Pre-emergent Sunflower Herbicides under Different Soil Moisture Conditions

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Abstract

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We ranked the most frequently used pre-emergent herbicides in sunflower (*Helianthus annuus*) according to their efficacy and selectivity under different soil moisture conditions within 2008–2011. The efficacy of oxyfluorfen, aclonifen, acetochlor, dimethenamid, and propisochlor on the majority of weeds (*Chenopodium album, Echinochloa crus-galli, Amaranthus retroflexus, Mercurialis annua,* and *Solanum physalifolium*) was only slightly affected by the soil moisture and these herbicides can be used in arid and semiarid regions. The efficacy of linuron, prosulfocarb, and pethoxamid was strongly affected by soil moisture and was insufficient under dry conditions. The majority of herbicides showed good selectivity for sunflower. Crop injury rate of 5–15% was recorded after application of flurochloridone and acetochlor. For flurochloridone, the phytotoxicity increased due to irrigation after herbicide application. The highest sunflower injury rate (27–35%) was recorded after application of oxyfluorfen.

Keywords: weed control; phytotoxicity; abiotic factors; irrigation; sunflower

Sunflower (*Helianthus annuus* L.) is sensitive to weed infestation. Weed interference can reduce seed yield of sunflower, with level of yield loss varying among weed species (Durgan *et al.* 1990; Onofri & Tei 1994; Carranza *et al.* 1995). According to Wanjari *et al.* (2001), the critical weed-free period is between the 20th and 49th day after sowing. Weed competition is manifested by a decrease of sunflower biomass and yield losses, which can reach up to 81%, depending on the weed density, time and duration of competition, weed spectrum, and other factors.

Sunflower is usually grown in semiarid regions of the temperate zone, where water is the most important limiting resource in competitive interactions between weeds and crops, especially in the early growth stages of sunflower (Norris 1996). The water use efficiency of common sunflower hybrids is two times lower than that of weeds with C4 metabolism (Dillman 1931; Moroke *et al.* 2011), which are the most problematic weeds in these areas. Therefore, pre-emergence (PRE) weed control in sunflower is very important for the elimination of crop-weed competition and corresponding yield losses. Post-emergence (POST) weed control in herbicide-tolerant (HT) varieties of sunflower treated with PRE can be delayed by approximately two weeks compared to sunflower canopies without PRE weed control (Elezovic *et al.* 2012).

For the PRE control of dicotyledonous weeds in sunflower, active ingredients such as linuron, flurochloridone, oxyfluorfen, pendimethalin, prosulfocarb, bifenox, aclonifen, flumioxazin, and lenacil are often used (Pannacci *et al.* 2007; Nadasy *et al.* 2008; Kilinc *et al.* 2011) in combination with acetamide herbicides (acetochlor, dimethenamid, pethoxamid, metolachlor, flufenacet,

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and propisochlor), which are intended for the control of grass weeds (de Prado *et al*., 1993; Pannacci *et al*. 2007; Nadasy *et al*. 2008). PRE herbicides with residual activity can also improve efficacy of POST acetolactate synthase (ALS)-inhibiting herbicides in controlling weeds in sunflower. PRE herbicides in HT crops are an effective anti-resistant strategy that reduces the risk of herbicide resistance development (Lopes Ovejero *et al*. 2013; Beckie & Hall 2014).

It is well known that the efficacy of PRE herbicides is significantly affected by soil moisture. Under dry conditions, the efficacy of PRE herbicides usually decreases (Zhang *et al*. 2001; Zanatta *et al*. 2008); however, intensive precipitation after application of these herbicides can cause crop injury (Stickler *et al*. 1969; Soukup *et al*. 2004). This effect is especially important for sunflower because the selectivity of most herbicides is dependent on the position of the herbicide layer on the soil surface and the distribution of seeds on the soil profile. Sandy soils with a lower sorption capacity are at a higher risk of herbicide leaching after heavy rainfall or irrigation, increasing the risk of crop injury.

The objective of the present work was to compare the efficacy and selectivity of frequently used PRE sunflower herbicides under different soil moisture conditions.

MATERIAL AND METHODS

Four plot field trials were carried out on sunflower (variety Alexandra®) in Prague, centre of Bohemia, Central Europe (300 m a.s.l., 50°7'N, 14°22'E), from 2008 to 2011. The study region is characterised by a temperate climate and water scarcity frequent in the beginning of the growing season. The soil of the experimental fields was classified as Haplic Chernozem with the content of clay 19%, sand 25%, silt 56% (silt loam soil), soil pH_{KCl} of 7.2, and sorption capacity of 212 $mmol^{(+)}$/kg. The nutrient content was 156 mg/kg P, 275 mg/kg K, 177 mg/kg Mg, and 7984 mg/kg Ca. Depth of the soil was 25 cm. Before sunflower sowing, the soil was fertilised with 90, 36, and 70 kg/ha of N, P, and K, respectively. Winter wheat was the previous crop in all of the experimental years. Weeds in previous crop were treated with tribenuron-methyl (20 g/ha). In intercrop period, the weeds were controlled by conventional tillage. Sunflower was sown on April 9, 2008, April 14, 2009, April 7, 2010, and April 4, 2011. The trials were arranged in a split plots design with herbicide treatment the main plot, irrigation the split plot. There were three replicate plots per herbicide treatment, arranged in a randomised complete block design. The area of the main plots was 24.5 m^2 (3.5 × 7 m). For planting, a precise small-plot sowing machine was used. The row spacing was 0.7 m, and the in-row plant spacing was 0.16 m. The dominant weed species (20–80 plants/m^2) was *Chenopodium album* L. Other weed species in the experimental fields were found at a medium density (8–20 plants/m^2 for individual species) and included *Echinochloa crus-galli* L., *Amaranthus retroflexus* L., *Mercurialis annua* L., and *Solanum physalifolium* Rusby.

Herbicides were used at the recommended rates (Table 1) and were applied shortly after sunflower sowing (on the same day). The experiments included

Table 1. Characteristics of used herbicides

Herbicide (active ingredient)	Trade name	Formulation	Content of a.i. (g/l)	Application rate (g a.i.)/ha	Supplier
Oxyfluorfen	Goal	EC	240	240	Dow Agro Sciences
Linuron	Afalon	SC	450	675	Makteshim Agan
Flurochloridone	Racer	EC	250	750	Makteshim Agan
Pendimethalin	Stomp	SC	400	1600	BASF
Prosulfocarb	Boxer	EC	800	3200	Syngenta
Aclonifen	Bandur	SC	600	2400	Bayer Crop Science
Acetochlor	Trophy	EC	768	2000	Dow Agro Sciences
Dimethenamid	Outlook	EC	720	1000	BASF
S-Metolachlor	Dual Gold	EC	960	1150	Syngenta
Propisochlor	Proponit	EC	720	2160	Arysta LifeScience
Pethoxamid	Successor	SC	600	1200	Stähler International

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Table 2. Weather conditions at the beginning of the growing season in experimental years

Meteorological characteristics		2008	2009	2010	2011
Total natural precipitation (mm)	from sowing to irrigation[a]	39.0	20.0	54.8	16.1
	from irrigation to canopy closure[b]	70.9	106.0	71.8	19.6
Mean monthly temperature (°C)	April	8.2	12.8	9.7	11.5
	May	14.1	14.0	12.2	14.2

[a]specific period in individual years: April 9–30, 2008; April 14–May 5, 2009; April 8–May 1, 2010; April 7–26, 2011; [b]specific period in individual years: May 1–June 3, 2008; May 6–June 8, 2009; May 2–June 2, 2010; April 27–June 8, 2011

untreated control plots. Herbicides were applied using a small-plot sprayer with Lurmark 015F110 nozzles at a spray volume of 250 l/ha and a pressure of 0.2 MPa. After the emergence of sunflowers (growth stage of cotyledon leaves was observed on April 30, 2008, May 5, 2009, May 1, 2010, and April 26, 2011), split plots (10 m^2) were irrigated by small plot irrigation. Delivered water dose was 30 mm; the irrigation took 30 minutes. The meteorological characteristics of the study region from the day of sunflower sowing to canopy closure are shown in Table 2.

Percentage scale from 0–100% was used for assessment of the herbicide efficacy (0% = without injury to weeds, 1–30% = not important injury to weeds, 31–60% = low control, 61–75% = insufficient control, 76–85% = sufficient control, 86–90% = acceptable control, 91–95% = good control, 96–99% very good control, 100% = full control) and crop injury (0% = without crop injury, 1–3% = very low symptoms of phytotoxicity, 4–10% = low symptoms of phytotoxicity, 11–20% = very well visible symptoms of injury, 21–30% = strong injury, 31–60% = very strong injury, 61–90% extremely strong injury, 91–99% most of plats dead, 100% = all plants dead). The first assessment was performed shortly after weed emergence (four true sunflower leaves), while the second assessment was performed shortly before canopy closure.

Results were tested by the Analysis of Variance (ANOVA) followed by *LSD* comparisons to corresponding controls once the differences among mean values have been determined using Statgraphics Plus software package (StatPoint, Inc., Herndon, USA). ANOVA effects and differences were considered significant at $P < 0.05$.

RESULTS

Efficacy of **oxyfluorfen** was very good on *A. retroflexus, M. annua*, and *S. physalifolium*, (control greater than 95%) and was not affected by soil moisture conditions in any year (Table 3). Oxyfluorfen was not as effective with *C. album* under non-irrigated conditions in 2009 (Table 3). *E. crus-galli* was controlled effectively by oxyfluorfen only in 2008 (Table 3). The sunflower phytotoxicity was the highest (25–47%) without effect of irrigation. Sunflower growth was inhibited and regeneration was slow; however, the seed yield was not significantly reduced in any year (Table 4).

Linuron fully controlled *A. retroflexus* and *C. album* only in 2008 (Table 3). In the years with lower natural precipitation rates in the first month after herbicide application (2009 and 2011), significant higher efficacy on *A. retroflexus* was recorded on irrigated treatment (Table 3). Control of *M. annua* and *S. physalifolium*, 88 and 95–100%, respectively, was satisfactory only in 2008 (Table 3). Intensive weed infestation on non-irrigated plots caused significant yield losses of sunflower in 2009 (Table 4). The selectivity of linuron for sunflower was high, and only slight chloroses and growth retardation were observed (Table 5).

Flurochloridone effectively controlled all of the tested weeds in 2008 and 2010 (Table 3). In dry years 2009 and 2011, efficacy of flurochloridone on *E. crus-galli, M. annua*, and *S. physalifolium* was not satisfactory, especially with treatments without irrigation (Table 3). Sunflower injury was greater on plots with irrigation (phytotoxicity 7–30%) than on those without irrigation (1–20%). Significant differences in crop injury were recorded in 2008 and 2009 (BBCH 14 stage). The recovery of sunflower was relatively fast, especially on plots without irrigation. The phytotoxicity was 0–6% shortly before the sunflower canopy closure (Table 5). The main symptom of phytotoxicity was leaf bleaching.

Pendimethalin effectively controlled *C. album* in both irrigation treatments (efficacy more than 95%) (Table 3). Efficacy on *E. crus-galli* ranged between

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Table 3. Efficacy (in %) of tested herbicides on *Amaranthus retroflexus*, *Mercurialis annua*, *Solanum physalifolium*, *Chenopodium album*, and *Echinochloa crus-galli* shortly before the sunflower canopy closed rows in experimental years (2008–2011)

Herbicide	Irrigation	*Amaranthus retroflexus*				*Mercurialis annua*				*Solanum physalifolium*				*Chenopodium album*				*Echinochloa crus-galli*			
		2008	2009	2010	2011	2008	2009	2010	2011	2008	2009	2010	2011	2008	2009	2010	2011	2008	2009	2010	2011
Oxyfluorfen	No	100^{b}	100^{e}	100^{d}	94^{def}	93^{d}	99^{g}	100^{g}	91^{de}	100^{g}	100^{h}	100^{h}	87^{ghi}	100^{d}	63^{c}	82^{e}	88^{fgh}	92^{ab}	10^{a}	65^{b}	85^{cde}
	Yes	100^{b}	100^{e}	100^{d}	99^{f}	94^{d}	99^{g}	100^{g}	98^{e}	100^{g}	100^{h}	100^{h}	98^{i}	100^{d}	77^{d}	80^{de}	98^{h}	92^{ab}	47^{b}	55^{b}	90^{ef}
Linuron	No	100^{b}	53^{a}	93^{ab}	68^{a}	88^{d}	7^{a}	30^{bc}	0^{a}	95^{fg}	20^{a}	53^{c}	33^{b}	100^{d}	10^{a}	47^{bc}	70^{efg}	90^{a}	67^{c}	77c	77^{bc}
	Yes	100^{b}	87^{bc}	92^{a}	93^{cdef}	88^{d}	7^{a}	70^{f}	0^{b}	100^{g}	53^{bc}	63^{d}	60^{c}	100^{d}	43^{b}	58^{cd}	78^{fg}	93^{abc}	67^{c}	80^{c}	87^{def}
Flurochloridone	No	100^{b}	100^{e}	100^{d}	97^{ef}	98^{d}	87^{e}	92^{g}	80^{d}	100^{g}	53^{bc}	90^{fg}	80^{efg}	100^{d}	90^{e}	100^{e}	98^{h}	96^{cd}	77^{cd}	97^{d}	87^{def}
	Yes	100^{b}	100^{e}	100^{d}	99^{f}	99^{d}	96^{efg}	97^{g}	90^{de}	100^{g}	53^{bc}	90^{fg}	93^{hi}	100^{d}	90^{e}	100^{e}	97^{h}	99^{de}	85^{de}	94^{d}	90^{ef}
Pendimethalin	No	100^{b}	83^{b}	93^{ab}	77^{ab}	90^{d}	88^{e}	92^{g}	43^{b}	92^{ef}	85^{fg}	96^{gh}	67^{cd}	100^{d}	100^{e}	95^{e}	95^{gh}	95^{bc}	95^{ef}	95^{d}	85^{cde}
	Yes	100^{b}	96^{de}	95^{abc}	88^{cde}	96^{d}	90^{ef}	92^{g}	63^{c}	96^{fg}	93^{gh}	100^{h}	85^{fghi}	100^{d}	100^{e}	98^{e}	96^{h}	96^{cd}	98^{ef}	98^{d}	88^{def}
Prosulfocarb	No	97^{a}	100^{e}	95^{abc}	98^{f}	88^{d}	60^{c}	10^{a}	0^{a}	99^{g}	63^{cd}	23^{a}	43^{b}	97^{cd}	0^{a}	10^{a}	33^{b}	92^{ab}	10^{a}	0^{a}	37^{a}
	Yes	100^{b}	100^{e}	97^{bcd}	99^{f}	88^{d}	73^{d}	30^{bc}	0^{a}	100^{g}	73^{de}	47^{c}	40^{b}	100^{d}	0^{a}	33^{b}	70^{efg}	90^{a}	40^{b}	0^{a}	75^{b}
Aclonifen	No	100^{b}	100^{e}	100^{d}	99^{f}	94^{d}	98^{fg}	95^{g}	63^{c}	30^{a}	70^{de}	27^{ab}	80^{efg}	100^{d}	100^{e}	97^{e}	99^{h}	92^{ab}	47^{b}	96^{d}	87^{def}
	Yes	100^{b}	100^{e}	100^{d}	100^{f}	99^{d}	100^{g}	98^{g}	90^{de}	40^{b}	72^{d}e	33^{b}	80^{efg}	100^{d}	100^{e}	100^{e}	100^{h}	92^{ab}	80^{cd}	95^{d}	93^{ef}
Acetochlor	No	97^{a}	100^{e}	100^{d}	97^{ef}	43^{bc}	0^{a}	23^{ab}	10^{a}	100^{g}	95^{gh}	100^{h}	83^{fgh}	97^{cd}	0^{a}	88^{e}	63^{cd}	100^{e}	100^{f}	100^{d}	93^{ef}
	Yes	100^{b}	100^{e}	100^{d}	100^{f}	53^{c}	0^{a}	50^{de}	63^{c}	100^{g}	100^{h}	100^{h}	93^{hi}	100^{d}	53^{bc}	83^{e}	82^{efg}	100^{e}	100^{f}	100^{d}	95^{ef}
Dimethenamid	No	98^{ab}	100^{e}	100^{d}	95^{def}	47^{c}	0^{a}	50^{de}	10^{a}	99^{g}	93^{gh}	98^{gh}	87^{ghi}	97^{cd}	50^{b}	88^{e}	60^{cd}	100^{e}	100^{f}	100^{d}	94^{ef}
	Yes	100^{b}	100^{e}	100^{d}	97^{f}	53^{c}	0^{a}	62^{ef}	53^{bc}	99^{g}	96^{h}	99^{gh}	93^{hi}	95^{c}	50^{b}	83^{e}	70^{efg}	100^{e}	100^{f}	100^{d}	96^{f}
S-Metolachlor	No	98^{ab}	95^{de}	100^{d}	85^{bc}	7^{a}	0^{a}	17^{ab}	0^{a}	78^{c}	75^{ef}	80^{f}	0^{a}	90^{ab}	0^{a}	53^{bc}	0^{a}	100^{e}	100^{f}	100^{d}	80^{bcd}
	Yes	100^{b}	100^{e}	100^{d}	93^{cdef}	30^{b}	0^{a}	20^{ab}	60^{c}	83^{cd}	80^{ef}	87^{fg}	73^{def}	93^{bc}	0^{a}	43^{bc}	68^{de}	100^{e}	100^{f}	100^{d}	93^{ef}
Propisochlor	No	99^{ab}	99^{e}	100^{d}	96^{ef}	40^{bc}	0^{a}	47^{cde}	0^{a}	95^{fg}	97^{h}	96^{fgh}	80^{efg}	87^{a}	0^{a}	85^{e}	7^{a}	100^{e}	100^{f}	100^{d}	87^{def}
	Yes	100^{b}	99^{e}	100^{d}	97^{f}	47^{c}	50^{b}	57^{ef}	60^{c}	100^{g}	98^{h}	100^{h}	85^{fghi}	88^{a}	47^{b}	87^{e}	57^{cd}	100^{e}	100^{f}	100^{d}	94^{ef}
Pethoxamid	No	98^{ab}	91^{cd}	99^{cd}	87^{cd}	30^{b}	0^{a}	33^{bcd}	0^{a}	85^{d}	50^{b}	90^{fg}	43^{b}	90^{ab}	0^{a}	90^{e}	7^{a}	93^{abc}	94^{ef}	93^{d}	90^{ef}
	Yes	97^{a}	97^{de}	95^{abc}	93^{cdef}	47^{c}	0^{a}	47^{cde}	10^{a}	88^{de}	75^{ef}	92^{fgh}	70^{cde}	95^{c}	53^{bc}	83^{e}	53^{c}	94^{bc}	97^{ef}	92^{d}	90^{ef}
Herbicide (*P*)		ns	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Irrigation (*P*)		ns	< 0.001	ns	< 0.001	0.026	< 0.001	< 0.001	< 0.001	0.003	< 0.001	0.001	< 0.001	0.040	< 0.001	ns	< 0.001	ns	< 0.001	ns	< 0.001
Herbicide × irrigation (*P*)		ns	< 0.001	ns	0,015	ns	< 0.001	ns	< 0.001	ns	< 0.001	0.049	< 0.001	ns	< 0.001	ns	< 0.001	ns	< 0.001	ns	< 0.001
LSD (0.05)[a]		2	6	5	9	16	9	19	11	6	10	10	13	4	13	23	14	4	14	11	10

Values within a column with the same letter are not significantly different at the 5% *LSD* (P = 0.05) level; ns – not significant

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85 and 98%, but was not significantly affected by irrigation in any year (Table 3). On the contrary, the efficacy of pendimethalin on *A. retroflexus*, *M. annua*, and *S. physalifolium* was significantly lower on plots without irrigation compared to irrigated plots in 2011 (Table 3). Pendimethalin injury to sunflower was minimal (less than 5%) and was not affected by precipitation or irrigation.

Prosulfocarb controlled only *A. retroflexus* with an efficacy greater than 95% in all experimental years (Table 3). Prosulfocarb was not consistently effective on any other weeds tested (Table 3). In 2008, prosulfocarb was effective also on *C. album* (Table 3). Prosulfocarb did not injure sunflower (visual injury less than 7%) and was not affected by natural precipitation or irrigation.

Aclonifen controlled *A. retroflexus* and *C. album* with an efficacy greater than 97%, regardless of irrigation (Table 3). Aclonifen controlled *M. annua* (efficacy over 90%) and *E. crus-galli* (efficacy over 80%), but only when irrigation was applied or natural precipitation at the beginning of the growing season was sufficient (Table 3). *S. physalifolium* was not controlled by aclonifen in any of the tested soil moisture conditions (Table 3). The selectivity of aclonifen for sunflower was good (phytotoxicity less than 7%) and was not significantly affected by irrigation (Table 5).

Acetochlor effectively controlled *A. retroflexus* (efficacy 97–100%), *S. physalifolium* (95–100%), and *E. crus-galli* (100%) in most of experimental years

Table 4. Yield of sunflower seeds in the tested treatments in experimental years (2008–2011)

Herbicide	Irrigation	Sunflower yield (t/ha)			
		2008	2009	2010	2011
Untreated	No	1.84^{a}	3.28^{abc}	1.65^{a}	0.94^{a}
Oxyfluorfen	No	3.83^{efghi}	4.13^{cdef}	2.57^{bcde}	3.01^{ij}
	Yes	3.74^{defgh}	4.03^{cdef}	3.11^{cdefg}	2.80^{hij}
Linuron	No	3.79^{efghi}	2.50^{a}	2.46^{bcd}	2.10^{cdefg}
	Yes	3.84^{efghi}	4.77^{f}	2.68^{cdef}	2.45^{efghi}
Flurochloridone	No	4.02^{fghi}	3.87^{bcdef}	3.12^{cdefg}	3.13^{j}
	Yes	3.90^{efghi}	4.77^{f}	3.30^{efg}	2.99^{ij}
Pendimethalin	No	4.14^{ghi}	4.03^{cdef}	3.69^{g}	3.27^{j}
	Yes	4.12^{ghi}	4.28^{cdef}	3.07^{cdefg}	3.06^{ij}
Prosulfocarb	No	3.94^{efghi}	3.95^{cdef}	2.40^{abc}	2.19^{cdefgh}
	Yes	4.08^{ghi}	4.35^{cdef}	2.47^{bcd}	2.76^{ghij}
Aclonifen	No	4.31^{hi}	4.85^{f}	3.33^{efg}	2.39^{defghi}
	Yes	4.53^{i}	4.38^{cdef}	3.08^{cdefg}	2.68^{fghij}
Acetochlor	No	3.56^{defgh}	4.50^{def}	3.24^{defg}	2.09^{cdefg}
	Yes	3.69^{defgh}	4.88^{f}	2.69^{cdef}	1.97^{cde}
Dimethenamid	No	3.47^{cdefg}	4.38^{cdef}	2.67^{cdf}	1.75^{bcd}
	Yes	3.57^{defgh}	4.18^{cdef}	2.97^{cdefg}	2.05^{cdef}
S-Metolachlor	No	2.77^{bc}	3.39^{abcd}	2,78^{cdef}	1.53^{abc}
	Yes	3.27^{bcdef}	4.37^{cdef}	2,78^{cdef}	1.93^{cde}
Propisochlor	No	3.01^{bcd}	3.62^{abcde}	3.60^{g}	1.73^{cde}
	Yes	3.29^{bcdef}	4.07^{cdef}	3.17^{cdefg}	1.92^{cde}
Pethoxamid	No	2.61^{ab}	3.39^{abcd}	3.39^{fg}	1.55^{abc}
	Yes	3.17^{bcde}	3.93^{cdf}	2.68^{cdef}	1.62^{bc}
Herbicide (*P*)		< 0.001	ns	< 0.001	< 0.001
Irrigation (*P*)		ns	0.012	ns	ns
Herbicide × irrigation (*P*)		ns	0.032	ns	ns
LSD (0.05) [a]		0.78	1.15	0.81	0.68

Values within a column with the same letter are not significantly different at the 5% *LSD* (P = 0.05) level

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(2008–2010). In the very dry spring of 2011, the efficacy of acetochlor on *E. crus-galli* was 93–95%, and the efficacy on *S. physalifolium* was 83–93%. The efficacy of acetochlor on these weeds was not significantly affected by irrigation (Table 3). Acetochlor was effective on *C. album* just once, in 2008 (Table 3). The selectivity of acetochlor for sunflower was low (phytotoxicity 3–30% at four true leaves stage of sunflower). Phytotoxicity was significantly affected by irrigation in 2008, 2010, and 2011 (Table 5). Symptoms of sunflower injury included growth retardation and shortening of low internodes. The sunflower recovery rate was the lowest among all of the tested herbicides. Phytotoxicity of 3–15% was observed shortly before sunflower row closure; however, significant yield losses were not detected in any year (Table 4).

The weed control results for **dimethenamid** were similar to those of acetochlor (Table 3). The sunflower tolerance to dimethenamid was good (phytotoxicity less than 7%), except in 2010 when sunflower injury ranged from 10% to 12% across irrigation treatments (Table 5). Differences in phytotoxicity between irrigated and non-irrigated treatments were significant only in 2011 in both assessment terms (Table 5).

S-metolachlor only controlled *A. retroflexus* and *E. crus-galli* (efficacy 93–100%). However, on treatment without irrigation in 2011, the efficacy of S-me-

Table 5. Sunflower injury caused by the application of herbicides in experimental years (2008–2011)

Herbicide	Irrigation	Crop injury (%)							
		sunflower at BBCH 14^{a}				sunflower at BBCH 32^{b}			
		2008	2009	2010	2011	2008	2009	2010	2011
Oxyfluorfen	No	25^{bc}	33^{d}	43^{f}	30^{e}	7^{cde}	23^{d}	42^{i}	22^{h}
	Yes	33^{d}	47^{e}	40^{f}	27^{e}	10^{e}	23^{d}	33^{h}	12^{g}
Linuron	No	0^{a}	2^{ab}	0^{a}	0^{a}	0^{a}	0^{a}	3a^{b}	1^{ab}
	Yes	0^{a}	2^{ab}	0^{a}	3^{ab}	1^{ab}	0^{a}	3^{ab}	7^{def}
Flurochloridone	No	20^{b}	1^{a}	10^{e}	8^{c}	3^{abc}	0^{a}	3^{ab}	6^{cde}
	Yes	30^{cd}	8^{c}	7^{cde}	8^{c}	3^{abc}	0^{a}	7^{bcde}	8^{efg}
Pendimethalin	No	0^{a}	0^{a}	2^{ab}	0^{a}	0^{a}	0^{a}	1^{a}	0^{a}
	Yes	0^{a}	0^{a}	5^{bcd}	3^{ab}	0^{a}	0^{a}	1^{a}	4^{bcd}
Prosulfocarb	No	0^{a}	0^{a}	0^{a}	0^{a}	0^{a}	0^{a}	2^{ab}	0^{a}
	Yes	0^{a}	0^{a}	3^{abc}	2^{ab}	0^{a}	0^{a}	7^{bcde}	2^{abc}
Aclonifen	No	2^{a}	5^{abc}	5^{bcd}	0^{a}	0^{a}	0^{a}	4^{abc}	0^{a}
	Yes	3^{a}	5^{abc}	3^{abc}	3^{ab}	0^{a}	0^{a}	7^{bcd}	2^{abc}
Acetochlor	No	23^{b}	3^{abc}	3^{abc}	5^{bc}	8^{de}	5^{bc}	10^{defg}	3^{abc}
	Yes	30^{cd}	7^{bc}	8^{de}	17^{d}	5^{bcd}	7^{c}	15^{g}	10^{fg}
Dimethenamid	No	0^{a}	0^{a}	2^{ab}	0^{a}	7^{cde}	0^{a}	10^{defg}	0^{a}
	Yes	3^{a}	5^{abc}	3^{abc}	5^{bc}	5^{bcd}	0^{a}	12^{efg}	4^{bcd}
S-Metolachlor	No	2^{a}	0^{a}	2^{ab}	0^{a}	2^{ab}	2^{ab}	2^{ab}	0^{a}
	Yes	2^{a}	3^{abc}	3^{abc}	0^{a}	5^{bcd}	2^{ab}	6^{abcd}	0^{a}
Propisochlor	No	2^{a}	0^{a}	0^{a}	0^{a}	5^{bcd}	0^{a}	10^{defg}	0^{a}
	Yes	3^{a}	0^{a}	2^{ab}	3^{ab}	7^{cde}	0^{a}	13^{fg}	2^{abc}
Pethoxamid	No	3^{a}	0^{a}	0^{a}	0^{a}	3^{abc}	0^{a}	9^{cdef}	0^{a}
	Yes	3^{a}	0^{a}	0^{a}	0^{a}	5^{bcd}	0^{a}	10^{defg}	0^{a}
Herbicide (*P*)		< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Irrigation (*P*)		< 0.001	< 0.001	ns	< 0.001	ns	ns	ns	< 0.001
Herbicide × Irrigation (*P*)		ns	0.008	ns	0.036	ns	ns	ns	ns
LSD (0.05) ^{c}		6	5	5	5	4	5	6	4

[a]sunflower had four true leaves; [b]shortly before the sunflower canopy closed rows; [c]values within a column with the same letter are not significantly different at the 5% *LSD* (P = 0.05) level

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tolachlor on *A. retroflexus* decreased by 8% (Table 3) and the efficacy on *E. crus-galli* decreased significantly by 13% (Table 3). The selectivity of S-metolachlor for sunflower was very good (phytotoxicity less than 6%) and was not affected by natural precipitation or irrigation (Table 5).

Propisochlor controlled *A. retroflrexus* (efficacy 96–100%), *E. crus-galli* (94–100%), and *S. physalifolium* (85–100%). The efficacy of propisochlor on these weeds was not significantly affected by irrigation (Table 3). However, without irrigation in 2011, efficacy on *E. crus-galli* and *S. physalifolium* was only 87 and 80%, respectively. This herbicide did not sufficiently control *C. album* and *M. annua*, except in 2008 and 2010, which displayed higher natural precipitation rates at the beginning of the growing season, when the efficacy on *C. album* was sufficient (more than 85%). Propisochlor did not injure sunflower, except in 2010, when sunflower injury was 10–13% at BBCH 32. Sunflower phytotoxicity was not affected by irrigation (Table 5).

Pethoxamid only controlled *A. retroflexus* (efficacy 91–99%) and *E. crus-galli* (90–97%) in all experimental years (Table 3). The efficacy of pethoxamid on *C. album* and *M. annua* was insufficient in both irrigation regimes and experimental years (Table 1). The efficacy on *S. physalifolium* was sufficient (85–92%) only in 2008 and 2010 (Table 3). The selectivity of pethoxamid to sunflower was very high (phytotoxicity less than 5%), except in 2010, when phytotoxicity 9 and/or 10% was observed shortly before sunflower row closure. Sunflower phytotoxicity was not affected by irrigation (Table 5).

DISCUSSION

E. crus-galli was controlled effectively by **oxyfluorfen** only in the year 2008, when higher natural precipitation rates and low temperatures occurred in the first month after herbicide application. Acceptable efficacy of oxyfluorfen on *E. crus-galli* in 2011 may be caused by suitable weather condition before sunflower sowing. Although oxyfluorfen has a low leaching potential (Footprint database 2011), it was the most injurious to sunflower of all the herbicides tested. This result is in line with that of Pannacci *et al*. (2007). The phytotoxicity of oxyfluorfen was mainly caused by raindrops bouncing from the soil surface, which contaminated leaves and caused necrosis and leaf deformation.

Efficacy of **linuron** was poor. In a study performed by Bell *et al.* (2000), the weed control of linuron was better than in our studies, but these experiments were carried out on sandy soil with regular irrigation. The selectivity of linuron for sunflower was high, but greater phytotoxicity may occur on sandy soils (de Prado *et al*. 1993).

Efficacy of **pendimethalin** on *A. retroflexus*, *M. annua*, and *S. physalifolium* was affected by irrigation. Pannacci *et al*. (2007) recorded significant differences in pendimethalin efficacy among individual experimental years as well. Although many weeds (especially *M. annua*) emerged after pendimethalin application, their growth was stalled for 6–8 weeks during the growth stage of cotyledon leaves because their growing point was destroyed. Subsequently, some of these plants regenerated from lateral buds. Thus, if the canopy is not fully closed, sunflower may be infested by weeds in the second part of the growing season. Pendimethalin injury to sunflower was minimal because of rapid metabolism by sunflower and low mobility in soil (Footprint database 2011). The creation of calluses at the base of sunflower stems is very common after pendimethalin application on stony soils and/or soils with declined structure, which can lead to crop lodging (Jursík *et al*. 2011). However, this effect was not observed in the present study.

Aclonifen selectivity to sunflower was high. Sunflower tolerance to aclonifen is ensured by low root uptake, conjugation in the roots, and low xylem transfer from root to shoot (Kilinc *et al*. 2011).

Efficacy of **acetochlor** on some weeds was lower in dry years. Nagy (2008) found that at least 14 mm of rainfall was required during the first two weeks after application to obtain optimal activation of acetochlor. Our findings are not in accordance with those of the study of de Prado *et al*. (1993), who observed high sunflower tolerance to acetochlor evaluating a PRE application of 1.5–5.0 kg/ha in a laboratory study.

Efficacy of **S-metolachlor** on *A. retroflexus* and *E. crus-galli* was affected by irrigation and experimental year. Large efficacy differences after application of S-metolachlor on grass weeds were also observed between growing seasons by Johnson *et al*. (2012). The selectivity of S-metolachlor for sunflower was not affected by natural precipitation or irrigation, although S-metolachlor leaching in soil is relatively high (Jursík *et al*., 2013).

Efficacy of **pethoxamid** was low, especially in dry condition. High weed densities led to yield losses

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of sunflower, especially on non-irrigated plots. According to Dhareesank *et al.* (2006), the activity of pethoxamid depends on changes in its concentration in soil over time, except when low soil moisture does not allow weed emergence.

CONCLUSION

The efficacy of oxyfluorfen, aclonifen, acetochlor, dimethenamid, and propisochlor was not significantly affected by the soil moisture; thus, these herbicides can be recommended for use in arid and semi-arid areas. On the contrary, the efficacy of linuron, prosulfocarb, and pethoxamid seems to be more dependent on the soil moisture. These herbicides are not suitable for use in dry areas or under dry conditions at and after sowing. All of the afore-mentioned herbicides, as well as S-metolachlor, propisochlor, dimethenamid, aclonifen, and pendimethalin, showed good selectivity for sunflower and can be used in areas with intensive precipitation or irrigation at the beginning of the growing season without higher risk of crop injury.

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