Effects of application terms of three soil active herbicides on herbicide efficacy and reproductive ability for weeds in maize

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ABSTRACT

The aim of this work was to compare herbicide efficacy and reduction of weed reproduction after the application of three frequently used soil residual herbicides during pre-emergent (PRE) and early post-emergent (EPOST) application in maize. Plot field trials were carried out in Central Bohemia during two growing seasons (2010 and 2011). Good efficacy (88%, resp. 83%) was found in isoxaflutole + thiencarbazone (ISF + THC) and terbuthylazin + S-metolachlor (TBA + SMC) on *Echinochloa crus-galli*, especially in PRE application use. Efficacy on *Amaranthus retroflexus* was 91% at both tested application periods and there were no significant differences between experimental years. Significant differences in *A. retroflexus* control were recorded among all tested herbicides (ISF + THC > TBA + SMC > pendimethalin (PEM) + dimethenamid (DMA)). No significant differences between PRE and EPOST were recorded in efficacy on *Chenopodium album*. Significant differences in efficacy on *C. album* were recorded among all tested herbicides (ISF + THC > TBA + SMC > PEM + DMA). *Mercurialis annua* was the most tolerant tested weed, which was significantly better controlled at EPOST herbicide application (73%) compared to PRE application (32%). TBA + SMC showed a significantly higher efficacy on *M. annua* compared with other tested herbicides. Seed production of all tested weeds was strongly effected by weather conditions, which were significant during 2011, when there was higher than average precipitation during May and June. The most seeds were produced by *A. retroflexus* > *C. album* > *E. crus-galli* > *M. annua.* ISF + THC best reduced seed production of *E. crus-galli*, *A. retroflexus* and *C. album*, especially when applied at PRE. TBA + SMC best reduced seed production of *M. annua.* Weed competition on untreated control plots caused yield loss by 90%and 47% in 2011 and 2012, respectively, compared to treatments with the highest yield (ISF + THC).

Keywords: *Zea mays*; pre-emergent and early post-emergent application of herbicide; seed reproduction of weeds

Production of maize (*Zea mays*) is increasing globally and this trend is evident throughout the Central Europe. We may expect this trend to continue in the future (Tatsumi et al. 2011). At the present time, maize is the most significant crop in the world. Weed management had a major affect on the success of maize growth, because the competition ability of maize is relative low.

The critical weed-free period for maize is between the 3rd and the 6th weeks after emergence (Zimdahl 2004). Weed competition is manifested by a decrease of maize biomass and yield losses, which is usually between 30% and 50%, depending on the weed density, time and duration of competition, weed spectrum and other factors (Hurle 1988).

Pre-emergent (PRE) and early post-emergent (EPOST) herbicides are widely used for weed control in maize in Europe, where glyphosate tolerant cultivars are not registered. High differences in soil

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residual activity, solubility in water, leaf uptake and other characteristics are among these herbicides.

Application timing for specific herbicides must be determined depending on the weed spectrum, current soil moisture and ability of leaf uptake of the herbicide. Johnson et al. (2012) showed better results for weed control and higher maize yields on treatments where two, three or four herbicides or tank-mix treatments were used than when a single active ingredient of herbicide was applied.

Herbicide Adengo (isoxaflutole + thiencarbazone) is the most widespread herbicide used in maize production in the Czech Republic. This herbicide is used at PRE and EPOST application. Isoxaflutole inhibits the hydroxyphenyl-pyruvate dehydrogenase enzyme. Adengo contains safener cyprosulfamide, which increases maize metabolism of isoxaflutole. Besides metabolic selectivity, site of action selectivity is also used in maize (deeper sowing) because isoxaflutole has little ability to move vertically in soil (Rouchaud et al. 2002). Sorption and degradation of isoxaflutole and its metabolites was higher in soil with higher contents of organic matter, clay, and lower pH (Rice et al. 2004). Sorption of isoxaflutole decreased when the soil pH increased from 4.5 to 8.5 (Mitra et al. 1999).

Thiencabazone is a relatively new active ingredient from the group of inhibitors of acetolactate synthase. According to Stephenson and Bond (2012), isoxaflutole + thiencarbazone provided better weed control than atrazine + S-metolachlor at PRE application in maize.

Gardoprim Plus Gold 500 EC (terbuthylazin + S-metolachlor) is a relatively old herbicide (Schulte and Allen 2000), but is still widely used. For both active ingredients, synergy effects were recorded for control of annual weeds (Schulte et al. 2002). Terbuthylazin, which belongs to the group of triazine herbicides, affected electron transport in photosystem II. S-metolachlor, which is an acetamide herbicide affected biosynthesis of very long-chain fatty acids (Yang et al. 2010). Metolachlor disappeared in soil more rapidly than terbuthylazine, while metolachlor moved more rapidly than terbuthylazine through the soil profile (Vischetti et al. 1998). The efficacy of S-metolachlor is strongly influenced by soil moisture and delayed under dry conditions (Jursík et al. 2013).

Herbicide Wing-P (pendimethalin + dimethenamid) is a relatively new herbicide, but it contains already used active ingredients. Pendimethalin inhibits the polymerization of tubulin basic units, production of protofilaments, microtubules and whole spindle apparatus. Dimethenamid is an acetamide herbicide, but with higher solubility in water, compared to S-metolachlor.

Reproductive ability of summer weeds in maize canopy is relative high. Seed production of *Amaranthus palmeri* in maize ranged between 140 000 and 514 000 seeds/m^2 in dependence on weed density (Massinga et al. 2001). Seed production of *Echinochloa crus-galli* in maize ranged between 1200 and 36 000 seeds/m^2 in dependence on time of emergence (Bosnic and Swaton 2001). According to Cardina et al. (1995), seed production of *Abutilon theophrasti* in maize is half compared to seed production without crop competition.

The aim of the presented paper was to compare the herbicide efficacy and reduction of weed reproduction ability after applications of frequently used soil residual herbicides under pre-emergent and early post-emergent application terms in maize.

MATERIAL AND METHODS

The plot field-trials with maize (hybrid Rivaldo) were carried out in Central Bohemia (Prague), the Czech Republic (300 m a.s.l.; GPS: 50°7'N, 14°22'E), during the years 2010 and 2011. The soil was classified as Haplic Chernozem, with a clay content of 19.3%, sand content 24.4%, silt content 56.3% (silt loam soil), soil pH_{KCl} of 7.5 and a sorption capacity of 209 $mmol_+$/kg. The nutrient content was as follows: 87 mg/kg P, 203 mg/kg K, 197 mg/kg Mg, 8073 mg/kg Ca. Winter wheat was the prior crop in both years. Maize was sown on the 21st of April, 2011 and the 26th of April, 2012.

The experimental plots were arranged in complete randomized blocks with three replicates, and the area of the plots was 24.5 m^2 (3.5 × 7 m). For planting, a precise small-plot sowing machine was used. 0.7 m was the row spacing and 0.14 m in-row plant spacing. *Chenopodium album* (10–80 plants/m^2) was the dominant weed species in both experimental years. Other weeds, found in plots at a lower density (4–12 plants/m^2 for individual species) included the following species: *Echinochloa crus-galli*, *Amaranthus retroflexus*, *Chenopodium album* and *Mercurialis annua.*

Three soil active herbicides were tested at two application times. The herbicides Wing-P (212.5 g/L of dimethenamid-P and 250 g/L of pendimethalin), Adengo (225 g/L of isoxaflutole and 90 g/L of thiencarbazone) and Gardoprim Plus Gold 500 EC

(312.5 g/L of S-metolachlor and 187.5 g/L of terbuthylazine) were used at their recommended rates (Wing-P 4.00 L/ha, Adengo 0.44 L/ha and Gardoprim Plus Gold 500 EC 4.00 L/ha).

The experiment included untreated control plots. Pre-emergent applications of the herbicides were made shortly after maize sowing (same day). Early post-emergent applications of the herbicides were performed in 2–3 leaves stage of maize and weeds were at growth stage BBCH 10–14 (13th May 2011 and 9th May 2012). A small-plot sprayer was used to apply the herbicides (application volume 300 L/ha, nozzle Lurmark 015 F 80, application pressure 0.3 MPa). Meteorological characteristics during the first half of maize growing season are shown in the Table 1.

The herbicide efficacy was assessed by estimation methods using a percentage scale from 0% to 100% (0% – untreated; 100% – full control), according to the European and Mediterranean Plant Protection Organisation (EPPO) 1/63 (3) guidelines. The efficacy assessment was done shortly before canopy closure. Seed production of weeds was calculated from the number of seeds collected from 1 m^2 of each plot. Weed-seed heads were collected continuously (according to ripening) up to maize harvest to avoid seed shed. The yield of maize grain was calculated from the two middle rows harvested in each plot.

The experimental data were evaluated using the software package Statgraphics Plus 4.0 (Statpoint, Inc., Herndon, USA). The significant differences among treatments were verified by the *LSD* test ($P < 0.05$).

RESULTS AND DISCUSSION

Efficacy on *Echinochloa crus galli* was significantly higher at PRE application term and during experimental year 2011 (Table 2), where the total precipitation during May and June was elevated (Table 1). *E. crus-galli* control by isoxaflutole + thiencarbazone (ISF + THC) and terbuthylazin + S-metolachlor (TBA + SMC) were significantly more efficient compared to pendimethalin + dimethenamid (PEM + DMA). Efficacy of PEM + DMA was higher by 7% and 60% at PRE application, compared to EPOST. Efficacy of ISF + THC was at 90–93% and 80% in 2011, and 2012, respectively, without significant differences between PRE and EPOST application term (Tables 3 and 4). Efficacy of TBA + SMC was insignificantly higher (by 5% and 8%, respectively) at EPOST application term compared to PRE application. Nagy (2008) found that at least 14 mm of rainfall was required during the first two weeks after application for efficient control of *E. crus-galli* by acetochlor.

Efficacy on *Amaranthus retroflexus* was 91% at both tested application terms and there were no significant differences between experimental year 2011 and 2012 (efficacy 90% and 92%, respectively). Significant differences in *A. retroflexus* control were recorded among all the tested herbicides (ISF + THC > TBA + SMC > PEM + DMA) (Table 2). Efficacy of PEM + DMA was insignificantly higher at EPOST application term in 2011, but during 2012, significantly higher efficacy was recorded on PRE treated plots, where higher total precipitation was recorded at the time of sowing (April). Efficacy of ISF + THC was 98–100% and 93–98%, in 2011, and 2012, respectively, without significant differences between PRE and EPOST application term. Efficacy of TBA + SMC was 85–92% and 95–97% in 2011 and 2012, respectively, without significant differences between PRE and EPOST application terms (Tables 3 and 4).

No significant differences between experimental years 2011 and 2012 and between PRE and EPOST were recorded in efficacy on *Chenopodium album* (Table 2). On the contrary, significant differences in efficacy on *C. album* were recorded among all tested herbicides (ISF + THC > TBA + SMC > PEM + DMA). Efficacy of PEM + DMA in 2011 and 2012 was significantly higher after PRE application (95% and 83%), compared to EPOST (82% and 68%), respectively. Efficacy of ISF + THC on *C. album* was excellent (above 97%), although EPOST application of this herbicide in 2011 showed significantly lower efficacy (88%). Efficacy of TBA + SMC was higher at EPOST application terms compared to PRE application (Tables 3 and 4). During 2011, the difference between PRE and EPOST application terms for this herbicide was significant (77% and 100%, respectively, probably due to low

Table 1. Weather conditions at the beginning of the growing season

Meteorological characteristic		2011	2012
Total precipitation (mm)	April	16.2	44.0
	May	35.7	23.4
	June	60.0	46.8
Mean monthly temperature (°C)	April	12.3	9.6
	May	15.0	15.8
	June	18.3	18.1

Table 2. Efficacy (%) of tested herbicides shortly before the maize canopy closed the rows, depending on herbicides used, application timing and experimental years

	Echinochloa crus-galli	*Amaranthus retroflexus*	*Chenopodium album*	*Mercurialis annua*
Effect of used herbicide				
Wing-P	55.8^{a}	84.2^{a}	82.1^{a}	49.6^{a}
Adengo	87.9^{b}	97.4^{c}	96.0^{c}	46.2^{a}
Gardoprim	82.5^{b}	92.1^{b}	89.5^{b}	65.0^{b}
$LSD_{0.05}$	8.5	4.3	4.6	12.6
F-ratio	34.25	20.13	19.05	5.34
P-value	0.0000	0.0000	0.0000	0.0114
Effect of application term				
Pre-emergent	81.6^{b}	91.4^{a}	90.1^{a}	32.2^{a}
Early post-emergent	69.1^{a}	91.1^{a}	88.3^{a}	75.0^{b}
$LSD_{0.05}$	2.4	3.5	3.8	10.3
F-ratio	13.6	0.04	0.99	73.18
P-value	0.0010	0.8475	0.3288	0.0000
Effect of year				
2011	84.7^{b}	90.2^{a}	89.8^{a}	51.1^{a}
2012	66.1^{a}	92.2^{a}	88.6^{a}	56.1^{a}
$LSD_{0.05}$	2.4	3.5	3.8	10.3
F-ratio	30.16	1.36	0.40	1.00
P-value	0.0000	0.2543	0.5321	0.3266

Means followed by the same letter within the column are not significantly different at $P < 0.05$

total precipitation at the time of sowing (Table 1). According to Stewart et al. (2010), cumulative precipitation during the 12 days after PRE application of metribuzin that exceeded the monthly average by at least 60%, reduced *C. album* control.

Mercurialis annua was the most tolerant weed tested; it was significantly better controlled after EPOST herbicide application (73%) compared to PRE application (32%). TBA + SMC showed significantly higher efficacy on *M. annua* compared with other tested herbicides (Table 2). Efficacy of all tested herbicides was more than 80% but only at EPOST applications in 2012 (Table 4). Jursík et al. (2008) also recorded low efficacy of PRE application of ISF on *M. annua*, especially under dry conditions.

Seed production of all tested weeds was strongly affected by weather conditions and it was significantly higher in 2011, when the total precipitation

Table 3. Efficacy (%) of tested herbicides in two tested application terms in 2011

		Echinochloa crus-galli	*Amaranthus retroflexus*	*Chenopodium album*	*Mercurialis annua*
Wing-P	PRE	85^{ab}	82^{a}	95^{cd}	33^{a}
	EPOST	78^{a}	85^{ab}	82^{ab}	73^{c}
Adengo	PRE	93^{b}	100^{d}	97^{d}	43^{ab}
	EPOST	90^{b}	98^{cd}	88^{bc}	53^{b}
Gardoprim	PRE	83^{ab}	85^{ab}	77^{a}	33^{a}
	EPOST	78^{a}	92^{bc}	100^{d}	70^{c}
$LSD_{0.05}$		10	7	8	16
F-ratio		3.21	10.87	14.24	11.94
P-value		0.0455	0.0004	0.0001	0.0003

Means followed by the same letter within the column are not significantly different at $P < 0.05$. PRE – pre-emergent; EPOST – early post-emergent

Table 4. Efficacy (%) of tested herbicides in two tested application terms in 2012

		Echinochloa crus-galli	*Amaranthus retroflexus*	*Chenopodium album*	*Mercurialis annua*
Wing-P	PRE	60^{b}	92^{b}	83^{b}	10^{a}
	EPOST	0^{a}	78^{a}	68^{a}	82^{bc}
Adengo	PRE	80^{c}	93^{b}	100^{d}	0^{a}
	EPOST	80^{c}	98^{b}	98^{d}	88^{c}
Gardoprim	PRE	88^{c}	97^{b}	88^{bc}	73^{b}
	EPOST	80^{c}	95^{b}	93^{cd}	83^{bc}
$LSD_{0.05}$		12	9	9	14
F-ratio		78.05	6.59	14.81	75.17
P-value		0.0000	0.0036	0.0001	0.0000

Means followed by the same letter within the column are not significantly different at $P < 0.05$. PRE –pre-emergent; EPOST – early post-emergent

during May and June was elevated. The highest seeds were produced by *A. retroflexus* > *C. album* > *E. crus-galli* > *M. annua* in both experimental years (Tables 5, 6 and 7). This result is compatible with the study of Satrapová et al. (2013), who recorded, that plants of *A. retroflexus* produced more seeds than plants of *E. crus-galli* in wide altitude ranges of the Czech Republic region. ISF + THC best reduced seed production of *E. crus-galli*, *A. retroflexus* and *C. album*, especially when it was applied at PRE. TBA + SMC best reduced seed production of *M. annua.* Seed production of *E. crus-galli* after application of ISF + THC (1780 seeds/m^2) was significantly lower compared to TBA + SMC (10 192 seeds/m^2). Seed production of *A. retroflexus* after application of ISF + THC (64 seeds/m^2) and TBA + SMC (5274 seeds/m^2) was significantly lower compared to PEM + DMA (31 406 seeds/m^2).

When ISF + THC was applied, *A. retroflexus* produced seeds only in 2012 on plots treated EPOST

Table 5. Seed production (seed/m^2) of weeds depending on used herbicides, application terms and experimental years

	Echinochloa crus-galli	*Amaranthus retroflexus*	*Chenopodium album*	*Mercurialis annua*
Effect of used herbicide				
Wing-P	5401^{ab}	$31\,406^{b}$	$21\,870^{a}$	$15\,432^{b}$
Adengo	1780^{a}	64^{a}	2513^{a}	9424^{ab}
Gardoprim	$10\,192^{b}$	5274^{a}		3419^{a}
$LSD_{0.05}$	5340	14 121	24 843	7639
F-ratio	5.28	11.95	2.19	5.22
P-value	0.0119	0.0002	0.1318	0.0124
Effect of application term				
Pre-emergent	5537^{a}	8816^{a}	$19\,662^{a}$	$15\,150^{b}$
Early post-emergent	6047^{a}	$15\,680^{a}$	$14\,139^{a}$	3700^{a}
$LSD_{0.05}$	4359	11 529	20 284	6237
F-ratio	0.06	1.50	0.31	14.24
P-value	0.8116	0.2320	0.5805	0.008
Effect of year				
2011	$11\,046^{b}$	$19\,606^{b}$	$33\,753^{b}$	$18\,380^{b}$
2012	537^{a}	4890^{a}	49^{a}	470^{a}
$LSD_{0.05}$	1500	11 529	20 284	6237
F-ratio	24.55	6.88	11.67	34.84
P-value	0.0000	0.0144	0.0021	0.0000

Means followed by the same letter within the column are not significantly different at $P < 0.05$

Table 6. Seed production of weeds (number of seeds/m^2) after application of tested herbicides in two tested application terms in 2011

		Echinochloa crus-galli	*Amaranthus retroflexus*	*Chenopodium album*	*Mercurialis annua*
Untreated control		7372^{ab}	154 865^{b}	109 504^{b}	13 300^{ab}
Wing-P	PRE	6778^{a}	34 052^{a}	14 465^{a}	53 463^{c}
	EPOST	14 213^{ab}	66 378^{ab}	73 017^{b}	7654^{a}
Adengo	PRE	2926^{a}	0^{a}	0^{a}	27 731^{b}
	EPOST	4090^{a}	0^{a}	9957^{a}	8845
Gardoprim	PRE	21 967^{b}	9580^{a}	103 413^{b}	7469^{a}
	EPOST	16 302^{ab}	7625^{a}	1667^{a}	5117^{a}
$LSD_{0.05}$		14 899	11 430	57 601	17 735
F-ratio		2.08	2.24	6.66	8.98
P-value		0.1215	0.1003	0.0017	0.0004

Means followed by the same letter within the column are not significantly different at $P < 0.05$. PRE – pre-emergent; EPOST – early post-emergent

(Table 7). *C. album* showed very low reproductive ability on herbicide treated plots in 2012. No seeds were produced on plots treated by PEM + DMA, ISF + THC at EPOST application term and TBA + SMC at PRE application term during 2012. Seed production of *C. album* significantly differed between PRE and EPOST applications of PEM + DMA and TBA + SMC in 2011 (Table 6). Seed production of *M. annua* was not significantly reduced by any tested herbicide. After application of TBA + SMC (3419 seeds/m^2), seed production of *M. annua* was significantly lower compared to PEM + DMA (15 432 seeds/m^2). Application timing significantly effected seed production of *M. annua* and this weed produced 5 times less seed after EPOST herbicide application (Table 5). High level of *M. annua* seed production on plots PRE treated by ISF were also shown by Jursík et al. (2008), especially under dry conditions.

The lowest grain yield of maize was harvested on untreated control plots in both experimental years (Table 8). Weed competition on untreated control plots caused yield loss of 90% and 47%, respectively, compared to treatments with the highest yield (12.81 and 9.38 t/ha) in 2011 and 2012. This result is compatible with the study of Harrison et al. (2001) and Massinga and Currie (2002) who recorded similar yield loss of maize after summer weeds competition. The highest yields were recorded on plots treated by ISF + THC in both experimental years. From herbicide treated plots, the lowest yield was obtained after PRE application of TBA + SMC (2011) and EPOST application of PEM + DMA (2012).

Table 7. Seed production of weeds (number of seeds/m^2) after application of tested herbicides in two tested application terms in 2012

		Echinochloa crus-galli	*Amaranthus retroflexus*	*Chenopodium album*	*Mercurialis annua*
Untreated control		275^{a}	38 692^{b}	3153^{b}	230^{ab}
Wing-P	PRE	245^{a}	7118^{a}	0^{a}	473^{abc}
	EPOST	371^{a}	18 077^{ab}	0^{a}	137^{a}
Adengo	PRE	48^{a}	0^{a}	97^{a}	929^{c}
	EPOST	56^{a}	257^{a}	0^{a}	190^{ab}
Gardoprim	PRE	1252^{b}	2145^{a}	0^{a}	835^{bc}
	EPOST	1248^{b}	1746^{a}	194^{a}	257^{abc}
$LSD_{0.05}$		861	25 297	2505	683
F-ratio		3.42	2.93	2.03	2.06
P-value		0.0271	0.0459	0.1297	0.1245

Means followed by the same letter within the column are not significantly different at $P < 0.05$. PRE – pre-emergent; EPOST – early post-emergent

Table 8. Grain yield of maize (t/ha) treated by tested herbicides in two tested application terms in both experimental years

		2011	2012
Untreated control		1.23[a]	4.96[a]
Wing-P	PRE	9.68[bcd]	7.35[abc]
	EPOST	8.03[bc]	5.95[ab]
Adengo	PRE	12.25[de]	9.38[c]
	EPOST	12.81[e]	9.23[c]
Gardoprim	PRE	7.32[b]	6.63[abc]
	EPOST	10.64[cde]	8.29[bc]
$LSD_{0.05}$		2.79	2.94
F-ratio		18.23	2.95
P-value		0.0000	0.0445

Means followed by the same letter within the column are not significantly different at $P < 0.05$. PRE – pre-emergent; EPOST – early post-emergent

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