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REGULAR ARTICLE

Alternatives to terbuthylazine for chemical weed control in maize

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ABSTRACT
Three field experiments were carried out on maize from 2012 to 2014 to assess weed control efficacy of herbicides' treatments with and without terbuthylazine applied in different mixtures and with different application timings. Considering pre-emergence herbicides, acetochlor and S-metolachlor alone seem not to be advisable due to their low efficacy against broadleaved weeds. Herbicide mixtures based on terbuthylazine gave the highest weed control, although thiencarbazone-methyl + isoxaflutole or s-metolachlor + mesotrione represent two valid alternatives to terbuthylazine. Post-emergence herbicides gave a good control of weeds, although mesotrione + nicosulfuron or tembotrione showed a higher efficacy than foramsulfuron. Crop yield losses in the untreated check compared to the highest yield obtained with herbicides treatments, ranging from 33% to 91%.

Key Words: *terbuthylazine; maize; weed control; herbicide mixtures; weeds/crops competition.*

INTRODUCTION

Production of maize (*Zea mays* L.) is increasing globally, and this trend is evident throughout the Central Europe (Andr et al. 2014). We may expect this trend to continue in the future (Tatsumi et al. 2011), with maize also being the most dominating crop for biogas production (Amon et al. 2007). Weed management had a major effect on success of maize growth because the competition ability of maize is relatively low (Ghanizadeh et al. 2014). With respect to weed control, due to its sowing period in Europe (Mars Bulletin 2012), this crop is very often characterised by a complex plurispecific weed flora, composed of grass and broadleaved weeds (Baghestani et al. 2007, Kolářová et al. 2014, Pannacci and Tei 2014). This weed flora has been traditionally controlled with pre-emergence applications based on terbuthylazine, because of its broad controlled weed spectrum, superior residual activity, excellent crop tolerance, perceivable speed of efficacy, and suitability as partner for other active ingredients (Schulte et al. 2012). However, short rotation cycles or monoculture of maize with repeated applications of the same pre-emergence herbicides have determined a strong increase in the frequency of several 'difficult to control' weed species, forcing farmers to adopt less simplified weed control strategies (Meissle et al. 2010).

In particular, in order to optimise weed control efficacy and minimise the application costs, the use of complex combinations of pre and post-emergence herbicides, as well as herbicide mixtures, has become the rule rather than the exception in many countries (Kudsk 2002, Pannacci et al. 2007). This strategy also represents an important tool to avoid problems related to herbicide resistance (Friesen et al. 2000, Norsworthy et al. 2012), but it requires some preliminary information to assist farmers with the process of herbicide and dosage selection, depending on the floristic situation (Matthews 2006). On the other hand, in recent years terbuthylazine was placed under observation for the environmental hazards that can occur due to its long persistence in soils and high leaching potential (Otto et al. 2007, EFSA 2011, Bottoni et al. 2013, Milan et al. 2015). Furthermore, for ground water protection, manufacturers and registration holders carry out a targeted management of terbuthylazine. It envisages a limitation of terbuthylazine usage in maize and sorghum only, one use per season in mixture with other active ingredients and a maximum use rate of 750 g ha^{-1}. For treatments in areas with vulnerable groundwater situations other herbicides than terbuthylazine are strongly recommended (Schulte et al. 2012). Finally, the use of terbuthylazine could be banned and this herbicide retired from the market in the future, as it happened for atrazine in EU in 2004 (European Commission 2004).

Because of the above mentioned reasons, the alternatives to terbuthylazine for weed control in maize need to be evaluated and reported, being scarce or outdated in the literature (Miesner 1990).The objective of this research was thus to investigate weed control efficacy and effects of herbicides treatments with and without terbuthylazine applied in different mixtures and with different application timings in maize.

MATERIALS AND METHODS

From 2012 to 2014, three field experiments on maize (*Zea mays* L.) were carried out in central Italy (Experimental Station of Papiano, 42°57'N, 12°22'E, 165 m a.s.l.) on a 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 good ordinary practices, as they concern soil tillage and seedbed preparation (Bonciarelli and Bonciarelli 2001), adopting low input in terms of irrigation and fertilization. Experimental design was a randomized block with four replicates and plot size of 17.5 m^2 (2.5 m width). In each trial, some herbicides were used in pre-emergence, early post-emergence or post-emergence applications at different dosages and in different mixtures with and without terbuthylazine, in order to assess weed control ability and effects to the crop. Herbicides under investigation were (Table 2): acetochlor (Trophy 40 CS, 400 g a.i. L^{-1}, Dow Chemical Company), S-metolachlor (Dual Gold, 960 g a.i. L^{-1}, Syngenta Crop Protection), S-metolachlor + terbuthylazine (Primagram Gold, 312.5 + 187.5 g a.i. L^{-1}, Syngenta Crop Protection), acetochlor + terbuthylazine (Erbifen Class, 333 + 166.5 g a.i. L^{-1}, Gowan Italia), s-metolachlor + terbuthylazine + mesotrione (Lumax, 312.5 + 187.5 + 37.5 g a.i. L^{-1}, Syngenta Crop Protection), thiencarbazone-methyl + isoxaflutole (Adengo, 20 + 50 g a.i. L^{-1}, Bayer CropScience Italia), s-metolachlor + mesotrione (Camix, 500 + 60 g a.i. L^{-1}, Syngenta Crop Protection), mesotrione + nicosulfuron (Elumis, 75 + 30 g a.i. L^{-1}, Syngenta Crop Protection), tembotrione (Laudis, 44 g a.i. L^{-1}, Bayer CropScience Italia) and foramsulfuron (Equip, 22,5 g a.i. L^{-1}, Bayer CropScience Italia) were applied with a backpack plot sprayer fitted with four flat fan nozzles (Albuz APG 110 – Yellow) and calibrated to deliver 300 L ha^{-1} aqueous solution at 200 kPa. Untreated plots were always added as checks.

Table 1. Agronomic practices in the field experiments.

Year	2012	2013	2014
Preceding crop	Maize	Maize	Maize
Sowing date	30 April	15 May	16 May
Maize cultivar	DKC4490	DKC4316	DKC4316
Density (plants m^{-2})	7	7	7
Spacing between rows (m)	0.75	0.75	0.75
Soil insecticide	chlorpyrifos	chlorpyrifos	chlorpyrifos
Fertilization (kg ha^{-1})	150 N; 75 P_2O_5	150 N; 75 P_2O_5	150 N; 75 P_2O_5
Emergence date	10 May	25 May	23 May
Pre-emergence treatments date	04 May	21 May	20 May
Early post-emergence treatments date	18 May	05 June	03 June
Post-emergence treatments date	30 May	21 June	10 June
Harvest	11 Sept.	26 Sept.	30 Sept.

Table 2. Herbicide treatments on maize.

Code	Herbicide treatments	Dose (g ai ha^{-1})	Application time
A	acetochlor	1600	pre-em.
B	s-metolachlor	1200	pre-em.
C	s-metolachlor + terbuthylazine	1250 + 750	pre-em.
D	acetochlor + terbuthylazine	1332 + 666	pre-em.
E	s-metolachlor + terbuthylazine + mesotrione	1250 + 750 + 150	pre-em.
F	thiencarbazone-methyl + isoxaflutole	40 + 100	pre-em.
G	s-metolachlor + mesotrione	1250 + 150	pre-em.
H	s-metolachlor + mesotrione	1000 + 120	early post-em.
I	s-metolachlor + terbuthylazine + mesotrione	938 + 563 + 113	early post-em.
L	thiencarbazone-methyl + isoxaflutole	30 + 75	early post-em.
M	mesotrione + nicosulfuron	113 + 45	post-em.
N	tembotrione	88	post-em.
O	foramsulfuron	61	post-em.
P	untreated check	-	-

Early post-emergence treatments were always performed when the crop was at 2-3 leaves stage, the broadleaved weeds at the cotyledons-2 true leaves stage, and the grasses were at 1-2 leaves stage. Post-emergence treatments were always performed when the crop was at 5-6 leaves stage, the broadleaved weeds ranged from 2-4 to 6-8 true leaves stage depending of species and years, and the grasses were at the beginning of tillering.

In each trial, weed ground cover (%) was rated visually 60 DACE (Days After Crop Emergence) by using Braun-Blanquet cover-abundance scale (Maarel 1979). Furthermore, in 2013 and 2014, height and dry weight of five plants of maize per plot were assessed 60 DACE, during the growth cycle. At harvesting time, 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 station. Decade averages were calculated and compared with multi-annual averages (Figure 1). The times and quantity (mm) of irrigations were reported (Figure 1).

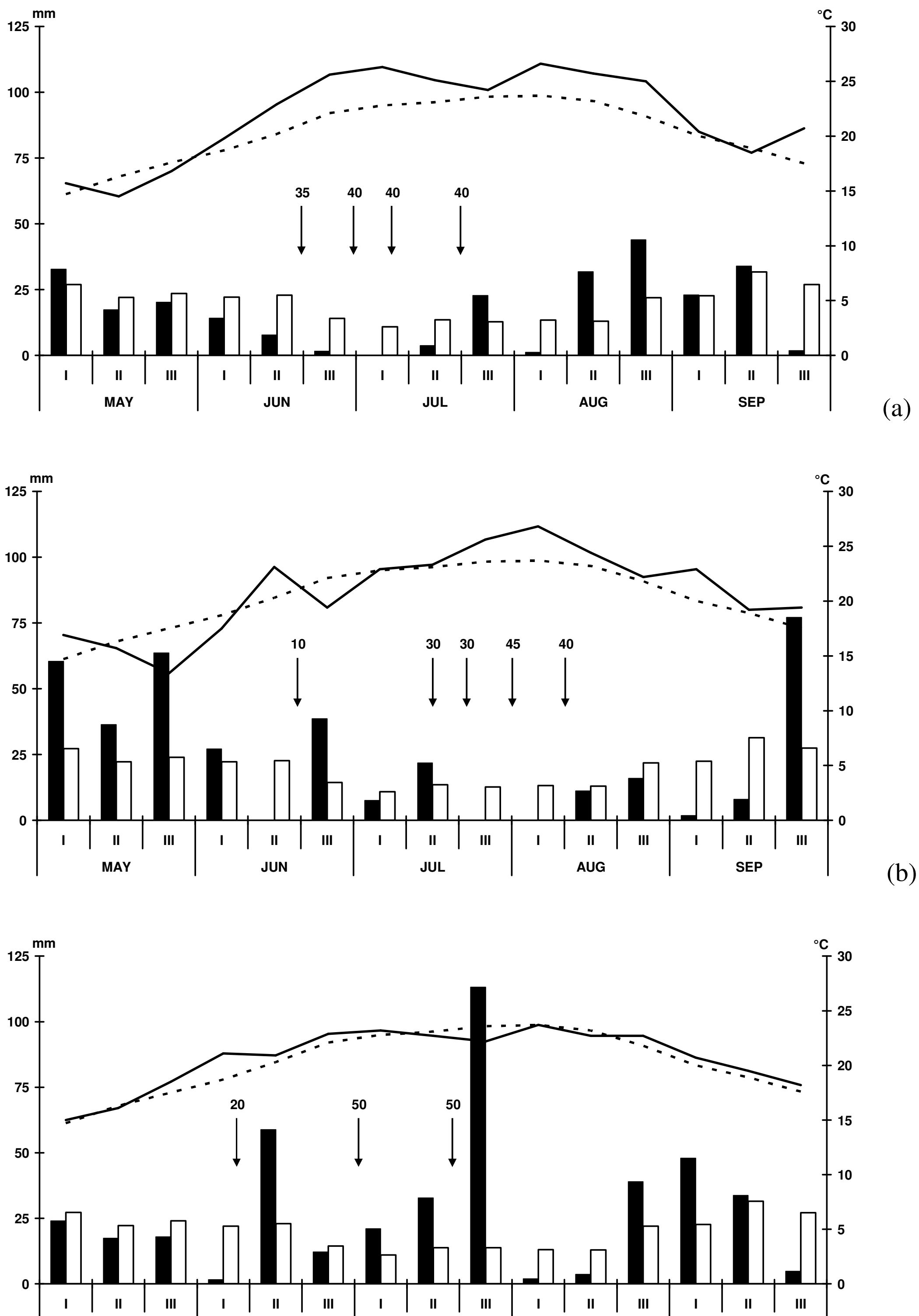

Figure 1. Average decade values of rainfall (mm; bold bar) and temperature (°C; solid line) recorded during the experimental trial in 2012 (a), 2013 (b) and 2014 (c), compared to multi-annual (1921-2014) averages (rainfall: mm, empty bar; temperature: °C, sketched line). The arrows show the times and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

Treatment means of dry weight per plant of maize were correlated to treatment means of total weed ground cover in order to asses Pearson's *r* correlation coefficient (Kozak et al. 2012). Such correlation should be interpreted as relation between these two traits in the population of the various weed control conditions; thus it should be interpreted as a relation between dry weight per plant and total weed ground cover for a particular treatment. Furthermore, crop yield was related to the total weed ground cover by linear regression $Y=A+BX$, with total weed ground cover (independent variable X) and crop yield (dependent variable Y). Pearson's *r* correlation coefficient and linear regression fitting were performed by using EXCEL® functions.

Prior to ANOVA, all data were checked for the assumptions of ANOVA. Data of total weed ground cover were log transformed. All data were subjected to ANOVA and treatment means were separated according Fisher's protected LSD at P = 0.05 level. ANOVA and its assumption check were performed with the EXCEL® Add-in macro DSAASTAT (Onofri and Pannacci 2014).

RESULTS AND DISCUSSION

WEED CONTROL ABILITY

In 2012, weed flora was mainly composed of *Echinochloa crus-galli* (L.) P. Beauv., *Polygonum lapathifolium* L., *Amaranthus retroflexus* L., *Solanum nigrum* L., *Chenopodium album* L., *Abutilon theophrasti* Medicus. and other sporadic species [*Portulaca oleracea* L., *Setaria viridis* (L.) P. Beauv.] with a total ground cover of 142% (Table 3). Against this weed flora, all treatments had efficacy higher than 90% (Table 3). In particular, all the pre-emergence herbicides had weed control of about 100%, except in the case of acetochlor (96% of weed control) and S-metolachlor (91% of weed control) alone, due to their reduced efficacy against *P. lapathifolium* and *A. theophrasti* (Table 3). It should be mentioned that all the most effective herbicide mixtures applied in pre-emergence contained terbuthylazine, except thiencarbazone-methyl + isoxaflutole and s-metolachlor + mesotrione (Table 3). The early post-emergence treatments showed an efficacy comparable to that of pre-emergence, except for the mixture s-metolachlor + mesotrione due to its reduced effectiveness against the two grasses *E. crus-galli* and *S. viridis* (Table 3). Also post-emergence treatments displayed a complete control of weeds, both with treatments based on sulfonylurea herbicides (foramsulfuron or mesotrione + nicosulfuron) and with tembotrione.

In 2013, weed flora was mainly composed of *E. crus-galli*, *A. retroflexus*, *P. lapathifolium*, *Sinapis arvensis* L., *C. album* and other sporadic species (*S. nigrum, P. oleracea*), with a total ground cover of 210% (Table 4). Against this weed flora, all the pre-emergence herbicides showed a weed control of about 100%, except for acetochlor and S-metolachlor alone, due to their reduced effectiveness against *S. arvensis* (Table 4). The most effective herbicide mixtures were those based on terbuthylazine as well as thiencarbazone-methyl + isoxaflutole or s-metolachlor + mesotrione, confirming the results of previous year (Table 4). The early post-emergence treatments displayed an efficacy comparable to that of pre-emergence, except for the mixture s-metolachlor + terbuthylazine + mesotrione due to its reduced effectiveness against *E. crus-galli*. All the post-emergence treatments had a high control of weeds, except foramsulfuron, which was not effective against *P. lapathifolium* because of its too high growth stage (6-8 true leaves) at the treatment time. Indeed, Kir and Doğan (2009) showed that foramsulfuron had the best efficacy against *P. lapathifolium* at the growth stage earlier than four true leaves.

In 2014, weed flora was mainly composed of *E. crus-galli*, *P. lapathifolium, A. theophrasti*, *A. retroflexus*, *S. nigrum*, and other sporadic species (*S. arvensis*, *C. album*, *Xanthium strumarium* L.) with a total ground cover of 174% (Table 5). All the pre-emergence herbicides showed good weed control, except acetochlor and S-metolachlor alone, due to their reduced effectiveness against *P. lapathifolium* and *S. arvensis* (Table 5); these two herbicides, due to their specific effectiveness against grasses and few broadleaves, seem to be not advisable in the presence of insensible broadleaves weeds. As in the previous years, the most effective pre-emergence herbicide mixtures contained terbuthylazine, except thiencarbazone-methyl + isoxaflutole or s-metolachlor + mesotrione. These results showed that terbuthylazine is the main herbicide for weed control in maize, although thiencarbazone-methyl + isoxaflutole or s-metolachlor + mesotrione represent two valid alternatives in order to reduce the treatments based on terbuthylazine or to replace it in the future, due to its environmental risks. The early post-emergence treatments showed an unsatisfactory efficacy under 90%, due to their reduced effectiveness against *E. crus-galli* (Table 5), as in the previous years.

Table 3. Effects of herbicide treatments on weed ground cover at 60 DACE (Days After Crop Emergence) (2012).

Herbicide treatments	Dose (g ai ha^{-1})	Application time	Weed ground cover (%)[a]							
			ECHCG	POLLA	AMARE	SOLNI	CHEAL	ABUTH	Other	Total
acetochlor	1600	pre-em.	1	3	0	0	0	1	0	5 c
s-metolachlor	1200	pre-em.	1	10	0	0	0	3	0	13 b
s-metolachlor + terbuthylazine	1250 + 750	pre-em.	0	0	0	0	0	1	0	1 e
acetochlor + terbuthylazine	1332 + 666	pre-em.	0	1	0	0	0	1	0	2 d
s-metol. + terbuthyl. + mesotrione	1250 + 750 + 150	pre-em.	0	0	0	0	0	0	0	0 e
thiencarbazone-methyl + isoxaflutole	40 + 100	pre-em.	0	0	0	0	0	0	0	0 e
s-metolachlor + mesotrione	1250 + 150	pre-em.	0	0	0	0	0	0	0	0 e
s-metolachlor + mesotrione	1000 + 120	early post-em.	5	1	0	0	0	0	3	8 bc
s-metol. + terbuthyl. + mesotrione	938 + 563 + 113	early post-em.	2	0	0	0	0	0	0	2 d
thiencarbazone-methyl + isoxaflutole	30 + 75	early post-em.	3	0	0	0	0	0	0	3 d
mesotrione + nicosulfuron	113 + 45	post-em.	0	0	0	0	0	0	0	0 e
tembotrione	88	post-em.	0	0	0	0	0	0	0	0 e
foramsulfuron	61	post-em.	0	0	0	0	0	0	0	0 e
untreated check	-	-	41	39	19	11	11	10	11	142 a

[a] Weed code: ECHCG: *Echinochloa crus-galli* (L.) P. Beauv.; POLLA: *Polygonum lapathifolium* L.; AMARE: *Amaranthus retroflexus* L.; SOLNI: *Solanum nigrum* L.; CHEAL: *Chenopodium album* L.; ABUTH: *Abutilon theophrasti* Medicus.; Other: *Portulaca oleracea* L., *Setaria viridis* (L.) P. Beauv.
In the column, values followed by at least one letter in common are not significantly different according to the Fisher's protected LSD test (P=0.05), performed on log(x+1) transformed data.

It should be noted that the same herbicide mixtures (s-metolachlor + terbuthylazine + mesotrione, thiencarbazone-methyl + isoxaflutole and s-metolachlor + mesotrione) showed a lower efficacy at early post-emergence than at pre-emergence, probably due to both the lowest dosages needed to guarantee the selectivity to maize at early post-emergence and to the reduced uptake of herbicides through coleoptiles of already emerged grass weeds. For these reasons, the early post-emergence treatments should be recommended only if the pre-emergence treatments were not carried out and with low infestation of grass weeds. As in 2013, all the post-emergence treatments had a good control of weeds; the only exception was lack of effectiveness against *P. lapathifolium* of foramsulfuron (Table 5). *P. lapathifolium* is a broadleaved weed with early emergence in maize and is characterized by high competitiveness, therefore needs to be under control in order to avoid high competition against maize with reduction in yield crop (Głowacka 2011). In the cases of high infestation of *P. lapathifolium*, it could be better to prefer mesotrione + nicosulfuron or tembotrione to foramsulfuron, due to their high efficacy, as observed by other authors as well Pannacci and Covarelli (2009).

Table 4. Effects of herbicide treatments on weed ground cover at 60 DACE (Days After Crop Emergence) (2013).

Herbicide treatments	Dose (g ai ha^{-1})	Application time	Weed ground cover (%)[a]						
			ECHCG	AMARE	POLLA	SINAR	CHEAL	Other	Total
acetochlor	1600	pre-em.	0	0	1	6	0	0	7 d
s-metolachlor	1200	pre-em.	0	0	1	39	0	0	40 b
s-metolachlor + terbuthylazine	1250 + 750	pre-em.	0	0	0	0	0	0	0 f
acetochlor + terbuthylazine	1332 + 666	pre-em.	0	0	0	0	0	0	0 f
s-metol. + terbuthyl. + mesotrione	1250 + 750 + 150	pre-em.	0	0	0	0	0	0	0 f
thiencarbazone-methyl + isoxaflutole	40 + 100	pre-em.	2	0	0	0	0	0	2 e
s-metolachlor + mesotrione	1250 + 150	pre-em.	0	0	0	0	0	0	0 f
s-metolachlor + mesotrione	1000 + 120	early post-em.	5	0	0	0	0	1	6 d
s-metol. + terbuthyl. + mesotrione	938 + 563 + 113	early post-em.	10	0	0	0	0	0	10 d
thiencarbazone-methyl + isoxaflutole	30 + 75	early post-em.	3	0	0	0	0	0	3 e
mesotrione + nicosulfuron	113 + 45	post-em.	0	0	2	0	0	0	2 e
tembotrione	88	post-em.	0	0	0	0	0	0	0 f
foramsulfuron	61	post-em.	0	0	16	0	0	0	16 c
untreated check	-	-	81	44	40	34	5	6	210 a

[a] Weed code: ECHCG: *Echinochloa crus-galli* (L.) P. Beauv.; AMARE: *Amaranthus retroflexus* L.; POLLA: *Polygonum lapathifolium* L.; SINAR: *Sinapis arvensis* L.; CHEAL: *Chenopodium album* L.; Other: *Portulaca oleracea* L., *Solanum nigrum* L.
In the column, values followed by at least one letter in common are not significantly different according to the Fisher's protected LSD test (P=0.05), performed on log(x+1) transformed data.

EFFECTS ON MAIZE GROWTH

In 2013, plant height and dry weight per plant were the lowest in the untreated check as well as in the post-emergence treatments that were significantly different to the other treatments (i.e., pre-emergence and early post-emergence) (Table 6). Similar results, although less evident, were also obtained in 2014 for the dry weight per plant data (Table 6). The significant reduction of plant growth observed only in the post-emergence treatments at 60 DACE was due to the weeds/crop competition that occurred in the first part of the growth cycle of maize, from the crop/weeds emergence to the weed control by the post-emergence treatments (i.e. about four weeks after emergence). These results confirm the sensitiveness of maize to weed competition during the "critical period" that may produce severe crop yield losses (Pannacci and Tei 2014). In particular, dry weight per plant data (Table 6) appeared to be significantly correlated to the total ground cover of weeds at 60 DACE (Table 4 and 5) (r = -0.708 and -0.705, respectively in 2013 and 2014).

It should be mentioned that no phytotoxic effects of herbicide treatments were visually observed in the three years (data not shown).

Table 5. Effects of herbicide treatments on weed ground cover at 60 DACE (Days After Crop Emergence) (2014).

Herbicide treatments	Dose (g ai ha^{-1})	Application time	Weed ground cover (%)[a]						
			ECHCG	POLLA	ABUTH	AMARE	SOLNI	Other	Total
acetochlor	1600	pre-em.	0	11	1	0	0	5	17 c
s-metolachlor	1200	pre-em.	0	38	0	0	1	3	42 b
s-metolachlor + terbuthylazine	1250 + 750	pre-em.	0	0	3	0	0	0	3 ef
acetochlor + terbuthylazine	1332 + 666	pre-em.	0	0	0	0	0	0	0 g
s-metol. + terbuthyl. + mesotrione	1250 + 750 + 150	pre-em.	0	0	0	0	0	0	0 g
thiencarbazone-methyl + isoxaflutole	40 + 100	pre-em.	6	0	0	0	0	0	6 d
s-metolachlor + mesotrione	1250 + 150	pre-em.	2	1	0	0	0	1	4 de
s-metolachlor + mesotrione	1000 + 120	early post-em.	38	0	0	0	0	0	38 b
s-metol. + terbuthyl. + mesotrione	938 + 563 + 113	early post-em.	31	0	0	0	0	0	31 bc
thiencarbazone-methyl + isoxaflutole	30 + 75	early post-em.	20	0	0	0	0	0	20 bc
mesotrione + nicosulfuron	113 + 45	post-em.	0	5	0	0	0	0	5 d
tembotrione	88	post-em.	0	0	1	0	0	0	1 fg
foramsulfuron	61	post-em.	0	28	0	0	0	0	28 bc
untreated check	-	-	94	44	13	8	5	11	174 a

[a] Weed code: ECHCG: *Echinochloa crus-galli* (L.) P. Beauv.; POLLA: *Polygonum lapathifolium* L.; ABUTH: *Abutilon theophrasti* Medicus.; AMARE: *Amaranthus retroflexus* L.; SOLNI: *Solanum nigrum* L.; Other: *Sinapis arvensis* L.; *Chenopodium album* L.; *Xanthium strumarium* L.
In the column, values followed by at least one letter in common are not significantly different according to the Fisher's protected LSD test (P=0.05), performed on log(x+1) transformed data.

CROP YIELD

As shown for dry weight per plant at 60 DACE, crop yield at harvest time (Table 7) also appears to be significantly correlated to the total ground cover of weeds (tables 3, 4 and 5) (r = -0.922, -0.866 and -0.948, in 2012, 2013 and 2014, respectively). This confirms that the growth reduction of maize during the first part of cycle due to the weeds competition, was not recovered, causing severe yield losses at harvest time, as already observed by Sattin et al. (1996). In particular, the untreated control always showed significantly lower yield values than those obtained with the other treatments (Table 7). The highest losses in untreated control were observed in 2013 and 2014 with a yield reduction as compared to the highest yield of 91% and 81% respectively. On the other hand, in 2012, the early sowing, the lower ground cover of weeds, the different cultivar, and probably the more uniform and favourable weather conditions, have reduced the yield losses to 33% (Table 7). Similar yield losses in maize were obtained by Pannacci and Tei (2014) in previous years, in the same area with similar weed infestations.

Table 6. Effects of herbicide treatments on growth of maize at 60 DACE (Days After Crop Emergence).

Herbicide treatments	Dose (g ai ha^{-1})	Application time	Plant height (m) and dry weight per plant (g)							
			2013				2014			
			Plant height		DW per plant		Plant height		DW per plant	
acetochlor	1600	pre-em.	1.43	ab	51	b	1.74	ab	62	ab
s-metolachlor	1200	pre-em.	1.29	b	51	b	1.71	ab	66	a
s-metolachlor + terbuthylazine	1250 + 750	pre-em.	1.51	a	69	a	1.79	a	73	a
acetochlor + terbuthylazine	1332 + 666	pre-em.	1.54	a	60	ab	1.73	ab	73	a
s-metol. + terbuthyl. + mesotrione	1250 + 750 + 150	pre-em.	1.46	ab	58	ab	1.69	ab	73	a
thiencarbazone-methyl + isoxaflutole	40 + 100	pre-em.	1.45	ab	48	b	1.73	ab	58	ab
s-metolachlor + mesotrione	1250 + 150	pre-em.	1.53	a	52	b	1.76	ab	75	a
s-metolachlor + mesotrione	1000 + 120	early post-em.	1.49	a	57	ab	1.58	b	72	a
s-metol. + terbuthyl. + mesotrione	938 + 563 + 113	early post-em.	1.51	a	53	b	1.69	ab	59	ab
thiencarbazone-methyl + isoxaflutole	30 + 75	early post-em.	1.54	a	58	ab	1.80	a	65	a
mesotrione + nicosulfuron	113 + 45	post-em.	1.01	c	30	c	1.63	ab	48	bc
tembotrione	88	post-em.	1.06	c	47	b	1.71	ab	67	a
foramsulfuron	61	post-em.	1.04	c	30	c	1.66	ab	46	bc
untreated check	-	-	0.95	c	13	d	1.40	c	32	c
LSD (P=0.05)			*0.18*		*15*		*0.18*		*17*	

In each column, values followed by at least one letter in common are not significantly different according to the Fisher's protected LSD test (P=0.05).

Table 7. Effects of herbicide treatments on crop yield.

Herbicide treatments	Dose (g ai ha^{-1})	Application time	Crop yield (t ha^{-1})					
			2012		2013		2014	
acetochlor	1600	pre-em.	12.80	ab	10.89	ab	9.19	ab
s-metolachlor	1200	pre-em.	11.65	c	10.65	ab	8.31	ab
s-metolachlor + terbuthylazine	1250 + 750	pre-em.	12.31	bc	12.34	a	9.55	ab
acetochlor + terbuthylazine	1332 + 666	pre-em.	13.17	ab	11.74	a	9.69	a
s-metol. + terbuthyl. + mesotrione	1250 + 750 + 150	pre-em.	13.56	a	12.23	a	9.49	ab
thiencarbazone-methyl + isoxaflutole	40 + 100	pre-em.	12.75	ab	11.50	a	8.96	ab
s-metolachlor + mesotrione	1250 + 150	pre-em.	13.34	ab	11.12	a	8.87	ab
s-metolachlor + mesotrione	1000 + 120	early post-em.	12.71	abc	11.13	a	5.93	c
s-metol. + terbuthyl. + mesotrione	938 + 563 + 113	early post-em.	13.29	ab	11.15	a	8.00	ab
thiencarbazone-methyl + isoxaflutole	30 + 75	early post-em.	12.54	abc	11.71	a	9.40	ab
mesotrione + nicosulfuron	113 + 45	post-em.	13.39	ab	7.92	c	9.70	a
tembotrione	88	post-em.	13.23	ab	9.05	bc	8.99	ab
foramsulfuron	61	post-em.	12.80	ab	7.41	c	7.74	bc
untreated check	-	-	9.13	d	1.10	d	1.88	d
LSD (P=0.05)			*1.09*		*1.98*		*1.89*	

In each column, values followed by at least one letter in common are not significantly different according to the Fisher's protected LSD test (P=0.05).

On average, yield levels with pre-emergence treatments were higher than those with early post-emergence and post-emergence treatments (Figure 2). Among pre-emergence treatments, the high crop yield levels were obtained from herbicide mixtures containing terbuthylazine (see code C, D and E in Figure 2), although the mixtures without terbuthylazine, such as thiencarbazone-methyl + isoxaflutole or s-metolachlor + mesotrione (see code F and G in Figure 2), gave comparable results (Figure 2).

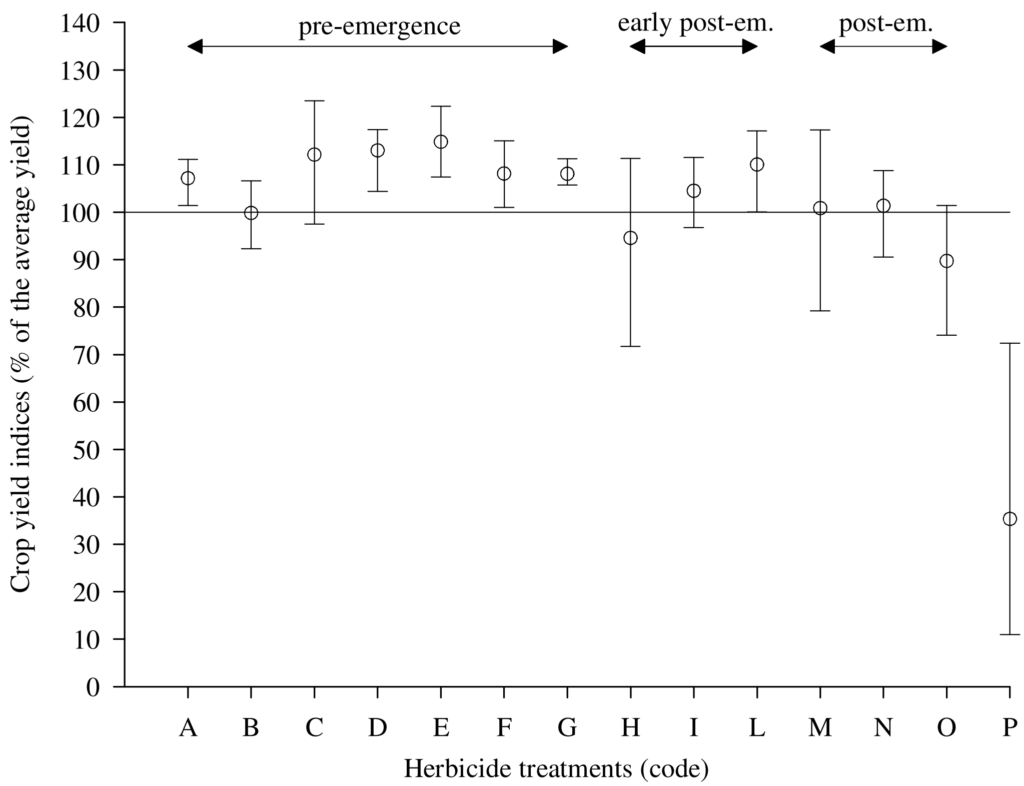

Figure 2. Crop yield indices (overall mean of each field trial carried out in 2012, 2013 and 2014 = 100) of herbicide treatments (see Table 2 for corresponding code). The bars show the inter-annual variations of indices.

In more detail, the equations relating total weed ground cover (independent variable *x*) to crop yield (dependent variable *y*) were, in 2012, 2013 and 2014 respectively:

$$y = 12.97 - 0.028x, \ (R^2 = 0.850) \qquad (1)$$

$$y = 10.97 - 0.047x, \ (R^2 = 0.751) \qquad (2)$$

$$y = 9.42 - 0.044x, \ (R^2 = 0.898) \qquad (3)$$

This means that in 2012, higher average yields were obtained for treatments at very low infestation levels (see intercept in linear equation), and lower yield damage for treatments with increasing infestation levels (see slope of regression line). Such behaviour may be explained considering that in 2012 an early sowing (30 April) with good weather conditions and the irrigations around flowering time, favoured maize growth, productivity and competitiveness (Figure 1a), while low rainfall level in May reduced the emergence of the weed flora, which was later also hindered by scarce water availability in June (Figure 1a). As a result, weed flora in 2012 was characterized by lower densities and low plant sizes, therefore it had small competitiveness (data not shown). On the contrary, in 2013 weed plants (*E. crus-galli*, *A. retroflexus*, *P. lapathifolium* and *S. arvensis*) were dense and very vigorous and competitive since the beginning of crop cycle, as a consequence of high and frequent rainfall in May (Figure 1b). Afterwards, dry summer made the competition for water very intense, resulting in very high yield losses in the most weed infested plots (Table 7). Also in 2014, weed plants (*E. crus-galli, A. retroflexus, A. theophrasti*) were dense and competitive since the beginning of crop cycle; furthermore, the very high rainfall and low temperature at flowering time (see the end of July, Figure 1c) temporarily reduced the growth of maize, favouring weeds growth and their competition against maize, which resulted in reduced yield (Table 7).

CONCLUSIONS

Considering pre-emergence applications, acetochlor and S-metolachlor alone seem not to be advisable due to their reduced efficacy against broadleaved weeds (i.e. *P. lapathifolium*, *A. theophrasti* and *S. arvensis*). Herbicide mixtures with terbuthylazine gave the highest control of weeds, confirming terbuthylazine as the main herbicide for weed control in maize, although thiencarbazone-methyl + isoxaflutole or s-metolachlor + mesotrione represent two valid alternatives in order to reduce the treatments based on terbuthylazine or to replace it in the future. Between these last two alternatives to terbuthylazine, thiencarbazone-methyl + isoxaflutole seem to be preferable in the case of treatments at early post-emergence; however, the early post-emergence treatments should be suggested if the pre-emergence treatments were not carried out and with low infestation of grass weeds, due to their lower efficacy.

Among the period treatments, the early treatments (i.e pre-emergence and early post-emergence) had the advantage of avoiding the weeds/crop competition in the first part of the growth cycle of maize (during the “critical period”), favouring maize growth and productivity and reducing yield losses. Post-emergence treatments should be suggested especially to manage scarce infestation and perennial weeds or in the cases of peat soil, for which pre-emergence herbicides are not effective.

The high correlation between crop yield and weed ground cover confirms the sensitiveness of maize to weed competition and suggests high levels of weed control in order to avoid severe damage to crop yield, especially in the cases of high infestation level or under unfavourable weather conditions during the growth cycle.

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REFERENCES

Amon T., Amon B., Kryvoruchko V., Zollitsch W., Mayer K. and Gruber L. (2007). Biogas production from maize and dairy cattle manure-Influence of biomass composition on the methane yield. *Agriculture, Ecosystems & Environment* 118, 173−182.

Andr J., Hejnák V., Jursík M., Fendrychová V. (2014). Effects of application terms of three soil active herbicides on herbicide efficacy and reproductive ability for weeds in maize. *Plant Soil and Environment* 60, 10, 452−458.

Baghestani M.A., 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 Protection* 26, 936−942.

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

Bottoni P., Grenni P., Lucentini L., Barra Caracciolo A. (2013). Terbuthylazine and other triazines in Italian water resources. *Microchemical Journal* 107, 136−142.

EFSA (2011). Conclusion on the peer review of the pesticide risk assessment of the active substance terbuthylazine. *EFSA Journal*, 9(1), 1969.

European Commission (2004). *Commission Decision concerning the non-inclusion of atrazine in Annex I to Council Directive 91/414/EEC and the withdrawal of authorisations for plant protection products containing this active substance*. Off. J. Eur. Comm. L 78, 53.

Friesen S.L.J., Ferguson G.M., Hall J.C. (2000). Management strategies for attenuating herbicide resistance: untoward consequences of their promotion. *Crop Protection* 19, 891−895.

Ghanizadeh H., Lorzadeh S., Ariannia N. (2014). Effect of weed interference on *Zea mays*: Growth analysis. *Weed Biology and Management* 14, 133−137.

Głowacka A. (2011). Dominant weeds in maize (*Zea mays* L.) cultivation and their competitiveness under conditions of various methods of weed control. *Acta Agrobotanica* 64, 2, 119−126.

Kir K., Doğan M.N. (2009). Weed control in maize (Zea mays L.) with effective minimum rates of foramsulfuron. *Turkish Journal of Agriculture and Forestry* 33, 601−610.

Kolářová M., Tyšer L., Soukup J. (2014). Weed vegetation of arable land in the Czech Republic: environmental a management factors determining weed species composition. *Biologia* 69, 4, 443−448.

Kozak M., Krzanowski W., Tartanus M. (2012). Use of the correlation coefficient in agricultural sciences: problems, pitfalls and how to deal with them. *Annals of the Brazilian Academy of Sciences* 84, 4, 1147−1156.

Kudsk P. (2002). Optimising Herbicide Performance. In: Robert E.L., Naylor (Eds.), *Weed Management Handbook*, Blackwell Science, 323−344.

Maarel van der E. (1979). Transformation of cover-abundance values in phytosociology and its effects on community similarity. *Vegetatio* 39, 2, 97−114.

Matthews G. (2006). *Pesticides: Health, Safety and the Environment. 1st ed*. Blackwell Publishing, Oxford, UK.

Mars Bulletin (2012). Crop Monitoring in Europe, Mars Bulletin, Vol. 20, No. 5. Available on-line at: http://mars.jrc.ec.europa.eu/mars/content/download/2728/13913/file/MARS_Bulletin_Vol20.

Meissle M., Mouron P., Musa T., Bigler F., Pons X., Vasileiadis V.P., Otto S., Antichi D., Kiss J., Pálinkás Z., Dorner Z., van der Weide R., Groten J., Czembor E., Adamczyk J., Thibord J.B., Melander B., Cordsen Nielsen G., Poulsen R.T., Zimmermann O., Verschwele A., Oldenburg E. (2010). Pests, pesticide use and alternative options in European maize production: current status and future prospects. *Journal of Applied Entomology* 134, 357−375.

Miesner M. (1990). Maize weeds controlled without atrazine. *DLG-Mitteilungen* 105, 7, 314−317.

Milan M., Ferrero A., Fogliettо S., Piano S., Vidotto F. (2015). Leaching of S-metolachlor, terbuthylazine, desethyl-terbuthylazine, mesotrione, flufenacet, isoxaflutole, and diketonitrile in field lysimeters as affected by the time elapsed between spraying and first leaching event. *Journal of Environmental Science and Health, Part B: Pesticides, Food Contaminants, and Agricultural Wastes* 50, 851−861.

Norsworthy J.K., Ward S.M., Shaw D.R., Llewellyn R.S., Nichols R.L., Webster T.M., Bradley K.W., Frisvold G., Powles S.B., Burgos N.R., Witt W.W., Barrett M. (2012). Reducing the Risks of Herbicide Resistance: Best Management Practices and Recommendations. *Weed Science* 60(SI1), 31−62.

Onofri A., Pannacci E. (2014). Spreadsheet tools for biometry classes in crop science programmes. *Communications in Biometry and Crop Science* 9, 3−13.

Otto S., Altissimo L., Zanin G. (2007). Terbuthylazine Contamination of the Aquifer North of Vicenza (North-East Italy). *Environmental Science and Pollution Research* 14, 109−113.

Pannacci E., Graziani F., Covarelli G. (2007). Use of herbicide mixtures for pre and post-emergence weed control in sunflower (*Helianthus annuus*). *Crop Protection* 26, 1150−1157.

Pannacci E., Covarelli G. (2009). Efficacy of mesotrione used at reduced doses for post-emergence weed control in maize (*Zea mays* L.). *Crop Protection* 28, 57−61.

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 Protection* 64, 51−59.

Sattin M., Berti A., Zanin G. (1996). Crop yield loss in relation to weed time of emergence and removal: analysis of the variability with mixed weed infestations. In: *Proceedings of 2nd IWCC*, Copenhagen, Vol. 1, 67−72.

Schulte M., Steinheuer M., Düfer B., Räder T. (2012). Why has terbuthylazine become the basic component of weed control in maize cropping of Central Europe? A benefit assessment. *Julius-Kühn-Archiv* 1 (434), 321−328. Available on-line at: http://pub.jki.bund.de/index.php/JKA/article/view/1748/2091.

Tatsumi K., Yamashiki Y., da Silva R.V., Takara K., Matsuoka Y., Takahashi K., Maruyama K., Kawahara N. (2011). Estimation of potential changes in cereals production under climate change scenarios. *Hydrological Processes* 25, 2715−2725.