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The effects of drift-reducing nozzles on herbicide efficacy and maize (*Zea mays* L.) yield

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Abstract

Field trials were carried out in 2009–2011 to compare the performance of herbicides for weed control in maize (*Zea mays* L.). Herbicides were applied by standard (API, “Albuz”) and by drift-reducing (AVI, “Albuz”) nozzles. Mixtures of herbicides based on 2,4-D, bentazon and foramsulfuron were applied post-emergence with a tractor mounted field boom sprayer at a spray volume of 150 or 300 l ha^{-1} in the form of droplets of different size classes (volume median diameter (VMD) from 100 to 800 µm). The main weed species in the field trials were: *Ambrosia artemisiifolia*, *Amaranthus retroflexus*, *Chenopodium album*, *Convolvulus arvensis*, *Elytrigia repens*, *Echinochloa crus-galii*, *Polygonum lapathifolium* and *Fallopia convolvulus*. The efficacy (%) of herbicides and maize yield were assessed. The impact of the studied factors on herbicide efficacy against broad-leaved weed species differed from that against narrow-leaved species. In comparison to the standard API nozzles, the overall efficacy of drift-reducing AVI nozzles was lower in 8 of 12 herbicide applications. The efficacy reduction ranged from 2% to 7%. The type of nozzle had a significant influence on the yield of maize cobs in 5 of 12 herbicide applications, and spray volume significantly affected maize cob yield in 7 of 12 herbicide applications. In all statistically significant cases, maize yield was higher when herbicides had been applied by standard nozzles (API, VMD 100–300 µm) at 300 l ha^{-1} spray volume. The highest yield reductions due to the use of AVI nozzles (7–11%) were determined in the case of low volume sprays (150 l ha^{-1}) consisting of big droplets (VMD more than 400 µm). Results suggest that AVI nozzles can cause poor weed control only if used for applications of small spray volumes (less than 200 l ha^{-1}) with droplet VMD values larger than 400 µm, otherwise weed control results comparable to standard API nozzles are achieved and the use of drift-reduction AVI nozzles does not result in maize yield reduction.

Key words: drift-reducing nozzles, *Zea mays*, weed control, 2,4-D, bentazon, foramsulfuron.

Introduction

Drift of agricultural sprays to adjacent non-agricultural areas (e.g., residential areas, water bodies, sensitive nature conservation areas, etc.) is criticised by the public and sanctioned by regulatory authorities therefore farmers need to devote proper attention to drift prevention. Drift of herbicides can cause high economic losses, especially in the case of broad spectrum highly systemic herbicides (glyphosate, 2,4-D, etc.), and direct environmental pollution (e.g., poisoning of aquatic organisms). The simplest method to avoid drift is to spray in non-windy conditions and to increase the droplet size, either by use of standard nozzles at low operating pressure or by use of drift-reducing nozzles producing large-size droplets.

The European Union (EU) directive on sustainable use of pesticides (2009/128/EC; Directive..., 2009) obliges farmers and EU state authorities to find advanced approaches for solving drift problems. In some countries the use of drift-reducing nozzles is mandatory. Farmers are obligated to use them when applying herbicides in most agricultural areas. Sometimes farmers oppose their use because they are not informed well on drift-reduction spray technologies. The fear of reduced coverage, and subsequently reduced weed control, contributes to the reluctance to use low-drift nozzles. It is well known that droplet size significantly affects herbicide efficacy (Knoche, 1994; Matthews, 2000; Ramsdale, Messersmith, 2001; Howarth, Holm, 2004; Jensen, 2006). There is a lot of data available on the effects of droplet size on herbicide efficacy, but in most cases the results of field trials are not accompanied by the data on related crop yield. Researchers studying the effects of drift-reducing nozzles often conclude that these nozzles provide the same level of weed control efficacy as standard nozzles (Gehring et al., 2006; Nuyttens et al., 2009). It was also demonstrated that certain combinations of herbicides, nozzles and application parameters (spray volume, droplet size, etc.) can lead to reduction of herbicide efficacy against some weed species (Vajs, Lešnik, 2005; Jensen, 2006; Brown et al., 2007; Sikkema et al., 2008).

Our previous study (Lešnik et al., 2005) suggested that the optimum nozzle type, water carrier volume, and spray pressure are herbicide- and weed species-specific. In the trials conducted in 2005, we established that herbicide type and water volume for herbicide application had a significant influence on the yield of maize ears, whereas nozzle type on average did not significantly influence the yield. In some trial plots, drift-reducing nozzles caused significant yield losses. Several years of research are needed to understand the complex relationships among the key parameters of herbicide application. As a result, we decided to perform trials involving several seasons.

For herbicide application by drift-reducing nozzles we are trying to find out the optimal balance between herbicide efficacy and the rate of drift reduction. This is especially important if we need to control mixed weed populations consisting of perennial grasses and hard to control annual and perennial broad-leaved weeds. This situation is often present also on Lithuanian maize fields (Auškalnienė, 2006; Auškalnienė, Auškalnis, 2007).

The aim of our study was to compare the efficacy of weed control carried out with standard and with drift-reducing nozzles and to relate the type of nozzles used to maize yield. Our hypothesis was that application of herbicides with drift-reducing nozzles does not cause reduction of maize yield because of lower herbicide efficacy.

Materials and methods

Experimental design and cropping technique. Field trials were carried out at the experimental station of the University of Maribor, Faculty of Agriculture and Life Sciences (43°34′ N, 15°38′ E), Hoče, Slovenia during the period of 2009–2011. Maize (*Zea mays* L.) was grown according to the standard cropping technique (standard ploughing and seedbed preparation, plant density 0.70 × 0.15 m = 95.000 plants ha^{-1}). The soil of the experimental site is classified as *Dystrict Cambisol* (*CMd*) (World reference base..., 2006) formed on diluvium with a pH value of 5.98. The content of humus was 29 g kg^{-1}. The main nutrient composition was 150 mg kg^{-1} K_2O and 97 mg kg^{-1} P_2O_5. Before pre-sowing tillage, complex fertilisers were applied. The soil received 150 kg N, 40 kg P_2O_5 and 150 kg K_2O per hectare.

Two trials were carried out each season at the same location (200 meters apart). The trials were marked as T1, T2, T3, T4, T5 and T6. Soil characteristics of trial plots were very similar, only weed population compositions were different. The proportion of grasses and broad-leaved species in the total number (mass) of weeds was different (Table 1). In season 2009 (T1 and T2 trials) the maize hybrid LG22.44 (maturity class FAO 320) was grown. The hybrid 'Panda' (maturity class FAO 300) was grown in 2010 (T3 and T4) and 2011 (T5 and T6) (http://www.amacoint.com/en/agriculture/seeds/corn/; http://www.bc-institut.hr/kukuruz_hr.htm). Classification of FAO maturity classes was first published by Jugenheimer (1958). There was no significant water shortage and summer weather conditions facilitated fast maize development and yield formation. Maize competitive ability against weeds was high. All experiments included five replications in a randomized block design. Plots were 4 m wide and 20 m long. We had sixteen different treatments which were combinations of four factors: nozzle type (API and AVI, "Albuz"), spray volume (150 or 300 l ha^{-1}), droplet size (small droplets with a diameter of 100–300 µm, large droplets with a diameter of 300–800 µm) and herbicide mixture (2 mixtures). The information about technical characteristics of API and AVI nozzles is available at <http://www.albuz-spray.com/en/lituanie.html>.

The data were subjected to analysis of variance (*ANOVA*). Tukey HSD test and t-test ($P < 0.05$) were used for determining the significant differences between treatment means. There was no need for transformation of data on herbicide efficacy (%) and maize yield to assure the homogeneity of data for analysis of variance. We also had to control weed-free plots and plots which were not treated with herbicides.

The weed population composition in trial plots is presented in Table 1. Before application of herbicides, the number of weeds per m^2 of a specific species was determined in the middle of each plot (randomly chosen 6 quadrates 0.25 × 0.25 m). On most of the chosen fields, the weed flora was uniform in terms of species diversity, only the share in total green mass among dominant species was different in different experimental fields throughout the seasons. Weeds were controlled only chemically, no mechanical control measures were used.

Table 1. Weed population composition of trial plots on the day of herbicide application

Weed	NW T1 2009	NW T2 2009	NW T3 2010	NW T4 2010	NW T5 2011	NW T6 2011
ABUTH	135–150	150–200	30–45	10–14	170–190	130–150
AMBAR	25–50	60–80	20–35	20–25	10–35	5–15
AMARE	100–130	185–230	100–130	80–95	60–75	80–120
CHEAL	30–50	140–170	70–90	40–85	130–150	60–90
CONAR	1.3–2.7	2.2–3.0	3.5–6.5	1.1–2.2	3.7–5.2	4.0–8.2
ECHCG	20–35	40–60	160–250	120–160	160–190	70–110
ELYRE	20–35	30–50	10–15	45–75	60–95	40–55
FALCO	10–15	30–40	20–50	10–30	20–35	15–20
POLLA	35–50	35–50	70–90	40–65	70–90	45–60
Other	30–40	20–30	40–50	30–50	40–60	40–70
All together	480–600	430–590	400–550	380–480	380–500	450–570

Notes. ABUTH – *Abutilon theophrasti* Medik., AMBAR – *Ambrosia artemisiifolia* L., AMARE – *Amaranthus retroflexus* L., CHEAL – *Chenopodium album* L., CONAR – *Convolvulus arvensis* L., ECHCG – *Echinochloa crus-galli* (L.) Beauv. ELYRE – *Elytrigia repens* (L.) Desv. ex Nevski, FALCO – *Fallopia convolvulus* (L.) A. Löwe, POLLA – *Polygonum lapathifolium* L., Other – other weed species. NW – number of plants per m^2; T1 – trial 1, T2 – trial 2, T3 – trial 3, etc.

The herbicide efficacy was assessed three times: twice visually, 4 and 8 weeks after application by protocol of chemical industry (BASF, Germany) (Bleiholder, 1989), and once by the assessment of fresh weed biomass 12 weeks after herbicide application. Only the data of the third assessment are presented. In the middle of each plot we randomly chose 6 quadrates by throwing a metal frame (0.5 m × 0.5 m). Weeds found within each quadrate were cut to the ground, separated by species and fresh mass was weighed. The efficacy of herbicide was expressed as relative reduction (%) in weed biomass in comparison to the biomass of weeds in untreated plots. The assessment was done for each weed species separately, but in this paper we present only average data for all species together (total biomass of all species together). Maize yield was determined by manually collecting fresh cobs (ears) from plants developing on the 10 m^2 area in the middle of plots (3 middle rows × 5 m).

Application technique and herbicides applied. In each trial, two herbicide mixtures were studied (foramsulfuron 50 g ha^{-1} + bentazon 850 g ha^{-1} and foramsulfuron 50 g ha^{-1} + 2,4-D 750 g ha^{-1}). Both mixtures were applied at two spray volumes (150 or 300 l ha^{-1}) with two types of nozzles (API and AVI) producing small or big droplets. Each trial included 80 plots (2 × 2 × 2 × 2 × 5 = 80) and several control plots (no weed control and weed-free control plots). Bentazon (Basagran 480, BASF) was chosen as a contact herbicide, and foramsulfuron (Equip, "Bayer", Germany) and 2,4-D (Herbocid, "Nufarm", Austria) as systemic herbicides. These three herbicides are frequently used by Slovenian farmers. They have different modes of action and translocation which enables testing the interaction between nozzle type and type of herbicide (systemic or contact). Both herbicide mixtures control a very broad spectrum of weeds (grasses and dicots, annuals and perennials). That enabled us to exclude the effects of individual weed species which were not completely controlled by a specific herbicide and could therefore prevail in the weed population. According to our previous trials, the effects of such weed species can mask the effects of trial treatments (nozzle type, spray volume, etc.).

All three herbicides were applied at 90% of full recommended rates. In all three seasons, the herbicides were applied within the period from May 15 to 25, when maize plants had 3 to 4 leaves and the majority of weeds had 2 to 5 leaves. Herbicides were applied after the emergence of the majority of weeds. The studied herbicides did not have any residual activity in the soil.

The herbicides were applied with a standard tractor mounted field boom sprayer ("Agromehanika AGS 600E-SD", Slovenia) set to deliver 150 or 300 l of spray per hectare. Technical parameters of applications are presented in Table 2. API nozzle is a standard 110 degree flat fan nozzle for the spray applications in field crops, and AVI is a drift-reducing air-inclusion nozzle with the same jet characteristics. Nozzle volume median diameter (VMD) values corresponding to the operating pressure were provided by nozzle producer "Albuz" ("Saint-Gobain", France).

Table 2. Technical parameters of applications

Nozzle type	Operating pressure kPa	Nozzle output l min^{-1}	Tractor speed km h^{-1}	Spray volume l ha^{-1}	Droplet VMD* 50 µm	No. imp. WSP**
API 110-02	350 ± 20	0.86 ± 0.05	7 ± 0.15	150 ± 10	128 ± 10	85–115
API 110-03	160 ± 20	0.86 ± 0.05	7 ± 0.15	150 ± 10	212 ± 10	40–95
AVI 110-02	350 ± 20	0.86 ± 0.05	7 ± 0.15	150 ± 10	445 ± 15	40–75
AVI 110-03	160 ± 20	0.86 ± 0.05	7 ± 0.15	150 ± 10	730 ± 20	25–50
API 110-03	620 ± 20	1.73 ± 0.05	7 ± 0.15	300 ± 10	125 ± 20	80–120
API 110-04	350 ± 20	1.73 ± 0.05	7 ± 0.15	300 ± 10	215 ± 20	55–95
AVI 110-03	620 ± 20	1.73 ± 0.05	7 ± 0.15	300 ± 10	375 ± 20	40–65
AVI 110-04	350 ± 20	1.73 ± 0.05	7 ± 0.15	300 ± 10	565 ± 15	35–75

Note. * – volume median diameter, ** – number of droplet impacts per cm^2 measured by "Optomax" droplet scorer on water sensitive paper deposited on soil surface at the distance of 90 cm from the nozzle.

Results and discussion

Efficacy of weed control and maize yield in the season of 2009. The data on herbicide efficacy and maize yield from trials T1 and T2 are shown in Tables 3 and 4. In T1 trial, standard API nozzle provided higher herbicide efficacy than AVI nozzle for both herbicide mixtures (F + B and F + D).

The use of AVI nozzles resulted in 7.4% maize yield reduction (2.12 *vs.* 2.29 kg m^{-2}) in the case of mixture of foramsulfuron and 2,4-D in comparison to the plots sprayed with API nozzles (Table 4). The reduction of yield caused by application of mixture of foramsulfuron and bentazon (2.16 *vs.* 2.24 kg m^{-2}) was not statistically significant. We think that the main reason could be high population of velvetleaf (*Abutilon theophrasti*, 135–150 m^{-2}). The reduction of efficacy due to the use of AVI nozzles was higher when we used 2,4-D, compared to bentazon applied with the same nozzles. 2,4-D had lower efficacy against velvetleaf than bentazon (Table 3). The established efficacy resulted from foramsulfuron action but not from that of 2,4-D. The increase of droplet size can additionally decrease the efficacy of 2,4-D against velvetleaf (Knoche, 1994; Wolf, 2000). Higher spray volume increased the average herbicide efficacy and consequently also the maize yield at both herbicide mixtures. The population of grasses (*Echinochloa crus-galii* and *Elytrigia repens*) was moderate and foramsulfuron performed well. The efficacy of the control of quackgrass (*E. repens*) was reduced by 10% when we delivered 150 l of spray per hectare by AVI 110-03 and AVI 110-02 nozzles. In T2 trial, we had a huge population of velvetleaf (150–200 m^{-2}), pigweed (*Amaranthus retroflexus*, 185–230 m^{-2}) and lambsquarters (*Chenopodium album*, 140–170 m^{-2}). API nozzles provided slightly higher efficacy than AVI nozzles for both herbicide mixtures, but these differences did not result in significant difference in maize yield (Table 4).

Table 3. The efficacy of herbicide combinations against individual weed species as influenced by the nozzle type (API and AVI) and spray volume (l ha^{-1}) for trials T1 and T2 in 2009

Weed	F + B API	F + B AVI	F + B 150	F + B 300	F + D API	F + D AVI	F + D 150	F + D 300
Trial T1, season 2009								
ABUTH	97.3 b	95.3 a	90.4 a	96.4 b	92.3 b	85.4 a	84.0 a	89.3 b
AMBAR	96.5 a	95.6 a	87.7 a	96.2 b	96.5 a	93.5 a	87.3 a	96.0 b
AMARE	99.3 a	99.1 a	97.6 a	99.7 a	97.4 a	99.8 a	94.9 a	99.5 b
CHEAL	99.2 a	99.7 a	98.3 a	99.5 a	98.2 a	99.1 a	95.1 a	99.1 b
CONAR	85.3 b	79.3 a	79.3 a	87.1 b	91.3 a	95.7 b	90.3 a	96.9 b
ECHCG	96.4 b	88.7 a	95.7 a	94.7 a	96.1 b	89.5 a	97.1 a	97.4 a
ELYRE	93.7 b	81.1 a	94.8 a	93.1 a	89.5 b	83.1 a	91.7 a	92.0 a
FALCO	96.9 b	93.7 a	95.3 a	95.4 a	96.9 a	97.4 a	92.9 a	99.7 b
POLLA	97.6 b	93.7 a	91.6 a	94.7 b	98.6 a	97.1 a	94.7 a	99.5 b
Average	**95.8 B**	**91.8 A**	**92.3 A**	**95.2 B**	**95.2 B**	**93.4 A**	**92.0 A**	**96.6 B**
Trial T2, season 2009								
ABUTH	95.3 a	92.3 a	91.7 a	94.3 b	82.4 a	92.0 b	90.1 a	95.3 b
AMBAR	93.3 a	94.1 a	84.3 a	90.1 b	93.9 a	91.6 a	91.3 a	92.7 a
AMARE	98.4 a	99.2 a	95.5 a	98.5 b	97.9 a	99.5 a	95.7 a	99.5 a
CHEAL	97.2 a	97.4 a	93.4 a	96.5 b	97.5 a	96.4 a	94.4 a	95.5 a
CONAR	81.3 b	75.2 a	72.4 a	80.3 b	89.3 a	95.3 b	61.9 a	87.7 b
ECHCG	94.1 b	90.1 a	95.3 a	92.3 a	94.1 b	80.1 a	96.1 a	93.3 a
ELYRE	90.1 b	85.5 a	92.8 b	85.5 a	83.3 b	70.5 a	90.4 b	84.7 a
FALCO	88.1 b	83.1 a	92.6 a	95.1 a	92.1 a	92.1 a	88.6 a	95.8 b
POLLA	91.1 b	87.7 a	89.3 a	93.6 b	92.1 a	90.7 a	85.3 a	93.4 b
Average	**92.1 B**	**89.4 A**	**89.7 A**	**91.8 B**	**91.4 B**	**89.8 A**	**88.2 A**	**93.1 B**

Notes. Values marked with the same letter within individual weed species and individual trial factor (nozzle API *vs*. AVI or spray volume 150 *vs*. 300) do not differ significantly according to the t-test ($P < 0.05$, n = 20). F + B – foramusulfuron 60 g ha^{-1} + bentazon 850 g ha^{-1}, F + D – foramsulfuron 60 g ha^{-1} + 2,4-D 750 g ha^{-1}.

Table 4. Herbicide efficacy and maize yield in the trials (T1 and T2) of the 2009 season as influenced by the nozzle type (API and AVI), spray volume, droplet volume median diameter (VMD) and herbicide mixture

Nozzle, spray volume, VMD	T1 (F + B)		T1 (F + D)		T2 (F + B)		T2 (F + D)	
	Eff.	Y	Eff.	Y	Eff.	Y	Eff.	Y
API, 150, 128	94.5 cd	2.17 b	92.7 b	**2.27** ab	92.5 cd	2.14 a	90.7 bcd	2.05 a
API, 150, 212	95.6 cd	2.19 b	93.6 bc	**2.30** ab	92.7 cd	2.07 a	90.3 bc	2.15 ab
AVI, 150, 445	90.8 ab	2.07 a	**93.7** bc	2.11 ab	88.7 b	1.89 a	87.8 b	1.99 a
AVI, 150, 730	88.4 a	2.05 a	87.9 a	1.95 a	84.6 a	1.90 a	83.9 a	1.94 a
API, 300, 125	96.7 d	2.20 b	94.8 bc	2.20 ab	90.4 bc	2.02 a	90.8 bcd	2.02 a
API, 300, 215	96.3 d	2.38 d	**99.7** c	2.38 b	92.5 cd	2.07 a	93.9 de	2.15 ab
AVI, 300, 375	95.6 cd	2.30 c	96.7 cd	2.25 ab	93.7 d	2.09 a	95.9 e	**2.27** b
AVI, 300, 565	92.3 bc	2.20 b	95.3 bc	2.18 ab	90.5 bc	2.12 a	91.7 ed	2.02 a
$\bar{x}$ 150 l ha^{-1}	92.3 A	2.12 A	92.0 A	2.16 A	89.7 A	2.00 A	88.2 A	2.03 A
$\bar{x}$ 300 l ha^{-1}	95.2 B	2.27 B	96.6 B	2.25 B	91.8 B	2.07 A	93.1 B	2.11 A
$\bar{x}$ API	95.8 B	2.24 A	95.2 B	2.29 B	92.1 B	2.07 A	91.4 B	2.09 A
$\bar{x}$ AVI	91.8 A	2.16 A	93.4 A	2.12 A	89.4 A	2.00 A	89.8 A	2.05 A

Notes. Means marked with the same small letters do not differ significantly according to the Tukey HSD test ($P < 0.05$, n = 5) and means marked with capital letters do not differ significantly according to the t-test ($P < 0.05$, n = 20). Bold numbers indicate statistically significant differences between F + B and F + D herbicide mixtures according to the t-test ($P < 0.05$, n = 5 or 20). F + B – foramusulfuron 60 g ha^{-1} + bentazon 850 g ha^{-1}, F + D – foramsulfuron 60 g ha^{-1} + 2,4-D 750 g ha^{-1}. VMD small – 125, 128, 212, 215 µm, big – 375, 445, 565, 730 µm. Eff. – efficacy %, Y – kg of fresh cobs m^{-2}.

Pigweed and lambsquarters control was equally successful with API and AVI nozzles (T1 and T2) (Table 3). In treatments T1 (F + B), T2 (F + B) and T2 (F + D), the differences in maize yield were not significant. In only one of four herbicide applications the use of AVI nozzles resulted in yield reduction, when compared to API nozzles. The results from the season 2009 suggest that the use of drift-reducing AVI nozzles did not result in significant maize yield reduction, compared to those achieved by API nozzles.

Efficacy of weed control and maize yield in the season of 2010. The data on herbicide efficacy and maize yield from trials T3 and T4 are shown in Tables 5 and 6. Weed population had a different structure than in 2009. The most frequent weeds were barnyard grass (*Echinochloa crus-galii*, 120–250 m^{-2}), pigweed (*Amaranthus retroflexus*) and knotweeds (*Polygonum lapathifolium* and *Fallopia convolvulus*). Both knotweeds played an important role in maize yield reduction because none of the three herbicides applied gave efficient control of the two species. In the autumn, the populations of these two species were abundant. In T3 trial, higher spray volume increased herbicide efficacy and API nozzles provided higher efficacy of weed control than AVI nozzles for both herbicide mixtures F + B and F + D (Table 5).

Table 5. The efficacy of herbicide combinations against individual weed species as influenced by the nozzle type (API and AVI) and spray volume (l ha^{-1}) for trials T3 and T4 in 2010

Weed	F + B API	F + B AVI	F + B 150	F + B 300	F + D API	F + D AVI	F + D 150	F + D 300
Trial T3, season 2010								
ABUTH	96.3 a	93.8 a	90.7 a	95.3 b	89.1 a	90.7 a	88.8 a	94.4 b
AMBAR	93.9 a	90.5 a	86.5 a	88.1 a	96.2 a	92.5 a	89.8 a	95.3 b
AMARE	98.8 a	98.1 a	93.5 a	98.1 b	99.3 a	99.1 a	96.3 a	99.6 a
CHEAL	98.2 a	97.1 a	95.8 a	98.2 a	99.8 a	97.2 a	98.9 a	97.3 a
CONAR	83.1 a	84.2 a	71.8 a	83.7 b	93.1 a	95.5 a	86.1 a	93.3 b
ECHCG	94.7 b	80.4 a	95.3 a	92.5 a	95.1 b	87.8 a	96.6 b	92.3 a
ELYRE	90.9 b	72.3 a	92.8 b	87.3 a	92.4 b	81.8 a	93.5 b	88.3 a
FALCO	90.6 a	91.4 a	89.9 a	95.2 b	94.5 a	95.7 a	94.7 a	98.1 a
POLLA	92.3 b	88.7 a	87.4 a	94.1 b	97.3 b	94.9 a	92.3 a	96.4 b
Average	**93.2 B**	**88.5 A**	**89.3 A**	**92.5 B**	**95.2 B**	**92.8 A**	**93.0 A**	**95.0 B**
Trial T4, season 2010								
ABUTH	94.8 a	95.5 a	90.5 a	95.3 b	84.7 a	88.6 a	80.4 a	92.8 b
AMBAR	92.3 a	96.3 b	87.1 a	94.1 b	90.3 a	92.2 a	81.5 a	95.8 b
AMARE	98.3 a	98.1 a	97.5 a	98.9 a	98.9 a	99.4 a	93.6 a	99.5 b
CHEAL	97.7 a	98.4 a	97.4 a	98.4 a	98.5 a	98.2 a	96.2 a	98.9 a
CONAR	84.2 a	83.7 a	76.5 a	89.8 b	91.1 a	95.6 b	86.2 a	95.2 b
ECHCG	93.5 b	87.5 a	94.5 b	90.7 a	94.6 b	83.6 a	97.8 b	91.5 a
ELYRE	90.3 b	83.5 a	90.8 a	88.7 a	89.9 b	77.8 a	93.6 b	89.5 a
FALCO	90.7 a	94.5 b	91.6 a	95.7 b	95.7 a	96.5 a	92.1 a	94.9 a
POLLA	88.9 a	93.2 b	89.5 a	94.4 b	96.9 a	96.1 a	92.2 a	96.9 b
Average	**92.3 A**	**92.3 A**	**90.6 A**	**94.0 B**	**93.4 A**	**92.0 A**	**90.4 A**	**95.0 B**

Note. Explanations under Tables 1 and 3.

The same is true for T4 trial. In F + B mixture of T3 trial this resulted in significant differences in maize yield (API 2.06 and AVI 1.85 kg m^{-2}) but in F + D mixture the differences in yield were not significant (API 2.15 and AVI 2.11 kg m^{-2}) (Table 6).

The efficacy of foramsulfuron for control of barnyard grass was reduced by more than 15% and in quackgrass by more than 10% when applied by AVI nozzles in both T3 and T4 trials (Table 6). The performance of API and AVI nozzles in terms of herbicide efficacy in T4 trial was totally comparable; as a result, the maize yields at both spray mixtures were not statistically different either. Based on the results from the 2010 season, we can conclude that the use of drift-reducing nozzles provides the same level of weed control and maize yield as standard nozzles. For grass control it is well known that better results can be achieved by using low spray volumes and smaller droplets, which have better adhesion and retention capacity (Knoche, 1994; Vajs, Lešnik, 2005; Brown et al., 2007). In our trial, it was demonstrated that drift-reducing nozzles should not be used for low volume applications because the efficacy of grass control could be reduced significantly. This is because of too low droplet density and droplet retention on grass surface.

In Table 2, when we compare AVI 110-03 at 160 kPa pressure (25–50 impacts) with API 110-03 at the same pressure (40–95 impacts), it is possible to notice the differences in the number of droplet impacts per cm^2. These differences in density of droplet impacts are important for small emerging barnyard grass plants. At 25 impacts per cm^2, many small emerging plants are not hit by droplets and consequently the amount of herbicide transposed to weed tissue is too low for achieving high efficacy. These results are consistent with those obtained by Ramsdale and Messersmith (2001) and by Brown et al. (2007). They demonstrated that the control of barnyard grass by the application of herbicide with drift-reducing nozzles can be improved by the increased operating pressure.

There are also other options to improve the efficacy of herbicides for grass control. The first is addition of adjuvant (McMullan et al., 2006) and the second is use of nozzles with non-vertical orientation (Jensen, 2010). Adjuvants can alter herbicide-nozzle interaction. McMullan et al. (2006) demonstrated the effects of adjuvants on foramulfuron efficacy. The efficacy of foramsulfuron was decreased by 30% when applied with air-induction nozzles without adjuvant, compared to that achieved with standard nozzles. When adjuvant was added the efficacy of foramsulfuron applied with air-induction nozzles was increased by 40%, compared to that achieved with standard nozzles. Jensen (2010) established that the efficacy of herbicides applied with standard and drift-reducing nozzles for grass control could be increased by angling the spray either forward or backward, relative to the direction of travelling. The highest improvement in the efficacy was obtained using a 60° forward-angled spray.

Table 6. Herbicide efficacy and maize yield in the trials (T1 and T2) of the 2010 season as influenced by the nozzle type (API and AVI), spray volume, droplet volume median diameter (VMD) and herbicide mixture

Nozzle, spray volume, VMD	T3 (F + B)		T3 (F + D)		T4 (F + B)		T4 (F + D)	
	Eff.	Y	Eff.	Y	Eff.	Y	Eff.	Y
API, 150, 128	92.5 b	2.09 a	93.7 ab	2.17 ab	91,5 ab	2.04 a	91.7 bc	2.15 ab
API, 150, 212	93.4 b	2.05 a	95.1 c	**2.23** b	91.7 ab	2.09 a	92.3 bc	2.18 ab
AVI, 150, 445	88.8 ab	1.80 a	**93.7** ab	**2.18** ab	90.7 ab	2.01 a	89.8 ab	2.07 a
AVI, 150, 730	82.4 a	1.66 a	89.5 a	**1.99** a	88.4 a	1.96 a	87.9 a	1.99 a
API, 300, 125	93.7 b	2.04 a	96.8 c	2.02 a	92.4 c	2.02 a	93.8 cd	2.22 ab
API, 300, 215	93.3 b	2.06 a	95.3 c	2.16 ab	93.5 c	2.17 a	95.9 d	2.18 ab
AVI, 300, 375	92.6 b	2.05 a	95.7 c	2.20 ab	96.7 d	2.19 a	96.5 d	2.25 b
AVI, 300, 565	90.3 b	1.90 a	92.3 ab	2.08 a	93.3 c	2.12 a	93.7 cd	2.22 ab
$\bar{x}$ 150 l ha^{-1}	89.3 A	1.90 A	**93.0** A	2.14 A	90.6 A	2.02 A	90.4 A	2.09 A
$\bar{x}$ 300 l ha^{-1}	92.5 B	2.01 B	95.0 B	2.12 A	94.0 B	2.12 B	95.0 B	2.21 B
$\bar{x}$ API	93.2 B	2.06 B	95.2 B	2.15 A	92.3 A	2.08 A	93.4 A	2.18 A
$\bar{x}$ AVI	88.5 A	1.85 A	**92.8** A	**2.11** A	92.3 A	2.07 A	92.0 A	2.13 A

Note. Explanations under Table 4.

The efficacy of weed control and maize yield in the season of 2011. Results for the 2011 season are presented in Tables 7 and 8. The weed population of trial plots in 2011 was larger than in 2010. We had a large population of velvetleaf (*Abutilon theophrasti*), barnyard grass (*Echinochloa crus-galii*), quackgrass (*Elytrigia repens*) and bindweed (*Convolvulus arvensis*, 3 to 8 m^{-2}). Especially the last two weed species had an important influence on the yield loss. At the end of the season we found dense stands of *Elytrigia* and *Abutilon* on many plots. In T5 trial, the use of AVI nozzles resulted in yield reduction for both herbicide mixtures (F + B, API-2.33/AVI-2.26 kg m^{-2} and F + D, API-2.30/AVI-2.15 kg m^{-2}) (Table 8). In T6 trial, AVI nozzles had worse performance only for F + B mixture. When we applied F + D mixture, both nozzles provided the same level of efficacy and maize yield. In plots of T6 trial, there were large populations of bindweed (*C. arvensis*) and black bindweed (*Fallopia convolvulus*). We noticed that increased spray volume and partially also bigger droplet size increased the efficacy of bentzone and 2,4-D against bindweed and partially against bindweed (FALCO, API (F + B) = 89.3% *vs*. AVI (F + B) = 94.9%) (Table 7). The difference among bindweed and other weed species could be noticed. The highest herbicide efficacy was achieved with higher spray volume and with medium-size droplets (API 110-04, 300, VMD 215 and AVI 110-03, 300, VMD 375). This demonstrates that the response of bindweed to the application technique is not the same as in annual broad-leaved species and grasses (e.g., T5, CONAR,

Table 7. The efficacy of herbicide combinations against individual weed species as influenced by the nozzle type (API and AVI) and spray volume (l ha^{-1}) for trials T5 an T6 in 2011

Weed	F + B API	F + B AVI	F + B 150	F + B 300	F + D API	F + D AVI	F + D 150	F + D 300
Trial T5, season 2011								
ABUTH	96.1 a	95.9 a	90.3 a	94.2 b	82.2 a	89.9 b	83.0 a	94.4 b
AMBAR	95.2 a	96.7 a	93.6 a	95.2 a	93.9 a	95.6 a	90.0 a	96.0 b
AMARE	97.9 a	98.9 a	98.5 a	98.6 a	99.5 a	99.3 a	97.6 a	99.0 a
CHEAL	98.5 a	98.8 a	97.5 a	98.1 a	99.3 a	99.2 a	98.2 a	98.9 a
CONAR	87.1 a	89.7 a	79.4 a	93.3 b	91.4 a	96.6 b	86.2 a	96.1 b
ECHCG	97.5 b	83.5 a	95.5 b	90.1 a	93.5 b	80.5 a	96.5 b	90.0 a
ELYRE	92.4 b	80.5 a	94.8 b	87.5 a	89.7 b	79.5 a	90.5 b	87.0 a
FALCO	89.3 a	94.9 b	90.6 a	96.7 b	95.9 a	96.1 a	87.0 a	94.1 b
POLLA	92.0 a	93.6 a	90.5 a	94.1 b	96.1 a	96.7 a	94.5 a	95.0 a
Average	**94.0 A**	**92.5 A**	**92.3 A**	**94.2 A**	**93.5 B**	**92.6 A**	**91.5 A**	**94.5 B**
Trial T6, season 2011								
ABUTH	97.4 a	94.7 a	94.4 a	92.0 a	83.6 a	84.0 a	84.3 a	94.0 b
AMBAR	97.7 a	93.3 a	94.1 a	94.6 a	94.0 a	95.9 a	92.5 a	95.9 b
AMARE	99.1 a	98.5 a	98.0 a	98.3 a	99.3 a	99.2 a	96.6 a	99.1 a
CHEAL	99.1 a	98.6 a	97.9 a	95.1 a	98.2 a	99.7 a	97.1 a	98.8 a
CONAR	88.6 a	89.7 a	89.9 a	90.5 a	91.5 a	96.7 b	86.2 a	96.5 b
ECHCG	95.5 b	83.5 a	96.6 b	90.0 a	94.9 b	85.0 a	96.1 a	91.6 a
ELYRE	91.3 b	81.0 a	93.8 b	87.1 a	90.8 b	84.6 a	92.0 a	89.2 a
FALCO	91.0 a	93.7 a	88.1 a	92.7 b	95.9 a	96.9 a	90.5 a	94.4 b
POLLA	93.4 a	93.2 a	94.1 a	93.3 a	96.9 a	96.9 a	93.6 a	95.5 a
Average	**94.8 B**	**91.8 A**	**94.1 B**	**92.6 A**	**93.9 A**	**93.2 A**	**92.1 A**	**95.0 B**

Note. Explanations under Tables 1 and 3.

F + B 150 (79.4%) *vs*. F + B 300 (93.3%) (Table 7). Nozzles and spray volumes had no significant effect on herbicide efficacy for the control of pigweed, ragweed and lambsquarters.

Table 8. Herbicide efficacy and maize yield in the trials (T1 and T2) of the 2011 season as influenced by the nozzle type (API and AVI), spray volume, droplet volume median diameter (VMD) and herbicide mixture

Nozzle, spray volume, VMD	T5 (F + B)		T5 (F + D)		T6 (F + B)		T6 (F + D)	
	Eff.	Y	Eff.	Y	Eff.	Y	Eff.	Y
API, 150, 128	91.5 ab	2.19 a	90.7 a	2.27 ab	**96.5** b	2.34 b	92.7 ab	2.35 a
API, 150, 212	94.4 b	2.28 ab	92.1 ab	2.13 ab	95.7 b	2.39 b	93.1 ab	2.28 a
AVI, 150, 445	90.8 a	2.17 a	90.5 a	2.07 a	93.7 ab	2.21 ab	91.8 ab	2.17 a
AVI, 150, 730	92.4 ab	2.21 ab	90.5 a	2.15 ab	90.4 a	1.92 a	90.9 a	1.93 a
API, 300, 125	94.7 ab	2.40 ab	94.8 ab	2.32 ab	93.4 ab	**2.27** ab	94.8 ab	2.12 a
API, 300, 215	93.5 ab	2.46 b	**96.3** b	2.46 b	93.8 ab	2.37 b	94.9 ab	2.28 a
AVI, 300, 375	93.6 ab	2.25 ab	93.7 ab	2.20 ab	92.7 ab	2.19 ab	95.5 b	2.45 a
AVI, 300, 565	93.3 ab	2.40 ab	93.3 ab	2.18 ab	90.3 a	2.03 a	**94.7** ab	2.32 a
$\bar{x}$ 150 l ha^{-1}	92.3 A	2.21 A	91.5 A	2.16 A	94.1 B	2.21 A	92.1 A	2.18 A
$\bar{x}$ 300 l ha^{-1}	94.2 A	**2.38** B	94.5 B	2.29 B	92.6 A	2,21 A	**95.0** B	2.29 A
$\bar{x}$ API	94.0 A	2.33 B	93.5 B	2.30 B	94.9 B	2.34 B	93.9 A	2.25 A
$\bar{x}$ AVI	92.5 A	2.26 A	92.6 A	2.15 A	91.8 A	2.08 A	93.2 A	**2.21** A

Note. Explanations under Table 4.

The difference between F + B and F + D mixture in T6 trial in terms of nozzle effect on yield lies in lower efficacy of bentazon against knotweed than 2,4-D and in higher population of barnyard grass and quackgrass in F + B plots. The season of 2011 revealed the whole complexity of nozzle-herbicide-weed species interactions and their impact on maize yield. In 3 of 4 herbicide applications, the use of AVI nozzles resulted in yield reduction, compared to API nozzles. The yield reduction ranged from 5% to 10%. This rate of yield reduction cannot be ignored. The results obtained in the season 2011 differed from the results of the seasons 2009 and 2010. Sikkema et al. (2008) established almost the same level of yield reduction in soybean when comparing standard and drift-reducing nozzles used for the control of very similar weed populations. In several trials, the use of drift-reducing nozzles, compared with the standard nozzles for bentazon application, decreased the soybean yield by 7%. The decrease of bentazon efficacy applied in a form of big droplets was noted by Prokop and Veverka (2003). They tested the effect of six different droplet sizes (VMD 183 to 911 µm) of bentazon spray in order to control *Chenopodium album* L. The efficiency significantly increased with smaller droplet sizes. The lowest efficacy was achieved by the droplet spectra of 586 and 911 µm.

Conclusions

1. The results of our trials showed that the response of different weed species to herbicide application parameters was not uniform and was also dependent on herbicide type (contact or systemic). Quite different effects of nozzles in different seasons were observed despite application of the same herbicide mixtures to the same weed populations in the same fields.

2. Nozzles and spray volume did not have any significant effect on the efficacy of the tested herbicide mixtures of foramsulfuron + bentazon or 2,4-D in the control of pigweed, ragweed and lambsquarters.

3. Bigger droplets and higher spray volume decreased the efficacy of the tested herbicide mixtures against grass weeds (quackgrass and barnyard grass) and increased the efficacy against velvetleaf, bindweed and knotweed.

4. In the case of moderate weed population with an equal ratio of grasses to broad-leaved weeds, the use of drift-reducing nozzles did not lead to such a decrease of herbicide efficacy which could cause a significant maize yield reduction.

5. Our investigation showed that there were many interactive effects which influenced herbicide efficacy. For a successful application of herbicides and at the same time the reduction of their drift, farmers need to develop nozzle selection skills. They must know how to select the most appropriate nozzles and corresponding application parameters – flow rates, pressures, droplet sizes (volume median diameter, VMD) – for specific combinations of weeds species and types of herbicides. Our study suggests that the mandatory use of drift-reducing nozzles can be a successful measure for herbicide drift reduction only when farmers are capable of balancing all the discussed aspects of nozzle and herbicide selection.

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Purkštukų tipo įtaka herbicidų efektyvumui ir paprastojo kukurūzo (*Zea mays* L.) derliui

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Santrauka

Siekiant palyginti herbicidų efektyvumą paprastojo kukurūzo (*Zea mays* L.) pasėliui, lauko bandymai vykdyti 2009–2011 m. Herbicidai purkšti standartiniais (API, "Albuz") ir specialiais (AVI, "Albuz") purkštukais, mažinančiais lašelių nunešimą pavėjui. Herbicidų mišiniai, sudaryti iš 2,4-D, bentazono ir foramsulfurono, purkšti pasėliui sudygus, naudojant pakabinamą lauko purkštuvą, 150 ir 300 l tirpalo hektarui. Išpurškiamo tirpalo lašeliai skyrėsi dydžiu, jų tūrio medianinis skersmuo buvo nuo 100 iki 800 µm. Bandymų pagrindinės piktžolių rūšys buvo *Ambrosia artemisiifolia*, *Amaranthus retroflexus*, *Chenopodium album*, *Convolvulus arvensis*, *Elytrigia repens*, *Echinochloa crus-galii*, *Polygonum lapathifolium* ir *Fallopia convolvulus*. Vertintas herbicidų efektyvumas (%) ir kukurūzų derlius. Nustatyta skirtinga tirtų veiksnių įtaka herbicidų efektyvumui plačialapėms ir siauralapėms piktžolėms. Palyginus su standartiniais API purkštukais, AVI purkštukų, mažinančių lašelių nunešimą pavėjui, efektyvumas buvo mažesnis 8 iš 12 herbicidų purškimo atvejų. Efektyvumo sumažėjimas svyravo nuo 2 iki 7 %. Kukurūzų burbuolių derliui reikšmingą įtaką purkštuko tipas turėjo 5 iš 12, o purškiamo tirpalo norma – 7 iš 12 herbicidų purškimo atvejų. Visais atvejais kukurūzų derlius iš esmės didesnis buvo herbicidus išpurškus standartiniais purkštukais (API, tūrio medianinis skersmuo – 100–300 µm), 300 l ha^{-1} tirpalo. Didžiausias derliaus sumažėjimas (7–11 %) naudojant AVI purkštukus nustatytas purškiant mažą (150 l ha^{-1}) normą dideliais lašeliais (tūrio medianinis skersmuo didesnis nei 400 µm). Tyrimo rezultatai parodė, kad purškiant AVI purkštukais gaunama prasta piktžolių kontrolė, jeigu purškiama maža (mažiau nei 200 l ha^{-1}) norma tirpalo, tūrio medianinio skersmens vertėms esant didesnėms nei 400 µm. Kitais atvejais piktžolių kontrolė yra panaši į gaunamą naudojant API purkštukus, o AVI purkštukų, mažinančių lašelių nunešimą pavėjui, naudojimas kukurūzų derliaus nesumažina.

Reikšminiai žodžiai: purkštukai, mažinantys lašelių nunešimą pavėjui, *Zea mays*, piktžolių kontrolė, 2,4-D, bentazonas, foramsulfuronas.