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Effect of different soil and weather conditions on efficacy, selectivity and dissipation of herbicides in sunflower

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Abstract: Six sunflower herbicides were tested at two application rates (1N and 2N) on three locations (with different soil types) within three years (2015–2017). Efficacy of the tested herbicides on *Chenopodium album* increased with an increasing cation exchange capacity (CEC) of the soil. Efficacy of pendimethalin was 95%, flurochloridone and aclonifen 94%, dimethenamid-P 72%, pethoxamid 49% and S-metolachlor 47%. All tested herbicides injured sunflower on sandy soil (Regosol) which had the lowest CEC, especially in wet conditions (phytotoxicity 27% after 1N application rate). The highest phytotoxicity was recorded after the application of dimethenamid-P (19% at 1N and 45% at 2N application rate). Main symptoms of phytotoxicity were leaf deformations and necroses and the damage of growing tips, which led to destruction of some plants. Aclonifen, pethoxamid and S-metolachlor at 1N did not injure sunflower on the soil with the highest CEC (Chernozem) in any of the experimental years. Persistence of tested herbicides was significantly longer in Fluvisol (medium CEC) compared to Regosol and Chernozem. Dimethenamid-P showed the shortest persistence in Regosol and Chernozem. The majority of herbicides was detected in the soil layer 0–5 cm in all tested soils. Vertical transport of herbicides in soil was affected by the herbicide used, soil type and weather conditions. The highest vertical transport was recorded for dimethenamid-P and pethoxamid (4, resp. 6% of applied rate) in Regosol in the growing season with high precipitation.

Keywords: *Helianthus annuus* L.; environmental factor; soil condition; metabolic selectivity; weed control; leaching

Linuron, flurochloridone, oxyfluorfen, pendimethalin, prosulfocarb, bifenox, aclonifen, flumioxazin, chlorbromuron, metobromuron, fenuron and lenacil are used in Europe for pre-emergent (PRE) control of dicot weeds in sunflower (De Prado et al. 1993, Pannacci et al. 2007, Nádasy et al. 2008, Jursík et al. 2015). Those herbicides are usually applied in tank-mixes along with acetamide herbicides (acetochlor, dimethenamid, pethoxamid, S-metolachlor, flufenacet, propisochlor and propachlor), which are intended mainly for the control of grass weeds (Nádasy et al. 2008, Bedmar et al. 2011, Jursík et al. 2013). Using tank-mixes may expand the control to more weed species, prevent weed population shifts, delay the evolution of resistance in weeds, reduce costs of application and, in some cases, be more efficacious than when single herbicides are used (Streibig et al. 1998, Das and Yaduraju 2012, Godwin et al. 2018a). Selectivity of these tank-mix combinations is usually not reduced (Erasmo et al. 2010, Jursík et al. 2019).

The efficacy of PRE herbicides is influenced by many factors, among the most important of which are environmental (weather and soil conditions). Soil temperature and moisture directly affect herbicides' behaviour by influencing herbicide solubility, movement and degradation. In addition, soil water availability and temperature can indirectly affect root characteristics, such as permeability and herbicide transport *via* transpiration flow. Under dry conditions, the efficacy of PRE herbicides usually diminishes (Zanatta et al. 2008, Jursík et al. 2015). Relative humidity and air temperature influence

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Table 1. Soil and climatic characterisation of experimental locations

Soil type	Ovcary Arenic Regosol	Dobromerice Haplic Fluvisol	Prague Haplic Chernozem
pH_{KCl}	7.5	7.3	7.1
pH_{H_2O}	8.1	7.8	7.9
Organic carbon content (%)	1.3	2.0	1.5
Clay content (%)	18.9	25.0	24.0
Silt content (%)	13.9	38.5	57.0
Sand content (%)	67.2	36.5	19.0
Cation exchange capacity ($mmol_+$/kg)	88	168	258
Long-term annual temperature (°C)	9.6	9.4	9.5
Long-term annual sum of precipitation (mm)	563.5	470.9	519.6

evaporation. Increasing evaporation can reduce droplet size and increase herbicide drift (Ziska and Dukes 2011). Herbicide selectivity is also affected by soil characteristics. For example, Steckel et al. (2013) reported maize to be more sensitive to damage from isoxaflutole plus flufenacet on soil with lower carbon content and higher soil pH. In addition, intensive precipitation after the application of herbicides can cause the transport of active ingredients (a.i.) within the soil profile and sunflower is often damaged by herbicides having low metabolic selectivity (Wischmeier and Mannering 1969).

Sandy soils, which usually have lower sorption capacity, present greater risk of herbicide leaching. Clay soils, meanwhile, are more vulnerable to erosion and runoff (Renaud et al. 2004).

High clay fraction content and high organic carbon increase metazachlor degradation (Sadowski et al. 2012) and residual activity can therefore be reduced. Imazamox availability was the greatest on sandy soils and decreased in soils with high clay or organic carbon content, where herbicide efficacy was less than 50%, with respect to non-sorptive media (Pannacci et al. 2006). According to Vischetti et al. (2002), pesticide leaching is affected mainly by the preferential flow, soil sorption capacity, pesticide half-life and diffusion inside the soil aggregates. Selectivity of most PRE herbicides used in sunflower depends on the position of the herbicide layer on the soil surface and the placement of achenes in the soil profile.

The aim of this work was to compare the efficacy, sunflower phytotoxicity and dissipation of six herbicides in different soil and weather conditions and to recommend effective and selective herbicide treatments for common soil and weather conditions of central Europe.

MATERIAL AND METHODS

Small-plot field trials were carried out in sunflower (cv. Biba) at three different locations in the Czech Republic during 2015–2017. Soil and climate characteristics of the experimental locations are described in Table 1. Winter wheat was the previous crop in all years and at all locations. Table 2 shows sowing dates for sunflower at all experimental locations and in all years. Experimental plots of 24.5 m^2 (3.5 × 7 m) were arranged in randomised blocks with three replicates. The row spacing was 0.7 m, in-row plant spacing was 0.16 m. The dominant weed species was *Chenopodium album* at all locations and in all experimental years. It occurred in density 20–40 plants/m^2. Other weeds (*Amaranthus retroflexus*, *Echinochloa crus-galli*, *Galium aparine* and *Fallopia convolvulus*) occurred at lower densities and only at some locations.

PRE herbicide applications were done 1 or 2 days after sunflower sowing. The herbicides Racer 250 EC (250 g/L of flurochloridone), Stomp 400 SC (400 g/L of pendimethalin), Bandur (600 g/L of aclonifen), Outlook (720 g/L of dimethenamid-P), Dual Gold 960 EC (960 g/L of S-metolachlor) and Successor 600 (600 g/L of pethoxamid) were used at the recommended (1N) and double (2N) rates (flurochloridone 750 and 1 500 g/ha a.i.;

Table 2. Sowing dates of sunflower on experimental locations

	Ovcary	Dobromerice	Prague
2015	27. 03.	20. 04.	16. 04.
2016	30. 03.	11. 04.	18. 04.
2017	04. 04.	03. 05.	19. 04.

pendimethalin 2 000 and 4 000 g/ha a.i.; aclonifen 2 600 and 5 200 g/ha a.i.; dimethenamid-P 1 000 and 2 000 g/ha a.i.; S-metolachlor 1 150 and 2 300 g/ha a.i.; and pethoxamid 1 200 and 1 400 g/ha a.i.).

The experiment included untreated plots. A small-plot sprayer with Lurmark 015F110 nozzles was used to apply the herbicides. Application pressure was 0.25 MPa and water volume applied was 300 L/ha. Table 3 summarizes the meteorological characteristics during the month following the herbicide application.

Soil samples for the measurement of herbicide concentrations in soils were collected 30 days after herbicide applications using soil cylinders (0.0001 m^3) from soil layers of depths 0–5 cm and 5–10 cm. Herbicide concentrations were determined in soil methanol extracts by high-performance liquid chromatography according to the modified method devised by Hurle and Walker (1980). Detection limits were 0.02 μg/mL for aclonifen, 0.05 μg/mL for dimethenamid-P, 0.015 μg/mL for flurochloridone, 0.03 μg/mL for S-metolachlor, 0.025 μg/mL for pethoxamid and 0.01 μg/mL for linuron. The amounts of herbicide present in soil extracts were expressed as the total amount of solute per mass unit (μg/g). Because the studied herbicides were applied at different rates, pesticide mobility was compared as the percentages of herbicide residuals in soil layers relative to the application rates.

Herbicide efficacy was assessed by estimation 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 guideline (EPPO 2007). Selectivity was assessed according to the EPPO 1/135 guideline (EPPO 2014). Visual assessment of phytotoxicity was performed at the four true leaves (BBCH 14) sunflower growth stage and again shortly before canopy closure (BBCH 32). The final assessment of efficacy on *C. album* was made at BBCH 32 (Meier 2018).

Two central rows were harvested and the achene moisture was measured after ripening (14 September 2015, 5 October 2016 and 27 September 2017). The recorded yields were recalculated to a constant-moisture (8%) basis. For individual treatments, the final yield was expressed as the percentage of the sunflower yield on the untreated plots.

The experimental data were evaluated using the software package Statgraphics Plus 4.0 (Plains, USA). by multifactorial ANOVA. The contrasts between treatments were verified by the Tukey's *HSD* (honestly significant difference) test (α = 0.05). The Bartlett's test was used to determine whether efficacy data violated the assumption of homogeneity of variance; in one case it showed the data to be heterogeneous, and therefore, arcsine square root percent transformation was carried out and the multiple comparisons test was applied to the transformed data.

RESULTS AND DISCUSSION

Efficacy in *Chenopodium album* control. Efficacy of flurochloridone, aclonifen (both 94%) and pendimethalin (95%) was significantly higher compared to the other tested herbicides. These herbicides showed good efficacy also in our previous study (Jursík et al. 2015), which were conducted on just one soil type (Chernozem). On the other hand, the efficacy of pendimethalin in *C. album* can be lower in arid climate conditions (Singh et al. 2016). Such effect was found in 2016, when the smallest amount of precipitation was recorded during the month after the herbicide application (Table 3). In that year, the efficacy in *C. album* was significantly weaker compared to that in other experimental years (Table 4). The most effective acetamide herbicide was dimethenamid-P (72%), whose efficacy was significantly higher compared to those of pethoxamid (49%) and S-metolachlor (47%).

Table 3. Weather conditions one month after application of herbicides

Weather characteristic	Year	Experimental location		
		Ovcary	Dobromerice	Prague
Total precipitation (mm)	2015	41.7	59.9	39.9
	2016	25.7	17.0	19.2
	2017	113.5	77.5	56.2
Mean temperature (°C)	2015	9.3	13.4	12.4
	2016	9.4	10.6	10.7
	2017	8.3	15.9	11.0

Efficacy of the tested herbicides in *C. album* improved with increasing cation exchange capacity (CEC) of the soil. These differences were significant between soils having the lowest (Regosol) and highest (Chernozem) CEC (70% and 83%, respectively). Our results are in contrast to those of greenhouse experiments reported by Gannon et al. (2014), who found strong correlation (R = 0.85) between bioactivity of the herbicide saflufenacil (pyrimidinedione chemical group) and soil organic matter content but only weak correlation (R = 0.49) between bioactivity of the same herbicide and CEC. Also, Soni et al. (2015) recorded decreasing pendimethalin and atrazine herbicide activity when biochar (a charcoal by-product of biofuel production used as a soil amendment) was added to four different soils. Results reported by these authors could have been influenced also by other soil characteristics than those examined in our study (e.g. pH, microbial activity) or by laboratory conditions of their experiments.

Figure 1 shows efficacy of the tested herbicides at different soils and weather conditions. The highest efficacy (> 98%) was recorded at plots treated with aclonifen, flurochloridone and pendimethalin at all the tested locations in 2017. These three herbicides showed similar efficacy (> 96%) on Chernozem in all experimental years. In addition, flurochloridone always fully controlled *C. album* at this location. The lowest efficacy was recorded in 2016 at soil with the lowest CEC (88 mmol$_+$/kg); the efficacy ranged there from 27% (S-metolachlor) to 88% (flurochloridone).

Sunflower injury. All tested herbicides caused some symptoms of sunflower phytotoxicity (Table 4). The significantly greatest sunflower injury was recorded after the application of dimethenamid-P (13% at BBCH 14 and 19% at BBCH 32). The lowest sunflower phytotoxicity was caused by aclonifen and S-metolachlor (1%). Sunflower phytotoxicity was strongly affected by the soil type and in particular soil CEC. At locations with high CEC (Chernozem and Fluvisol), relatively low sunflower injury was recorded (1% and 2%, respectively). Sunflower injury was significantly greater at location with low soil CEC (Regosol). On the same sandy soil, Andr et al. (2017) recorded high phytotoxicity of linuron and oxyfluorfen to sunflower without a significant mitigating effect from the tested soil adjuvants. High phytotoxicity of flumioxazin to flax (*Linum usitatissimum*) was reported also by Kurtenbach et al. (2019) on the soil with the highest sand content (54%) and by Godwin et al. (2018b), who recorded greater injury to rice (*Oryza sativa*) after PRE application of acetamide herbicides on sandy soil compared to clay soil. Kerr et al. (2004) described a beneficial effect of soil CEC on phytotoxicity of carfentrazone to sunflower; their result was similar to that in our study. The main reason for the low selectivity of soil-active herbicides in sandy soils is easy leaching of herbicides into the soil profile, where the herbicide is easily taken up by crop roots. This effect is typical for herbicides with low metabolic selectivity (Jursík et al. 2011).

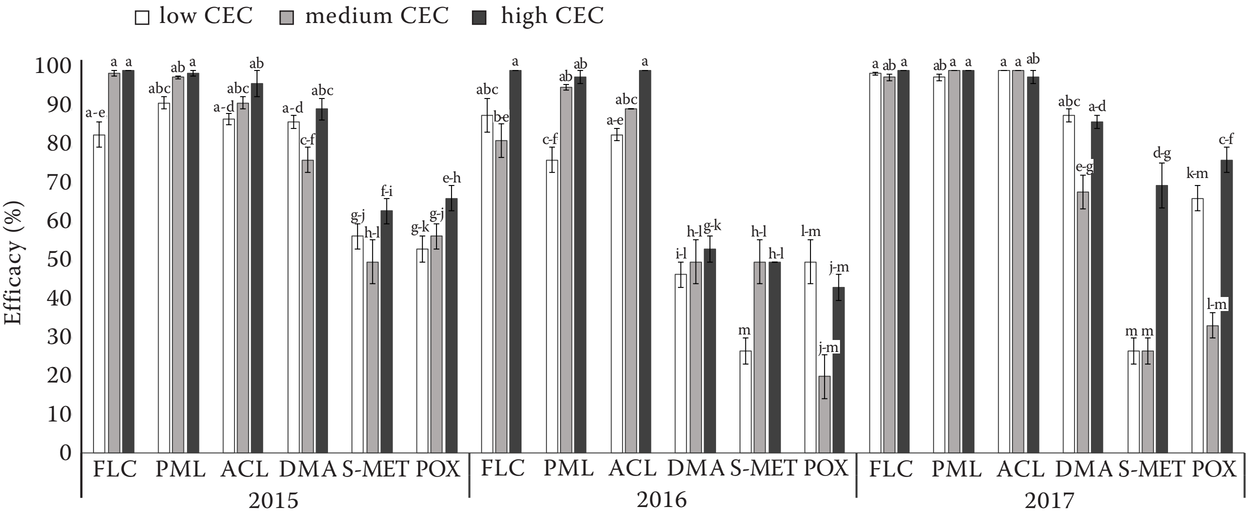

Figure 1. Efficacy of tested herbicides (at registered rate – 1N) on *Chenopodium album* in different soil conditions (low CEC – 88 mmol$_+$/kg, middle CEC – 168 mmol$_+$/kg, high CEC – 258 mmol$_+$/kg) in all experimental years. CEC – cation exchange capacity; FLC – flurochloridone; PML – pendimethalin; ACL – aclonifen; DMA – dimethenamid-P; S-MET – S-metolachlor; POX – pethoxamid

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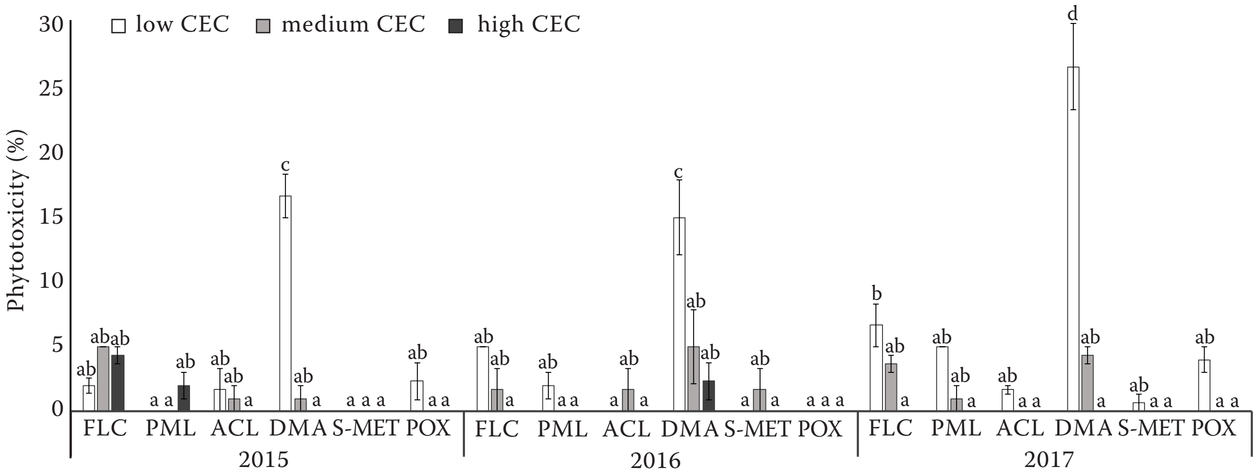

Figure 2. Visual sunflower phytotoxicity of tested herbicides (at registered rate – 1N) in different soil conditions (low CEC – 88 mmol$_+$/kg, middle CEC – 168 mmol$_+$/kg, high CEC – 258 mmol$_+$/kg) in all experimental years; data from the first assessment (BBCH 14). CEC – cation exchange capacity; FLC – flurochloridone; PML – pendimethalin; ACL – aclonifen; DMA – dimethenamid-P; S-MET – S-metolachlor; POX – pethoxamid

The effect of CEC on sunflower phytotoxicity in all experimental years is detailed in Figure 2. All tested herbicides injured sunflower on sandy soil (Regosol), which had the lowest CEC, especially in 2017 when intensive precipitation shortly after application occurred (Table 3). A similar effect of precipitation on crop injury after PRE herbicide application was recorded in our previous studies (Jursík et al. 2008, 2015). In 2017, sunflower phytotoxicity reached 27% after the application of dimethenamid-P at the 1N rate.

On the contrary, aclonifen, pethoxamid and S-metolachlor at the 1N application rate did not injure sunflower in any experimental year on the soil having the highest CEC (Chernozem). Pethoxamid caused sunflower phytotoxicity (0–4%) only on the sandy soil (with lowest CEC) at the 1N application rate.

Main symptoms of dimethenamid-P phytotoxicity were leaf deformations and necrosis along with damage of growing tips (Figure 3). This damage led to the destruction of some plants, especially at the 2N application rate. Injury of sunflower significantly increased (from 19% to 45%) in case of the 2N application rate of dimethenamid-P when applied on the soil with low CEC (Regosol). In other tested soils, no significant differences between 1N and 2N rates were recorded (Figure 4). In addition, sunflower injury after the application of S-metolachlor (when means are compared within the low CEC group only) and pethoxamid at the 2N rate was significantly greater (5% and 9%, respectively) compared to the 1N rate (0% *versus* 2%) only in soil with the lowest CEC (Figure 4). Phytotoxicity of these herbicides appeared as slight leaf chloroses. The main symptom of flurochloridone phytotoxicity was leaf bleaching, which subsided very quickly. Rather large differences in sunflower injury caused by flurochloridone were recorded between the 1N and 2N application rates in all tested soil types (Figure 4). The sunflower injury after the application of aclonifen and pendimethalin was not affected by application rate in any tested soil type and only slight leaf chloroses were recorded shortly after the application.

Figure 3. Sunflower phytotoxicity caused by dimethenamid-P on Regosol (cation exchange capacity 88 mmol$_+$/kg)

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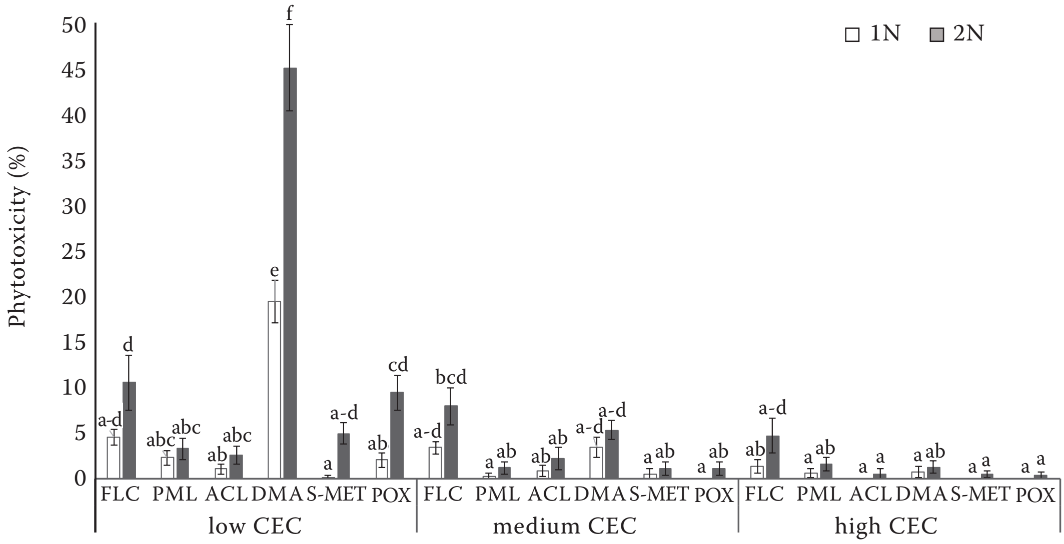

Figure 4. Visual sunflower phytotoxicity of tested herbicides at both tested application rates (1N and 2N) in different soil conditions (low CEC – 88 mmol_+/kg, middle CEC – 168 mmol_+/kg, high CEC– 258 mmol_+/kg); data from the first assessment (BBCH 14) and all experimental years. CEC – cation exchange capacity; 1N – registered application rate; 2N – double application rate; FLC – flurochloridone; PML – pendimethalin; ACL – aclonifen; DMA – dimethenamid-P; S-MET – S-metolachlor; POX – pethoxamid

Sunflower yield. Yield of sunflower achenes was significantly affected by herbicide, soil type and experimental year (Table 4). The main factor influencing yield of sunflower achenes was the level of herbicide efficacy. The highest yields (159–164% compared to untreated plots) were recorded on plots treated by aclonifen, flurochloridone and pendimethalin. Yields were significantly lower (120–128% of untreated plots) on plots treated with dimethenamid-P, pethoxamid and S-metolachlor. The largest differences between yields of plots treated with herbicides and untreated plots (70%) were at the location with Regosol. On the contrary, the lowest effects of herbicide application on sunflower yields (25%) was recorded at the location with Fluvisol.

Similar results were recorded by Olson et al. (2011), who assessed the sensitivity of pyroxasulfone to sunflower. According to Wanjari et al. (2001), weed competition can decrease sunflower yield by as much as 81%, depending on the weed density, time and duration of competition, and weed spectrum. In our study, competition from *C. album* decreased sunflower yields by almost 40%.

Herbicide dissipation from soil. Dissipation of herbicides from the soil was evaluated as the percentage amounts of herbicides remaining in comparison to the applied rate in both soil layers (0–5 cm and 5–10 cm) because different herbicide application rates were used. Thirty days after herbicide applications, 18–75% of the applied herbicide was still detected in the 0–5 cm soil layer (Figure 5). Herbicide degradation in the soil was affected by herbicide, application rate, soil physical and chemical properties (soil type), and weather conditions in experimental years. The weakest persistence was shown in case of dimethenamid-P (40% of the applied rate was detected 30 days after application in the 0–5 cm soil layer). Other tested herbicides showed significantly longer persistence (52–59% of the applied rates). Persistence of the tested herbicides was significantly longer in Fluvisol compared to Regosol and Chernozem. The different dissipation of herbicides in different experimental years was documented also in other studies (Jursík et al. 2013, 2016, Andr et al. 2017). The results obtained suggest that weather conditions, and especially rainfall, play a key role in herbicides behaviour and can have stronger effects than do soil properties.

Persistence of the tested herbicides was significantly shorter at the 1N rate compared to the 2N rate (Table 4). A longer pendimethalin half-life for a doubled application rate was reported by Lin et al. (2007). On the contrary, an insignificant effect of doubled application rate on herbicides dissipation was documented by Tsiropoulos and Miliadis (1998), Kewat et al. (2001) and Jursík et al. (2016). Finally, Kočárek et al. (2016) observed a shorter half-life for pendimethalin when the pendimethalin application rate was doubled.

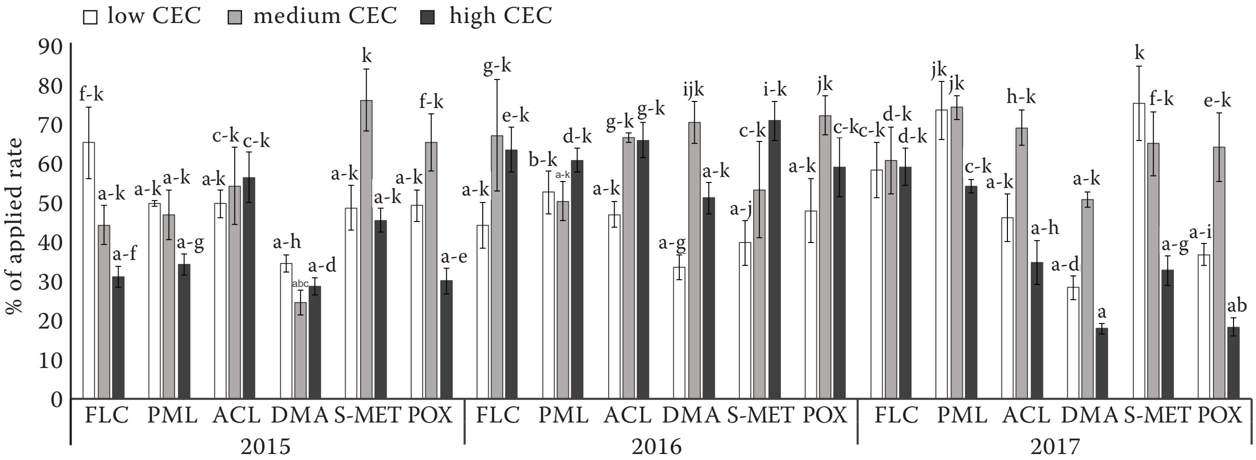

Figure 5. % of applied rate of tested herbicides in soil layer 0–5 cm at registered rate (1N) in different soil conditions (low CEC – 88 mmol$_+$/kg, middle CEC – 168 mmol$_+$/kg, high CEC – 258 mmol$_+$/kg) in all experimental years. CEC – cation exchange capacity; FLC – flurochloridone; PML – pendimethalin; ACL – aclonifen; DMA – dimethenamid-P; S-MET – S-metolachlor; POX – pethoxamid

Vertical soil transport of herbicides. The majority of herbicides was detected within the 0–5 cm soil layer in all tested soils. The percentage amounts of herbicide detected in the 5–10 cm soil layer was used to evaluate the herbicide vertical transport. This was affected by the herbicide, soil type and weather in experimental years. In 2015 and 2016, rather low amounts of herbicides (up to 2% of applied rates) were found in the 5–10 cm soil layer. The greatest vertical transport was recorded for dimethenamid-P and pethoxamid (4% and 6% of the applied rate, respectively) in Regosol in 2017 (Figure 6).

Herbicides transport through the soil profile can cause significant troubles in terms of groundwater contamination (Mueller et al. 1999, Vasilakoglou et al. 2001, Si et al. 2009). Herbicides transport and dissipation is affected mainly by physical and chemical properties of herbicides, soil properties (Kočárek et al. 2010), and weather conditions (Jursík et al. 2013, Andr et al. 2017). Rainfall immediately after the herbicide application affects herbicide behaviour in the soil (Shipitalo et al. 1990, Sigua et al. 1993, Jursík et al. 2013). In our study, pethoxamid and dimethenamid-P showed the greatest leaching potential. According to Dhareesank et al. (2006), pethoxamid has a relatively good environmental profile. Our study showed that pethoxamid and S-metolachlor leaching can occur only on sandy soil with low sorp-

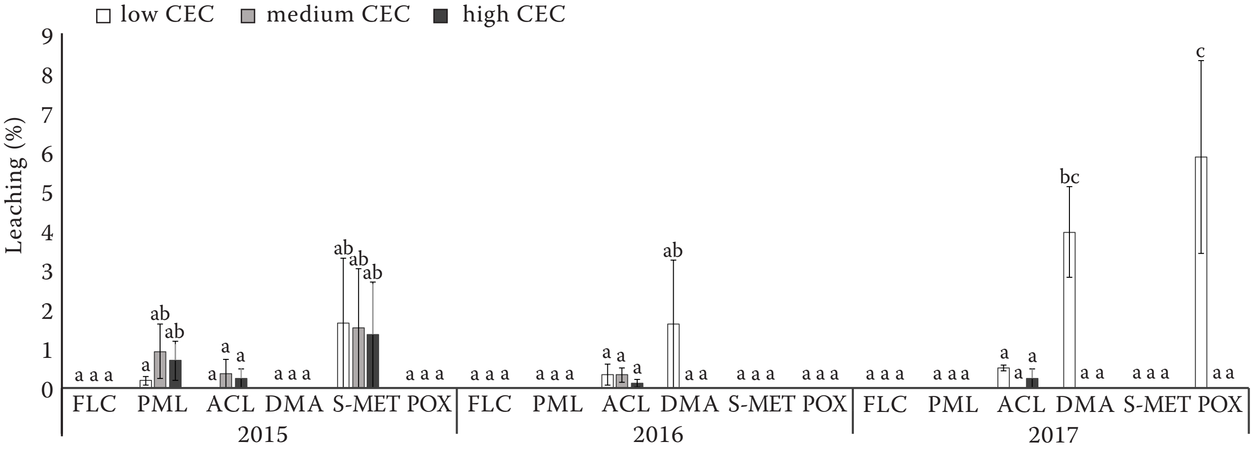

Figure 6. Leaching (% of applied rate in soil layer 5–10 cm) of tested herbicides (at registered rate – 1N) in different soil conditions (low CEC – 88 mmol$_+$/kg, middle CEC – 168 mmol$_+$/kg, high CEC – 258 mmol$_+$/kg) in all experimental years. CEC – cation exchange capacity; FLC – flurochloridone; PML – pendimethalin; ACL – aclonifen; DMA – dimethenamid-P; S-MET – S-metolachlor; POX – pethoxamid

tion capacity (Regosol). On the contrary, according to Inoue et al. (2010), S-metolachlor leaching into groundwater proceeds primarily by macropore flow, which is greater in clay soil than in sandy soil, and it occurs mainly during long dry conditions in spring and summer. Si et al. (2009), on the other hand, recorded a more intensive leaching of S-metolachlor in sandy soils than in clay soils, which is in agreement with our results.

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