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Suppressing *Alopecurus myosuroides* in winter cereals by delayed sowing and pre-emergence herbicides

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Abstract: Delayed sowing of winter cereals in Western Europe is a preventive method to reduce *Alopecurus myosuroides* infestations. Two series of on-farm studies including 36 experiments were conducted in South-Western Germany to analyse the combined effects of delayed sowing and pre-emergence herbicide application on *A. myosuroides* density, weed control efficacy and cereal grain yield. From 2006 until 2009, pendimethalin + flufenacet was applied one week after sowing winter barley and winter wheat. From 2018 until 2020, cinmethylin was used in winter wheat and winter triticale. Densities of *A. myosuroides* in the untreated early sown control plots amounted up to 1 233 plants/m^2. Delayed sowing on average reduced densities by 43%. The mixture of pendimethalin + flufenacet in combination with delayed sowing controlled 87% of the *A. myosuroides* plants and increased cereal grain yields from 6.4 t/ha in the early sown untreated control to 7.9 t/ha. Cinmethylin in combination with delayed sowing resulted in 91% weed control efficacy and increased grain yields from 5.3 t/ha to 8.8 t/ha. Average grain yields of all delayed sowing treatments were 0.7 t/ha higher than in the early sown treatments. Therefore, delayed sowing combined with pre-emergence herbicide application is a cost-effective strategy of integrated weed management (IWM) in winter cereals reducing dependency on post-emergence herbicide use and mitigating the risk of herbicide resistance development.

Keywords: preventive weed control; pest; monotonous crop rotation; cereal yield; blackgrass

European Union directives for Integrated Pest Management (IPM) (2009) prescribe diverse tactics of weed control including preventive methods to reduce the reliance on herbicides, avoid their negative environmental impacts and prevent the evolution of herbicide resistance in weed populations (Mortensen et al. 2012). Riemens et al. (2022) suggested a pro-active strategy of IPM with diverse cropping practices and multiple tactics of weed control. The pro-active approach aims at suppressing problematic weed species such as *Alopecurus myosuroides* Huds. and favour functionally diverse weed communities (Adeux et al. 2019, Moss et al. 2019).

Monotonous crop rotations with high proportions of winter cereals and reduced tillage practices have caused a rapid increase of *A. myosuroides* densities and a dominance of this species in the weed species community in many areas (Lutman et al. 2013, Gerhards et al. 2016). *Alopecurus myosuroides* has been observed to cause up to 50% yield losses (Blair et al. 1999, Zeller et al. 2018, 2021) and has a persistent soil seed bank of approximately 8 years (Moss 1990, Gerhards et al. 2016, Moss 2017). Frequent selection pressure of herbicides with the same mode of action contributed to the evolution of herbicide-resistant populations (Moss et al. 2019). Resistance development was favoured by the annual life cycle, cross-pollination and relatively high seed production of *A. myosuroides* (Moss 1990, 2017, Moss et al. 2019).

Once a herbicide-resistant *A. myosuroides* population has been developed, immense efforts need to be spent to overcome this problem (Gerhards et al. 2016). Studies in the UK and Germany suggested fallows, integration of spring cropping and clover-

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grass leys, inversion tillage, stale seedbed and stubble treatments to manage fields with high infestations of herbicide-resistant *A. myosuroides* (Lutman et al. 2013, Gerhards et al. 2016, Zeller et al. 2018, 2021). However, those measures can reduce the contribution margin up to 22% and often require investments in new machinery (Gerhards et al. 2016). Therefore, farmers hesitate to re-design their cropping systems. They rather try to react to herbicide-resistant weed population with methods that can be easily realised, such as changing the herbicide mode of action, selecting more competitive crop cultivars or delayed sowing of winter cereals, all of which contribute to a reduction of *A. myosuroides* infestations (Lutman et al. 2013, Gerhards et al. 2016).

Delayed sowing of winter cereals in Western Europe can be included in a pro-active IPM strategy to reduce *A. myosuroides* infestation if it was combined with other preventive and direct weed control tactics (Riemens et al. 2022). Sowing winter cereals after mid-October instead of September and early October can reduce *A. myosuroides* emergence by 50% (Melander 1995, Rasmussen 2004, Lutman et al. 2013). But, delayed sowing might also result in higher *A. myosuroides* densities (Melander 1995). The impact of delayed sowing on cereal yield is not clear (Lutman et al. 2013). A Danish study reported about lower grain yields after late sowing, even when this measure was combined with effective herbicides to control annual broadleaved weeds and volunteer oat (Rasmussen 2004). Milder climate conditions over winter in South-Western Germany could proceed with the vegetative development (leaf growth and tillering until BBCH 29) of cereals (Geisler 1983), which provides the basis for higher grain yields. We would therefore assume, that delayed sowing of winter cereals in South-Western Germany would result in equal grain yields as early sown cereals and result in better efficacy of pre-emergence herbicides.

The objectives of this study were to determine the combined effects of late sowing and pre-emergence herbicide application on *A. myosuroides* density, control efficacy and winter cereal grain yield. The hypotheses were that (*i*) delayed sowing reduces *A. myosuroides* densities and (*ii*) increases the efficacy of pre-emergence herbicide against *A. myosuroides*. It was further hypothesised that (*iii*) delayed sowing of winter cereals does not result in lower grain yields than early sowing.

MATERIAL AND METHODS

Experimental sites. Two series of field studies were conducted on winter cereals. Four to ten experiments per season were carried out for the first trial protocol with winter barley and winter wheat from 2006 until 2009 and one to two experiments per season for the second protocol with winter wheat and winter triticale from 2018 until 2020. In total, 36 experiments were included in this study. All experiments were located in South Western Germany in a radius of approximately 50 km around Stuttgart-Hohenheim (48.71°N, 9.19°E). Climatical conditions were similar at all locations. Average monthly temperatures were 1–2.5 °C above the long-term mean during all

Table 1. Average monthly temperatures and precipitation at Ihinger Hof Research Station from September 2005 until August 2009 and from October 2017 until August 2020 and long-term means from 1961 until 1990

Month	Mean temperatures (°C)									
	2005	2006	2007	2008	2009	2017	2018	2019	2020	long-term average
Jan		–2.5	4.4	3.1	–2.1		3.9	–0.9	2.3	–0.4
Feb		–0.4	4.4	3.6	0.2		–2.4	3.5	4.8	0.7
March		2.1	5.3	4.3	4		2.9	6.1	4.7	4.0
April		8.1	12.2	7.5	11.6		12.4	8.6	10.9	7.9
May		13.2	14.1	14.8	14.7		14.9	10.1	11.9	12.2
June		17.4	17.1	17.2	15.9		17.4	18.5	15.5	15.5
July		22	16.9	17.7	17.8		19.9	18.7	18.3	17.5
Aug		14.4	16.4	16.8	18.5		19.6	18.2	19.3	16.8
Sep	14.6	16.3	11.8	11.7			14.8	13.7		13.6
Oct	11	11.9	8.2	9		10.3	10.1	10.8		9.0
Nov	3.8	7.1	3.2	4.4		4.0	4.5	3.9		3.7
Dec	0.1	3.4	0.8	0.5		1.1	2.6	2.7		0.7

*source ("Wetter-bw," 2020)

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seven years (Table 1). In late autumn 2007, 2009 and 2019, precipitation was much lower than the long-term means. Longer periods of droughts were also recorded in the spring of 2007, 2018 and 2020 (Table 2). Experimental sites were characterised by different types of cambisols containing 30–42% clay.

Experimental design. A two-factorial randomised complete block design with three repetitions was realised in all experiments. Plots had a length of 12 m in direction of sowing and a width of 3 m, which corresponds to the working width of the seeder and field plot sprayer. Seedbed was prepared after non-inversion tillage using a chisel plough and a rotor tiller.

The first factor was the sowing date of winter cereals including an early date and a late date at least 10 days after the first sowing (Table 3). The seed rate was slightly adjusted to the sowing date with 300 seeds/m^2 until 19 October, 320 seeds/m^2 between 20 October until 31 October and 350 seeds/m^2 after 31 October to achieve the same number of heads/m^2 as later sowing decreases the number of heads per plant. Seed rate was not included as a factor in the analysis because it was assumed that seed rate had no effect on *A. myosuroides* densities until the end of tillering in spring.

The second factor was the weed control method against *A. myosuroides* in winter cereals including a pre-emergence application of 4 L/ha Malibu® (60 g/L flufenacet + 300 g/L pendimethalin, EC, BASF) from 2006 until 2009 and 0.66 L/ha Luxinum® (750 g/L cinmethylin, BASF) from 2018 until 2020 and untreated control. Both herbicides were applied at the label rate four to 7 days after sowing with a plot sprayer (Schachtner-Gerätetechnik, Ludwigsburg, Germany). The sprayer was calibrated for a volume of 200 L/ha and a speed of 3.6 km/h. Nozzles with a spray rate of 0.8 L/min at 3 bar pressure were used. Broadleaved weed species were controlled in all plots with synthetic auxins (800 g a.i. (active ingredient)/ha 2,4-D or 600 g a.i./ha MCPA) in spring.

Assessments. The density of *A. myosuroides* was measured approximately 45 and 120 days after sowing (DAS). The first date corresponds to the end of the vegetation period in the year of sowing and the second date represents the end of tillering in spring (re-growing). *A. myosuroides* plants were counted within a 0.1 m^2 frame randomly placed four times in each plot. The measurements were multiplied by 10 to determine density/m^2. Average densities/m^2 per plot were analysed. Weed control efficacy (WCE) was calculated according to Eq. 1:

$$WCE = 100 \times (1 - w_t/w_u) \quad (1)$$

where: w_t – density of weeds in the treated plots and w_u – density of weeds in untreated control plots. Grain yields were measured in a 1.5 m × 12 m strip in the centre of each plot with a plot harvester (Wintersteiger, Elite 3, Ried im Innkreis, Austria). Grain water content was measured for each plot. Grain weights were then related to a homogenous water content of 14%.

Table 2. Average monthly precipitation at Ihinger Hof Research Station from September 2005 until August 2009 and from October 2017 until August 2020 and long-term means from 1961 until 1990

Month	Mean precipitation (mm)								
	2005	2006	2007	2008	2009	2017	2018	2019	2020	long-term average
Jan		11.4	48.6	39.3	27.1		89.0	45.6	11.2	50.0
Feb		26.4	68.7	20.5	37.9		19.4	13.1	88.2	45.0
March		59.8	49.6	64.4	47.6		21.2	47.1	49.7	51.3
April		62.8	0.6	102.6	28.9		17.4	26.7	4.8	60.1
May		69.1	103.5	101	124.1		75.1	107.2	45.6	80.1
June		32.6	107.2	92.5	63.4		32.5	52.2	85.4	92.6
July		56.7	68.7	56.8	174.9		32.0	53.9	15.3	67.5
Aug		137.7	64.3	99.1	81.6		28.8	82.4	11.2	73.6
Sep	41.5	50.1	47.6	70.2		5.8	78.0	28.4		57.2
Oct	31.5	73.6	6.7	96.7		51.1	26.4	53.6		45.2
Nov	25.7	22.1	62.6	23.4		63.0	19.5	43.4		62.0
Dec	28.6	21.7	53.1	27.4		32.5	83.9	37.4		53.3

*source ("Wetter-bw," 2020)

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Table 3. Experimental details of the field experiments

Exp.	Location	Crop	Previous crop	Year	Sowing dates	
					early	late
1	Hohenheim	winter barley	winter wheat	2005	19 Sept.	27 Sept.
2	Schw. Hall	winter barley	winter wheat	2005	20 Sept.	30 Sept.
3	Altheim	winter barley	winter triticale	2005	13 Sept.	23 Sept.
4	Weikersheim	winter barley	spring barley	2005	20 Sept.	30 Sept.
5	Elztal	winter barley	winter wheat	2005	10 Sept.	20 Sept.
6	Hohenheim	winter wheat	sugar beet	2005	06 Oct.	16 Oct.
7	Sigmaringen	winter wheat	spring oats	2005	11 Oct.	25 Oct.
8	Bittelborn	winter wheat	oilseed rape	2005	09 Sept.	30 Sept.
9	Reubach	winter wheat	winter wheat	2005	18 Sept.	18 Oct.
10	Weldingfelden	winter wheat	oilseed rape	2005	27 Sept.	10 Oct.
11	Schw. Hall	winter barley	winter triticale	2006	21 Sept.	11 Oct.
12	Dallau	winter barley	winter wheat	2006	14 Sept.	27 Sept.
13	Altheim	winter barley	winter triticale	2006	11 Sept.	21 Sept.
14	Hohenheim	winter barley	winter wheat	2006	18 Sept.	28 Sept.
15	Schw. Hall	winter wheat	winter wheat	2006	18 Sept.	18 Oct.
16	Rohrdorf	winter wheat	oilseed rape	2006	29 Sept.	10 Oct.
17	Waibstadt	winter wheat	oilseed rape	2006	30 Sept.	18Oct.
18	Hohenheim	winter wheat	peas	2006	25 Sept.	13 Oct.
19	Schw. Hall	winter barley	winter wheat	2007	25 Sept.	11 Oct.
20	Hohenheim	winter barley	winter wheat	2007	14 Sept.	01 Oct.
21	Schw. Hall	winter wheat	oilseed rape	2007	20 Sept.	20 Oct.
22	Westernach	winter wheat	winter wheat	2007	06 Oct.	20 Oct.
23	Hohenheim	winter wheat	peas	2007	01 Oct.	16 Oct.
24	Schw. Hall	winter barley	winter triticale	2008	24 Sept.	14 Oct.
25	Dallau	winter barley	winter wheat	2008	17 Sept.	30 Sept.
26	Altheim	winter barley	winter triticale	2008	10 Sept.	22 Sept.
27	Unterifflingen	winter wheat	oilseed rape	2008	27 Sept.	–
28	Stuttgart	winter wheat	spring oats	2008	10 Oct.	–
29	Poppenhausen	winter wheat	oilseed rape	2008	06 Oct.	–
30	Hohenheim	winter wheat	faba bean	2008	29 Sept.	–
31	Rottweil	winter wheat	maize	2008	28 Sept.	–
32	Schw. Hall	winter wheat	oilseed rape	2008	26 Sept.	–
33	Renningen	winter wheat	maize	2017	19 Oct.	04 Dec.
34	Renningen	winter triticale	winter wheat	2018	08 Oct.	10 Nov.
35	Entringen	winter triticale	winter wheat	2018	25 Sept.	25 Oct.
36	Renningen	winter wheat	winter wheat	2019	08 Oct.	31 Oct.

240 g/ha flufenacet + 1 200 g/ha pendimethalin* were applied from 2005 until 2009 and 500 g/ha cinmethylin** were sprayed from 2017 until 2020. *Malibu®(60 g/L flufenacet + 300 g/L pendimethalin, EC, BASF); **Luxinum® (750 g/L cinmethylin, BASF)

Statistical analysis. For data analysis, the statistical software R (version 3.6.2, RStudio Team, Boston, USA) was used. Prior to ANOVA, the data were checked for homogeneity of variance and normal distribution of residuals. If necessary, data were square-root transformed to homogenise variances and normalise the distribution. In the figures, back-transformed means are shown. In the ANOVA, sowing date, herbicide treatment and crop were included as fixed effects. Locations were taken as random effects. Multiple

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mean comparison tests were performed using the Tukey *HSD* (honestly significant difference)-test at a significance level of α ≤ 0.05. The relation between weed density and relative yield loss was estimated with a non-linear regression model proposed by Cousens (1985).

$$Y_L = \frac{Id}{1 + \frac{I}{A}d} \quad (2)$$

where: Y_L – relative yield loss; d – weed density; I – yield loss per unit of weed parameter for $d \rightarrow 0$ and A – maximum yield loss.

RESULTS

The crop (P = 0.082), previous crop (P = 0.1034), year (P = 0.1786) and location (P = 0.1242) had no significant effect on weed density and grain yield. Therefore, data were pooled over all crops, previous crops, years and locations. Significant interactions of sowing date and weed control (P < 0.01) were calculated for the measured parameters of weed density and grain yield, with the lowest densities and highest yield in the pre-emergence herbicide plots after delayed sowing and the highest densities and lowest yields in the early sown control plots.

Densities of *A. myosuroides* in the untreated early sown plots amounted to 355 plants/m^2 (2006–2009) and 400 plants/m^2 (2018–2020). Densities were lowest for the combination of pre-emergence herbicide after delayed sowing with 16 plants/m^2 for the trials with flufenacet + pendimethalin (Figure 1) and 9 plants/m^2 for the experiments with cinmethylin (Figure 2). Average densities were more than threefold higher when pre-emergence herbicides were applied after early sowing. Delayed sowing in the untreated control plots reduced average *A. myosuroides* densities by 52% in the 2006–2009 experiments and 34% in the 2018–2020 experiments (Figures 1 and 2).

Efficacy of pre-emergence herbicide was not affected by sowing date (P = 0.36). Efficacy of flufenacet + pendimethalin on *A. myosuroides* was 85.4% (standard error (SE) = 3.2) after early sowing and 86.7% after late sowing (SE = 4.8). Efficacy of cinmethylin was 85.5% (SE = 11.1) after early sowing and 91.1% (SE = 7.9) after late sowing. However, the efficacies of both herbicides on *A. myosuroides* varied between locations and years (P < 0.01). Flufenacet + pendimethalin efficacy varied between 92.4% in 2006 and 79.7% in 2007. Efficacy of cinmethylin was significantly lower (in 2020 than in 2018 and 2019 (Figure 3). The lowest efficacies were observed in 2007, 2009 and 2020, which had also the lowest precipitations in late autumn.

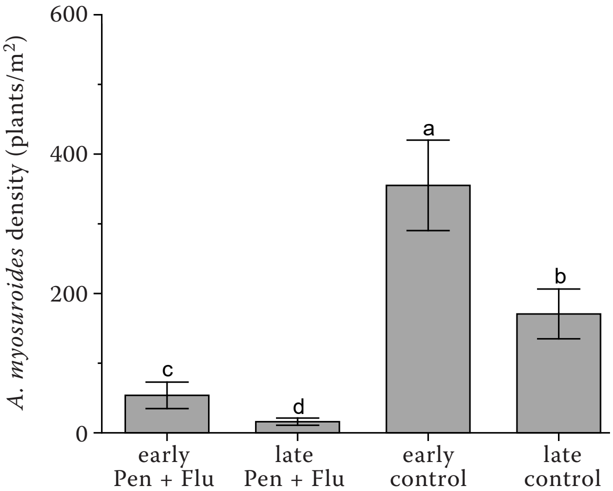

Figure 1. Average *Alopecurus myosuroides* density approximately 120 days after sowing in relation to weed control with pre-emergence herbicides and sowing date for 32 experiments in Baden-Württemberg in winter wheat and winter barley from 2006 until 2009. Bars represent the standard error of the mean. Means with the same letter are not significantly different according to Tukey *HSD* (honestly significant difference)-test at P ≤ 0.05; Pen + Flu – pendimethalin + flufenacet

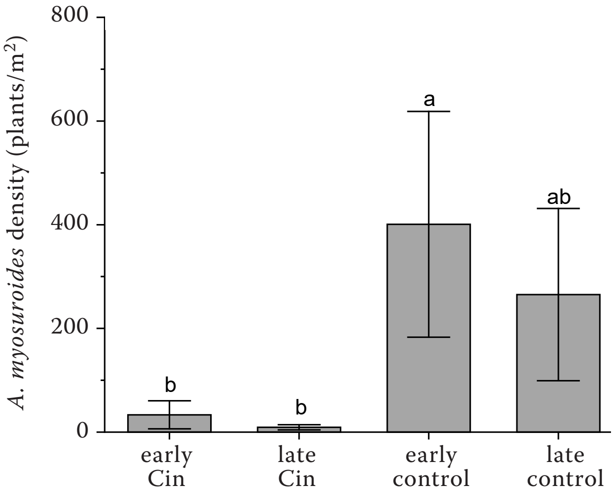

Figure 2. Average *Alopecurus myosuroides* density approximately 120 days after sowing in relation to weed control with pre-emergence herbicides and sowing date for four experiments in winter wheat at Ihinger Hof in 2018 and 2020 and winter triticale at Ihinger Hof and Entringen in 2019. Bars represent the standard error of the mean. Means with the same letter are not significantly different according to Tukey *HSD* (honestly significant difference)-test at P ≤ 0.05; Cin – cinmethylin

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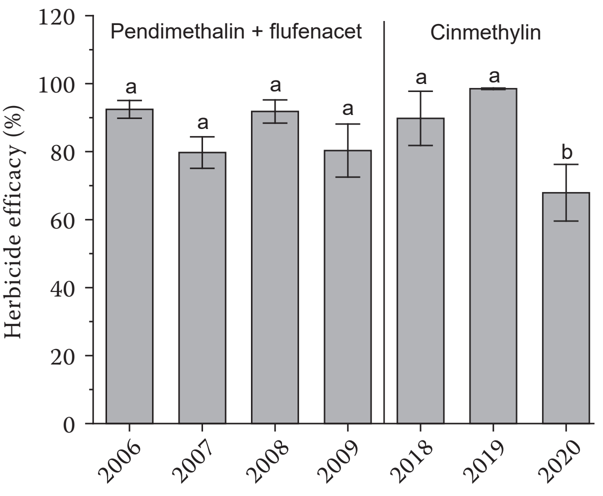

Figure 3. Average efficacy (%) of pendimethalin + flufenacet on *Alopecurus myosuroides* in winter wheat and winter barley in 2006–2009 and average efficacy (%) of cinmethylin on *Alopecurus myosuroides* in winter wheat and winter triticale in 2018–2020. Bars represent the standard error of the mean. Means with the same letter are not significantly different according to Tukey *HSD* (honestly significant difference)-test at $P \leq 0.05$

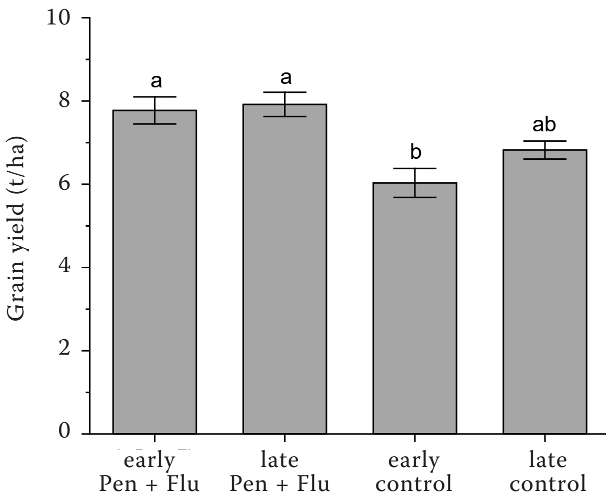

Figure 4. Average grain yield (t/ha) in relation to weed control with pre-emergence herbicides and sowing date for 32 experiments in Baden-Württemberg in winter wheat and winter barley from 2006 until 2009. Bars represent the standard error of the mean. Means with the same letter are not significantly different according to Tukey *HSD* (honestly significant difference)-test at $P \leq 0.05$; Pen + Flu – pendimethalin + flufenacet

Treatments with pendimethalin + flufenacet after delayed sowing resulted in the highest average grain yields of 7.9 t/ha compared to 6.4 t/ha for the early sown untreated control. On average, pendimethalin + flufenacet treatments increased winter cereal yields by 23%. Similar results were measured for cinmethylin with the highest grain yield of 8.8 t/ha in the treatment with cinmethylin after late sowing compared to only 5.3 t/ha in the early sowing untreated control. On average, cinmethylin treatments increased winter cereal yields by 32% (Figures 4 and 5).

The hyperbolic function by Cousens (1985) predicted 14% grain yield losses for *A. myosuroides* densities of 100 plants/m^2 and a maximum 47% yield loss at densities of more than 1 000 plants/m^2 (Figure 6).

DISCUSSION

Delayed sowing of winter cereals resulted in 43% lower *A. myosuroides* densities when averaged over all 36 experiments, even though in some experiments there was only a 10 days delay between the first and second date of sowing. This agrees with previous studies (Hakansson 2003, Lutman et al. 2013) with approximately 50% less *A. myosuroides* seedlings after late sowing. Weed suppression was explained by the seasonal variation of germination of *A. myosuroides.* The germination rate increases until late September before seeds partly fall into secondary

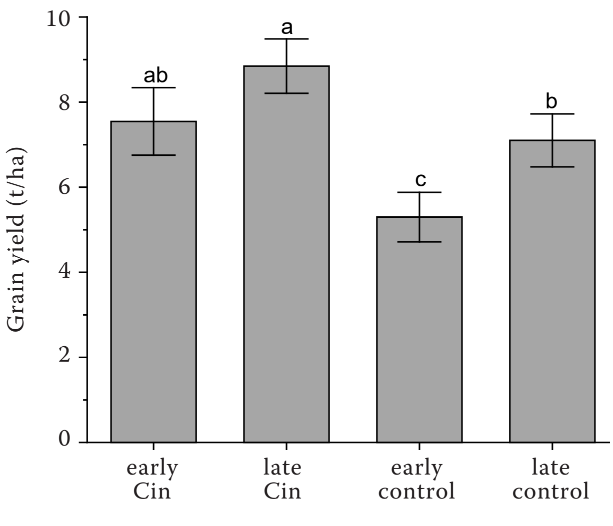

Figure 5. Average grain yield (t/ha) in relation to weed control with pre-emergence herbicides and sowing date for four experiments in winter wheat at Ihinger Hof in 2018 and 2020 and winter triticale at Ihinger Hof and Entringen in 2019. Bars represent the standard error of the mean. Means with the same letter are not significantly different according to Tukey *HSD* (honestly significant difference)-test at $P \leq 0.05$; Cin – cinmethylin

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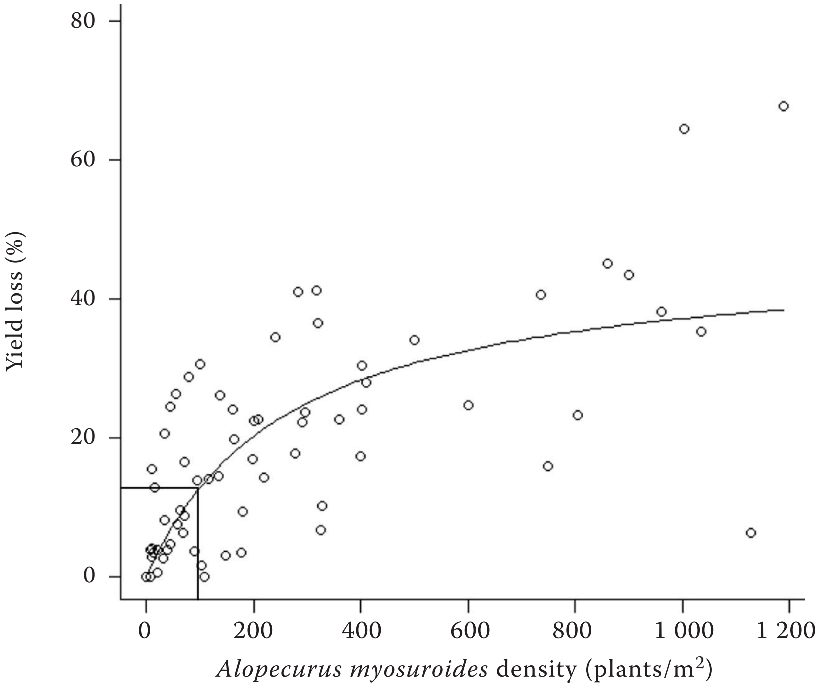

Figure 6. Relationship between *Alopecurus myosuroides* density and grain yield loss based on the hyperbolic model of Cousens (1985) in 36 field experiments in winter cereals; maximum yield loss (A) = 47.1, yield loss per unit of weed parameter for $d \rightarrow 0$ (I) = 0.18

dormancy in late autumn. If seedbed preparation and sowing occur in late September, more *A. myosuroides* seeds can germinate and emerge (Moss 1990, 2017). Delayed sowing suppressed *A. myosuroides* in almost all 36 experiments. This contradicts to Melander (1995), who observed less *A. myosuroides* plants after delayed sowing in one year and higher densities in the second year of study. Delayed sowing of winter cereals in the present study hardly caused any additional costs for farmers, if soils do not get too moist for soil cultivation.

Besides lower *A. myosuroides* densities, efficacies of pendimethalin + flufenacet and cinmethylin after late sowing remained on the same level as for the early sowing treatments. Those positive effects were also pointed out by Moss et al. (2019). Messelhäuser et al. (2021) observed higher efficacies of cinmethylin after delayed sowing in winter wheat and winter triticale in similar experiments in adjacent field sites from 2018 until 2020. Usually, pre-emergence herbicides such as flufenacet, pendimethalin, prosulfocarb and diflufenican and combinations of those without any additional preventive weed control method controlled a maximum of 80% of *A. myosuroides* plants until early spring (Bailly et al. 2012, Menne et al. 2012, Menegat and Nielsson 2019, Messelhäuser et al. 2021).

In the present study, pre-emergence herbicide efficacy was higher when it was combined with late sowing compared to early sowing. Weed densities after delayed sowing and pre-emergence application were below the economic weed threshold of 20–30 plants/m^2 for *A. myosuroides* with 16 plants/m^2 for pendimethalin + flufenacet (87% efficacy) and 9 plants/m^2 for cinmethylin (91% efficacy) (Gerowitt and Heitefuss 1990). Therefore, additional weed control methods were not needed after delayed sowing and pre-emergence herbicide use.

Reduced reliance on post-emergence herbicides decreases the risk for *A. myosuroides* to evolve resistance to herbicides (Moss et al. 2019). Herbicide resistance in *A. myosuroides* populations is a serious problem for weed management in Western Europe. Resistant populations of *A. myosuroides* against almost all herbicide modes of action have been found in Western Europe. More populations were resistant to post-emergence herbicides inhibiting the photosystem II, acetyl CoA carboxylase and acetolactate synthase than to pre-emergence herbicides (Drobny et al. 2006, Délye et al. 2007, Menne et al. 2012, Menne and Hogrefe 2012, Bailly et al. 2012, Heap 2014). The results of the present study showed that the integration of delayed sowing could replace an additional post-emergence herbicide and therefore reduce the selection of herbicide-resistant weed population. Previous studies in the UK and Germany showed that other preventive methods can also be very efficient in suppressing *A. myosuroides* and preventing herbicide resistance. Growing of spring

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crops reduced *A. myosuroides* densities by up to 88%, inversion tillage by 69% and competitive crop cultivars or increased crop density by up to 40% (Moss and Clarke 1994, Lutman et al. 2013, Zeller et al. 2018, 2021). Cover cropping, non-selective herbicide application on the stubble and stubble tillage suppressed *A. myosuroides* densities in the fall-to-spring season by more than 90% (Schappert et al. 2018). However, similar to post-emergence harrowing and hoeing, efficacies of those preventive methods can also be lower than 30% under unfavourable conditions, whereas the efficacy of herbicides was more stable (Zeller et al. 2021).

Farmers are concerned about weather-related risks of delayed cultivation and sowing in autumn, especially on soils with high clay contents. The Danish study showed lower grain yields after late sowing compared to early sowing (Rasmussen 2004). However, this effect could not be observed in the present study. On contrary, yields after late sowing were slightly higher than in the early seeded plots, especially when delayed sowing was combined with the application of a pre-emergence herbicide. This might be explained by different climatical conditions between Denmark and South-Western Germany during autumn and winter. In South-Western Germany, winter cereals usually find more suitable conditions for leaf development and tillering from late October until March than in Denmark. Therefore, winter cereals can produce more tillers after delayed sowing in South-Western Germany before vernalisation and days with long sunlight induce the generative growth stages of winter cereals. The formation of strong tillers during autumn and winter is essential for yield production. It can only partly be compensated by higher seed rates (Geisler 1983). Therefore, the risk of yield depression due to delayed sowing is lower in Southern Germany than in Northern parts of Europe.

Combining pre-emergence herbicides with delayed sowing can be considered a cost-effective and sustainable weed management approach with efficient use of the applied herbicides.

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