Influence of Sowing Date of Winter Cereals on the Efficacy of Cinmethylin on Alopecurus myosuroides (Huds.)

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Abstract: Cinmethylin, a pre-emergent applied active ingredient, inhibits the fatty acid thioesterase and offers a new option in the chemical control of Alopecurus myosuroides, one of the most problematic weeds in arable farming in Europe. It was assumed that with the delayed sowing of winter wheat and winter barley due to more humid and cooler conditions, the efficacy of cinmethylin against A. myosuroides increases. Four field trials were conducted in Southwestern Germany from 2019 to 2022. From mid-September until early November, winter wheat and winter barley were sown in at four dates each year, with intervals of fourteen days. After each sowing, 500 and 250 g cinmethylin ha⁻¹ were applied subsequently to winter wheat and winter barley, respectively. Flufenacet (240 g ha⁻¹) served as a comparison in both crops. A herbicide efficacy of over 90% was achieved for winter wheat sown in mid-October, while it was only 70% for winter wheat sown in mid-September. Similar results were observed for winter barley. On average, cinmethylin achieved a significantly higher efficacy in winter wheat than flufenacet. The presented approach with cinmethylin and delayed sowing date provides a basis for the comprehensive control of A. myosuroides. However, further measures of integrated weed management (crop rotation, situational ploughing, and stale seedbed) need to be applied for 100% control.

Keywords: blackgrass; mode of action; integrated weed management; pre-emergence herbicide; herbicide efficacy

1. Introduction

The central aim of arable farming is the supply of plant products. In order to achieve the site-specific yield potential, disturbances such as plant diseases, insect pests, and weeds must be controlled. Weeds in particular cause the highest potential loss of 34% on average compared to plant diseases and insect pests [1]. To prevent yield loss caused by weeds, herbicides are the most efficient and, especially in industrial nations, the most economical method.

After the introduction of the first selective and synthetic herbicides in the 1940s, labor-intensive and inefficient weed control measures were substituted in many indications [2]. However, only a few years after the successful introduction of synthetic herbicides, resistance has already been identified [3], cited in [4]. With the introduction of further herbicides with different mode of actions, resistant biotypes of different species were detected, whereby the duration between the introduction of the herbicide and the detection of resistance differed. Especially grass weeds, which represent 32% of all herbicide-resistant species registered so far [5], constitute a challenge in weed control. One of the most widespread weed grasses in Europe is Alopecurus myosuroides (Huds.). Many regions show a high occurrence of this grass. Densities of A. myosuroides increase due to the economically driven extensive cultivation of winter crops in the crop rotation, as well as early sowing dates and reduced tillage [6].
Generally, the diploid, allogamous, and wind-pollinated grass has a high potential to reduce the yield of winter wheat and other winter crops. A density of *A. myosuroides* at 100 plants m\(^{-2}\) can reduce the winter wheat yield by up to 50% [7,8]. Compared to other weed species, the persistence of the seeds of *A. myosuroides* is relatively low. Under arable conditions, the soil seed bank decreases annually by up to 80% [9]. Nevertheless, high seed production (more or less than 500 viable seeds per plant (reviewed in [10])) results in a risk of high soil seed potential and associated pressure on the subsequent crop. Therefore, high level of control against *A. myosuroides* should be achieved.

So far, the focus of *A. myosuroides* control has been mainly on the use of post-emergence herbicides belonging to the acetyl-coenzyme A carboxylase (ACCase, HRAC group 1) and acetylacetate synthase (ALS, HRAC group 2) inhibitors. The first proven resistance of *A. myosuroides* was in the United Kingdom in 1982 [11]. Since then, target-site-based resistance (TSR) and non-target-site-based resistance (NTSR) in *A. myosuroides* against different modes of action have spread across Europe [12-14]. Additionally, cross- and multiple herbicide-resistant biotypes were observed, with cases accumulating in recent years [15].

The frequently inadequate efficacy of post-emergence herbicides increases the pressure on pre-emergence herbicides, which are seen as the last option for chemical control in cereals at several sites. The example of flufenacet (HRAC group 15) illustrates the increasing dependence on the few still effective active ingredients. The total amount of flufenacet used in winter wheat has (almost) doubled from 2011 to 2019 in Germany (2011: 129,000 kg per year, 2019: 248,000 kg per year) [16]. Such an increase consequently leads to higher selection pressure and the associated occurrence of resistant biotypes. For flufenacet, higher expression levels of several glutathione transferases confer NTSR in *A. myosuroides* [17]. However, the introduction of an active ingredient with a different mode of action would reduce the selection pressure of herbicides that are already on the market.

Cinmethylin, a benzyl-ether, which was used for grass–weed control in transplanted rice in Asia [18], inhibits the fatty acids thioesterase (HRAC group 30) [19]. Furthermore, it is characterized by a high selectivity in cereals and high efficacy against multi-herbicide-resistant *Lolium rigidum* L. [20] and *A. myosuroides* [21]. Cinmethylin has been approved in the UK since June 2022 [22], and the approval process is currently in progress in the EU. Properties of cinmethylin are characterized in Table 1. Such an active ingredient provides the opportunity to reduce the selection pressure of actual available active ingredients and also offers control of resistant biotypes due to the different mode of action.

### Table 1. Characterization of the properties of cinmethylin [23].

<table>
<thead>
<tr>
<th>Property</th>
<th>Unit</th>
<th>Cinmethylin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solubility in water (20 °C)</td>
<td>mg L(^{-1})</td>
<td>58.0</td>
</tr>
<tr>
<td>Dissociation constant (25 °C)</td>
<td>mPa</td>
<td>Not available</td>
</tr>
<tr>
<td>Vapor pressure</td>
<td>d</td>
<td>8.1</td>
</tr>
<tr>
<td>Dissipation time 50 (field)</td>
<td>d</td>
<td>22.4</td>
</tr>
<tr>
<td>Dissipation time 90 (field)</td>
<td>d</td>
<td>111.5</td>
</tr>
<tr>
<td>Koc (soil adsorption)</td>
<td>d</td>
<td>6850</td>
</tr>
</tbody>
</table>

The efficacy of cinmethylin as a pre-emergence herbicide depends mainly on the soil moisture at the time of application. Under central European weather conditions, it can be assumed that the efficacy of cinmethylin against *A. myosuroides* increases in late autumn, due to the higher amounts of precipitation and the lower temperatures. Therefore, the objective of this study was to determine the influence of the sowing date of winter wheat and winter barley on the efficacy of cinmethylin applied in pre-emergence. Fields with different infestation degrees and resistance levels (against post-emergence herbicides) of *A. myosuroides* were available for this study. The following hypotheses were tested: (i) With delayed sowing, the efficacy of cinmethylin and the flufenacet against *A. myosuroides*
increases, (ii) the combination of delayed sowing and pre-emergence herbicides offers an approach for comprehensive *A. myosuroides* control.

2. Materials and Methods

2.1. Experimental Design

Four field trials were conducted between the winter cereal growing periods 2019/2020 and 2021/2022 at the two sites, Bingen (49°58′ N 7°54′ E) and Waldalgesheim (49°95′ N 7°83′ E), Germany (Table 2). Both sites are characterized by extensive cultivation of winter crops such as winter cereals and winter oilseed rape. Furthermore, the low precipitation during the vegetation season (average annual precipitation: 490 l m⁻²) encourages farmers to reduce tillage. These aspects led to an increased spread of *A. myosuroides* in this arable region.

<table>
<thead>
<tr>
<th>Field Trial</th>
<th>Site</th>
<th>Vegetation Season</th>
<th>Previous Crop</th>
<th>Soil Type</th>
<th>OM (LOI %)</th>
<th>pH-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bingen</td>
<td>2019/20</td>
<td>Lupine</td>
<td>Sandy loam</td>
<td>2.1</td>
<td>6.9</td>
</tr>
<tr>
<td>2</td>
<td>Bingen</td>
<td>2020/21</td>
<td>Wheat</td>
<td>Loam</td>
<td>2.0</td>
<td>6.6</td>
</tr>
<tr>
<td>3</td>
<td>Waldalgesheim</td>
<td>2020/21</td>
<td>Wheat</td>
<td>Loam</td>
<td>2.2</td>
<td>7.6</td>
</tr>
<tr>
<td>4</td>
<td>Bingen</td>
<td>2021/22</td>
<td>Maize</td>
<td>Loam</td>
<td>2.3</td>
<td>7.5</td>
</tr>
</tbody>
</table>

(OM = organic matter, LOI: Loss on ignition).

On the fields in Bingen, there was slight to no infestation with *A. myosuroides*. Therefore, in all trial years at the Bingen site, 2000 *A. myosuroides* seeds m⁻² were sown in the trial fields at the end of August with the plot seeder. For sowing, the *A. myosuroides* seeds were mixed with sterile wheat grains in equal proportions to ensure better transverse distribution of the seed in the seeder. After sowing, the seeds were mixed into the soil layer 0–15 cm with a cultivator. Subsequently, the fields were levelled with a rotary harrow. In Waldalgesheim, additional input of *A. myosuroides* seeds was not necessary, due to high “natural” infestation. The sown as well as the already occurred *A. myosuroides* populations differed in resistance against ACCase- and ALS-inhibitors (Table 3). The resistance characterization follows the classification scheme of Clark et al. [24].

<table>
<thead>
<tr>
<th>Field Trial</th>
<th>Alopecurus myosuroides Population</th>
<th>Resistance Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.2 L ha⁻¹ Axial® 50²</td>
<td>2.5 L ha⁻¹ Focus® Ultra³</td>
</tr>
<tr>
<td>1</td>
<td>Occurred</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Sown</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>Occurred ¹</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Sown</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>Occurred</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Sown</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>Occurred ¹</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Sown</td>
<td>3</td>
</tr>
</tbody>
</table>

¹) Proven TSR ACCase (Ile-1781) and TSR ALS (Trp-574). ²) 50 g pinoxaden L⁻¹, emulsifiable concentrate, supplier: Syngenta Agro GmbH. ³) 100 g cycloxidim L⁻¹, emulsifiable concentrate, supplier: BASF SE. ⁴) 68.3 g pyroxasulam + 22.8 g florasulam kg⁻¹, water dispersible granule, supplier: Corteva Agriscience Germany GmbH. ⁵) 67.5 g propoxycarbazone + 43.8 g mesosulfuron + 90 g mfenpyr kg⁻¹, water dispersible granule, supplier: Bayer CropScience Deutschland GmbH.
The herbicide regime was characterized by pre-emergence active ingredients (Table 4). No post-emergence herbicides were applied to simulate a situation without further options in chemical control. All herbicides were applied with a one-wheel plot sprayer (air mix 120-025 flat fan nozzle, spray pressure 210 kPa, spray volume 200 L ha\(^{-1}\), speed 4.5 km h\(^{-1}\)) with a working width of 2.5 m. The herbicides were applied immediately after sowing the corresponding crop (see Table 5).

Table 4. Used herbicide in winter wheat and winter barley in all field trials.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Treatment</th>
<th>Herbicide (Supplier)</th>
<th>Formulation</th>
<th>Active Ingredient</th>
<th>HRAC Code</th>
<th>Concentration (g L(^{-1}) or kg(^{-1}))</th>
<th>Applied (g a.i. ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter wheat</td>
<td>1</td>
<td>Luxinum(^{®}) (BASF SE)</td>
<td>EC</td>
<td>cinmethylin</td>
<td>30</td>
<td>750</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pico(^{®}) 750 (BASF SE)</td>
<td>WDG</td>
<td>picolinafen</td>
<td>12</td>
<td>750</td>
<td>50.25</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Herold(^{®}) SC (ADAMA)</td>
<td>SC</td>
<td>flufenacet</td>
<td>15</td>
<td>400</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>diflufenican</td>
<td>12</td>
<td>200</td>
<td>120</td>
</tr>
<tr>
<td>Winter barley</td>
<td>1</td>
<td>Luxinum(^{®}) (BASF SE)</td>
<td>EC</td>
<td>cinmethylin</td>
<td>30</td>
<td>750</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pontos(^{®}) (BASF SE)</td>
<td>SC</td>
<td>flufenacet</td>
<td>15</td>
<td>400</td>
<td>144</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Herold(^{®}) SC (ADAMA)</td>
<td>SC</td>
<td>flufenacet</td>
<td>12</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>diflufenican</td>
<td>20</td>
<td>200</td>
<td>120</td>
</tr>
</tbody>
</table>

1) BASF SE, Ludwigshafen am Rhein, Germany; ADAMA Deutschland GmbH, Köln, Germany. 2) EC = emulsifiable concentrate; SC = suspension concentrate; WDG = water dispersible granule. 3) HRAC: Herbicide Resistance Action Committee.

Table 5. Sowing date of winter barley and winter wheat with corresponding precipitation (l m\(^{-2}\)) as well as average temperature (°C) 7 days before and 7 days after sowing.

<table>
<thead>
<tr>
<th>Field Trial</th>
<th>Site</th>
<th>Vegetation Season</th>
<th>Sowing Date</th>
<th>Precipitation (l m(^{-2}))</th>
<th>Average Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7 Days before Sowing (Sum)</td>
<td>7 Days after Sowing (Sum)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7 Days before Sowing</td>
<td>7 Days after Sowing</td>
<td>7 Days before Sowing</td>
</tr>
<tr>
<td>1</td>
<td>Bingen</td>
<td>2019/20</td>
<td>16th September</td>
<td>0.0</td>
<td>20.0 1)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30th September</td>
<td>12.5</td>
<td>17.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15th October</td>
<td>7.0</td>
<td>19.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30th October</td>
<td>2.6</td>
<td>20.0</td>
</tr>
<tr>
<td>2</td>
<td>Bingen</td>
<td>2020/21</td>
<td>23rd September</td>
<td>0.0</td>
<td>15.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5th October</td>
<td>10.1</td>
<td>9.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19th October</td>
<td>2.0</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2nd November</td>
<td>13.4</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>Waldalgesheim</td>
<td>2020/21</td>
<td>23rd September</td>
<td>14.0</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5th October</td>
<td>5.0</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>19th October</td>
<td>4.5</td>
<td>12.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2nd November</td>
<td>0.0</td>
<td>22.0</td>
</tr>
<tr>
<td>4</td>
<td>Bingen</td>
<td>2021/22</td>
<td>21st September</td>
<td>7.7</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5th October</td>
<td>6.2</td>
<td>4.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18th October</td>
<td>3.0</td>
<td>10.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2nd November</td>
<td>10.9</td>
<td>14.8</td>
</tr>
</tbody>
</table>

1) additional irrigation.

Winter barley and winter wheat were sown in a two-week rhythm on four different dates between mid-September and the early November. Depending on the year and location, the weather conditions differed during the study period (Table 5). The usual local period for sowing winter barley is between the middle and end of September, for winter
wheat between the end of September and the middle of October. The seed rate of the hybrid barley variety ‘Wootan’ increased with later sowing dates (150, 175, 280, and 320 grains m⁻²). The same procedure was done for winter wheat (variety ‘RGT Reform’ with 200, 225, 320, and 380 grains m⁻²). Use of winter barley hybrid variety resulted in more flexible sowing time without risk of yield reduction caused by late sowing [25]. According to each sowing date, the seedbed was prepared by a rotary harrow.

In total, sixteen treatments (four sowing dates, two crops, and two different herbicide treatments per crop) were organized in a randomized strip-split-plot design (Figure S1). All treatments were replicated four times. Due to different harvesting times the crops were sown in separated strips. Within the strips, the sowing dates were randomly allocated as main plots. Four sub plots (Bingen: 2.5 × 8 m, Waldalgesheim: 2.5 × 12 m) were arranged randomly per main plot, whereby each sub-plot includes one herbicide treatment for the corresponding crop.

2.2. Data Collection

2.2.1. Assessment of Herbicide Efficacy and *A. myosuroides* Density

Herbicide efficacy was determined for each plot. Therefore, a panel with an area of 1 m² was placed in the middle of the plot before applying the pre-emergence herbicides. After sprouting of *A. myosuroides* (BBCH- (Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie) code 10-12), the number of plants was counted within the covered area (herbicide-untreated) and outside of this area (herbicide-treated). Herbicide efficacy was calculated with following equation:

\[
\text{Herbicide efficacy (%) } = \left( \frac{A - B}{A} \right) \times 100,
\]

whereby \(A\) is the density of *A. myosuroides* in herbicide-untreated areas and \(B\) is the density of *A. myosuroides* in herbicide-treated areas. In spring, *A. myosuroides* heads as well as cereal heads were counted in both areas per plot. Counting of plant density was conducted with a counting frame with an area of 0.25 m².

2.2.2. Determination of Yield

In all field trials, yield was assessed for a core plot. In Bingen, an area of 12 m² (1.5 × 8 m) per plot was harvested, in Waldalgesheim an area of 18 m² (1.5 × 12 m) per plot. A representative sample was taken from each plot to determine the yield at 14% moisture content.

2.3. Statistical Analysis

Statistical analysis was conducted with R (version 4.2.1) [26]. Linear mixed effects models (LMM) were used to explore the responsible variables: herbicide efficacy, density of *A. myosuroides* in autumn as well as spring in herbicide-treated areas, number of cereal heads in herbicide-treated, and untreated areas and yield of the crops. Statistical analysis was done separately for winter barley and winter wheat. For herbicide efficacy, data had to be transformed for LMM with arcsine transformation. Log transformation was used for the data of the density of *A. myosuroides* plants and heads in herbicide-treated areas. The models included two random effects: (1) split-plot of corresponding field trial (nested design); (2) the environment (site and year). Herbicide treatment and sowing date were considered as fixed effects. No significant interactions between the two fixed effects were observed. Variance inflation factor (VIF) was used for checking collinearity among the explanatory variables for all models. The marginal R² and the conditional R² were calculated, whereby the marginal R² represents the percentage of the variance explained by the fixed effects and the conditional R² represents the percentage of the variance of the fixed and random effects [27]. For multiple means comparison, Tukey’s honest significant difference (HSD) post hoc test was conducted with Bonferroni–Holm adjustment.
3. Results

3.1. Herbicide Efficacy and A. myosuroides Density

For the responsible variable herbicide efficacy, both random effects included in the model caused similar variances for winter barley and winter wheat (Table 6). For *A. myosuroides* density (plants and heads), a higher proportion of observed variance was accounted for the random factor environment in winter wheat, whereas in winter barley, the factor split plot explained the higher proportion of variance. Between 13 and 30% percent of the variance could be explained by the fixed effects (marginal $R^2$), while 60 to 79% percent could be explained by random and fixed effects (conditional $R^2$).

Table 6. Summary of crop-specific linear mixed effects models for the responsible variables: herbicide efficacy and *A. myosuroides* density (plants and heads) in herbicide-treated areas.

<table>
<thead>
<tr>
<th>Responsible Variable</th>
<th>Crop</th>
<th>Random Effect</th>
<th>Variance</th>
<th>Standard Deviation</th>
<th>Marginal $R^2$</th>
<th>Conditional $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Herbicide efficacy [%]</td>
<td>barley</td>
<td>Split plot</td>
<td>0.02</td>
<td>0.13</td>
<td>0.131</td>
<td>0.614</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environment</td>
<td>0.02</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>0.03</td>
<td>0.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>wheat</td>
<td>Split plot</td>
<td>0.01</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environment</td>
<td>0.03</td>
<td>0.16</td>
<td>0.224</td>
<td>0.603</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>0.04</td>
<td>0.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>A. myosuroides</em> plants m$^{-2}$ herbicide-treated</td>
<td>barley</td>
<td>Split plot</td>
<td>0.37</td>
<td>0.61</td>
<td>0.255</td>
<td>0.763</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environment</td>
<td>0.94</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>0.61</td>
<td>0.78</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>wheat</td>
<td>Split plot</td>
<td>0.43</td>
<td>0.66</td>
<td>0.275</td>
<td>0.698</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Environment</td>
<td>0.79</td>
<td>0.89</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>0.87</td>
<td>0.93</td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>A. myosuroides</em> heads m$^{-2}$ herbicide-treated</td>
<td>barley</td>
<td>Split plot</td>
<td>0.53</td>
<td>0.73</td>
<td>0.303</td>
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<td>Environment</td>
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</table>

1) arcsine transformation; 2) log transformation.

3.1.1. Occurrence of *A. myosuroides* in Field Trials

In three out of the four environments, the occurrence of *A. myosuroides* plants decreased with delayed sowing in the herbicide-untreated areas (Figure 1). The highest density was found in Bingen in 2020, whereby the levels of infestation were similar between field trials. The number of *A. myosuroides* plants tended to be higher in winter wheat than in winter barley.
Figure 1. Density of *A. myosuroides* plants in herbicide-untreated areas \( [m^{-2}] \) in winter barley and winter wheat depending on the sowing date (Mid-September–End-October) and the field trial (site and year), error bars represent the standard error.

3.1.2. Herbicide Efficacy

With delayed sowing, the efficacy of the pre-emergence herbicides increased regardless of the crop (Figure 2). When the herbicides were applied in mid-October, they reached an average efficacy of 90%. In contrast, only a 70% efficacy was achieved for application in mid-September against *A. myosuroides*, which was significantly lower compared with the later sowing dates. Between the two different herbicide treatments, the treatment with cinmethylin or cinmethylin combined with flufenacet achieved a higher efficacy than a flufenacet-based treatment. With an average higher efficacy of 11% against *A. myosuroides*, 500 g cinmethylin ha\(^{-1}\) differed significantly from the combination of 240 g flufenacet and 120 g diflufenican ha\(^{-1}\) in winter wheat.
Herbicide efficacy against A. myosuroides [%] in winter barley and winter wheat depending on sowing date and used active ingredient(s) (winter wheat: 500 g cinmethylin ha\(^{-1}\), winter barley: 250 g cinmethylin ha\(^{-1}\) + 144 g flufenacet ha\(^{-1}\), both crops: 240 g flufenacet + 120 g diflufenican ha\(^{-1}\)). Error bars represent the standard error, different letters indicate significant differences between sowing date or herbicide treatment (bold letters: winter barley), \(p \leq 0.05\), Tukey-HSD-Test.

3.1.3. A. myosuroides Plants and Heads in Herbicide-Treated Areas

The density of A. myosuroides plants in herbicide-treated areas decreased with later sowing, irrespective of the crop (Figure 3). Even a delay from mid to late September reduced the number of plants by half on average to about 40 plants m\(^{-2}\). Such a decline was observed for winter barley and winter wheat. The density of A. myosuroides differed significantly between the herbicide treatments only in wheat, whereby fewer A. myosuroides plants were counted in cinmethylin treated plots.

A. myosuroides plants in herbicide-treated area [m\(^{-2}\)] in winter barley and winter wheat depending on sowing and used active ingredient(s) (winter wheat: 500 g cinmethylin ha\(^{-1}\), winter
barley: 250 g cinmethylin ha\(^{-1}\) + 144 g flufenacet ha\(^{-1}\), both crops: 240 g flufenacet + 120 g diflufenican ha\(^{-1}\), box = 25% and 75% quartile, bold line = median, error bars = 5th and 95th percentile, black circles illustrate outliers, different letters indicate significant differences between sowing date or herbicide treatment (bold letters: winter barley), \(p \leq 0.05\), Tukey-HSD-Test.

In plots where pre-emergence herbicides were applied in mid or the end of October, fewer \(A.\) myosuroides heads were counted (Figure 4). Although the density of \(A.\) myosuroides was similar in winter barley and in winter wheat in autumn, fewer \(A.\) myosuroides heads were counted in winter barley in spring. The number of heads did not differ significantly between the herbicide treatments in both winter barley and winter wheat.

Figure 4. \(A.\) myosuroides heads in herbicide-treated areas [m\(^{-2}\)] in winter barley and winter wheat depending on sowing and used active ingredient(s) (winter wheat: 500 g cinmethylin ha\(^{-1}\), winter barley: 250 g cinmethylin ha\(^{-1}\) + 144 g flufenacet ha\(^{-1}\), both crops: 240 g flufenacet + 120 g diflufenican ha\(^{-1}\)), box = 25% and 75% quartile, bold line = median, error bars = 5th and 95th percentile, black circles illustrate outliers, different letters indicate significant differences between sowing date or herbicide treatment (bold letters: winter barley), \(p \leq 0.05\), Tukey-HSD-Test.

3.2. Assessment of Density and Yield of Winter Barley and Winter Wheat

The different sites and weather conditions (random effect environment) caused a higher proportion of variation in the density of winter barley than winter wheat, regardless of the area considered (Table 7). Only 22% of the variance could be explained by the fixed effects of the used model for the winter barley density in herbicide-treated and untreated areas. About 65% of the variance in density in the herbicide-untreated areas and 75% of the variance in density in the herbicide-treated areas was explained by fixed and random effects in both crops. Approximately 93% and 84% of the variance for the grain yield of winter barley and winter wheat could be explained by the fixed and random effects, respectively. About 40% of variance was accounted by the fixed effects.
Table 7. Summary of crop-specific linear mixed effect models for the responsible variables, cereal heads (herbicide-treated and untreated areas) as well as the grain yield.

<table>
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<tr>
<th>Responsible Variable</th>
<th>Crop</th>
<th>Random Effect</th>
<th>Variance</th>
<th>Standard Deviation</th>
<th>Marginal R²</th>
<th>Conditional R²</th>
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<tbody>
<tr>
<td>Cereal heads m⁻²</td>
<td>barley</td>
<td>Split plot</td>
<td>898.6</td>
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<td>Cereal heads m⁻²</td>
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<td>Residual</td>
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<td>Grain yield dt/ha</td>
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<td>Split plot</td>
<td>153.2</td>
<td>12.38</td>
<td>0.368</td>
<td>0.926</td>
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<td>Residual</td>
<td>71.2</td>
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</table>

In both crops, a significantly lower density of heads was counted in the plots sown in September, regardless of the herbicide application (Figure 5). The difference in head density between the two areas considered was significantly higher for winter wheat than for winter barley.

![Figure 5](image-url)
indicate significant differences between sowing date or herbicide treatment (bold letters: winter barley), \( p \leq 0.05 \), Tukey-HSD-Test.

A higher grain yield depression for early sowing dates was observed for winter wheat than for winter barley (Figure 6). The lowest yields were harvested from cereals sown in mid-September. For both crops, highest yield was achieved for mid-October sown treatments. The comparison between the herbicide treatments showed no appreciable differences in grain yield for both crops.

![Figure 6](image.png)

**Figure 6.** Grain yield, 86% DM [dt ha\(^{-1}\)] of winter barley and winter wheat depending on sowing date and used active ingredient(s) (winter wheat: 500 g cinmethylin ha\(^{-1}\), winter barley: 250 g cinmethylin ha\(^{-1}\) + 144 g flufenacet ha\(^{-1}\), both crops: 240 g flufenacet + 120 g diflufenican ha\(^{-1}\)), error bars = standard error, different letters indicate significant differences between sowing date or herbicide treatment (bold letters: winter barley), \( p \leq 0.05 \), Tukey-HSD-Test.

4. **Discussion**

The mentioned precarious situation in *A. myosuroides* control forces farmers to exhaust all possibilities for weed control. The presented study offers an approach, which relies on a combination of two components: delayed sowing of winter cereals and the inclusion of an active ingredient with a new mode of action applied in pre-emergence. The results clearly showed that herbicide efficacy of cinmethylin and flufenacet against *A. myosuroides* increases with later application. Therefore, the first hypothesis can be accepted. The higher efficacy with delayed sowing of winter cereals can be explained by two reasons: (i) The delay of sowing resulted in a lower *A. myosuroides* density. The mechanical removal of *A. myosuroides* before sowing and the lower germination rate of *A. myosuroides* at colder temperatures [28] reduced the number of *A. myosuroides* plants to be controlled. In most cases, these conditions result in a higher pre-emergence herbicide efficacy [29]. (ii) Furthermore, the probability for more favorable soil conditions for high efficacy of pre-emergence herbicide increases with late sowing dates in autumn (precipitation in October
Table 5). Nevertheless, the active ingredients in pre-emergence herbicides achieve different efficacies under given soil moisture conditions [30]. For cinmethylin, it was demonstrated on a site with sandy loam that cinmethylin achieved the highest efficacy against species such as Echinochloa crus-galli and Sida spinosa with immediate irrigation on dry soil after application [31].

It is reported that sowing winter wheat after the end of the vegetation period and subsequent application of cinmethylin leads to a reduction in the density of winter wheat plants [21]. It appears that the higher precipitation during the winter months and the resulting greater trickling of the herbicide into the soil affect the germinating winter wheat plants at the beginning of the vegetation season. In consequence, to avoid crop damage to winter cereals, cinmethylin must be applied before the end of the vegetation season in autumn. This fact limits the approach of delayed sowing combined with cinmethylin application in A. myosuroides control.

In winter wheat, cinmethylin was more efficient in the A. myosuroides control than the combination of flufenacet and diflufenican. This observation is in line with the results of previous research [21]. Losses of susceptibility up to resistance to flufenacet are known in some A. myosuroides accessions [17]. However, in most cases, resistance to flufenacet is not responsible for higher cinmethylin efficacy. It is more likely that different interactions with environmental conditions of these active ingredients influenced their efficacy against A. myosuroides.

Higher herbicide efficacy at later sowing dates was associated with a higher yield in both crops. Late sowing of winter wheat also led to a higher yield in other studies when the sites were heavily infested with A. myosuroides [32]. Therefore, the expectation of many farmers that an early sowing date increases the yield needs to be adjusted. This only applies if effective post-emergence herbicides are still available.

However, previous studies proved that pre-emergence herbicides play an important role in the control of A. myosuroides, especially for populations with multiple herbicide-resistant biotypes [33]. Although the delay of sowing significantly improved the herbicide efficacy of pre-emergence herbicides, an absolute control was not achieved. Therefore, the second hypothesis of this study needs to be rejected. It should be considered that the high dependence on soil moisture exacerbates the use of pre-emergence herbicides. Model calculations assume that the expected variable precipitation will cause a decline of the efficacy of pre-emergence herbicides. Using the examples of atrazine, acetochlor, S-metolachlor, and mesotrione, such lower efficacies were predicted for the future [34]. Consequently, additional measures are required for a comprehensive control. The use of herbicide sequences consisting of pre- and post-emergence herbicides could provide a higher efficacy. This only applies if there is no resistance to post-emergence herbicides. Furthermore, a greater use of herbicide sequences or mixtures in the A. myosuroides control is associated with higher levels of generalist resistance mechanisms such as enhanced metabolism of herbicides [35]. For a better control of A. myosuroides, additional cultural practices are needed. Two cultural practices were already integrated in the presented approach: i) delayed sowing, which is considered an effective method for suppressing A. myosuroides [6]; ii) the cultivation of a winter barley hybrid variety. The hybrid barley plants were able to compensate for the lower herbicide efficacy in autumn, which is demonstrated by lower densities of the A. myosuroides heads in winter barley plots. In addition, the density of barley heads was reduced to a lesser extent than in winter wheat without herbicide application (Figure 5). It was shown in a previous study that weed control of Avena fatua L. was influenced by the development of winter barley varieties such as stand height and density [36]. In this study, increasing the seed rate for the delayed-sowing hybrid variety, which is not usually recommended, was an additional method of controlling A. myosuroides. The resulting higher seed costs should be considered as costs for the A. myosuroides control.

In conclusion, the presented data should encourage farmers to implement cinmethylin in an integrated weed management strategy, whereby cultural practices take on a
crucial role. Thereby, the approach of a combination of delayed sowing and pre-emergence herbicides with active ingredients such as cinmethylin or flufenacet represents a basis for such a strategy. Nevertheless, the combination of several cultural practices (situational ploughing, increase of the proportion of summer crops in crop rotation, and conducting stale seedbed [37]) are inevitable for A. myosuroides control.

**Supplementary Materials:** The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy13010037/s1, Figure S1: Used randomized strip-split-plot design in the four trials (stripe: winter wheat or winter barley; split plot: sowing date; sub plot: herbicide treatment).

**Author Contributions:** Conceptualization, B.K. and J.P.; methodology, B.K. and J.P.; validation, B.K. and J.P.; formal analysis, B.K. and J.P.; investigation, B.K.; writing—original draft preparation, B.K.; writing—review and editing, J.P.; visualization, B.K.; supervision, J.P.; project administration, J.P.; funding acquisition, J.P.; All authors have read and agreed to the published version of the manuscript.

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**References**


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