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# Impact of Panicle Cutting and Chaff Milling on the Panicle and Seed Density of Three Grass Weeds and Grain Yield of Winter Wheat

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## ABSTRACT

The grass species *Alopecurus myosuroides* Huds., *Lolium multiflorum* Lam. and *Bromus sterilis* L. are abundant and dominant weeds in European winter wheat fields. They cause significant yield losses and impede grain harvest. Many populations of these grass weeds are resistant to one or more herbicide modes of action in Europe. Therefore, additional non-chemical control measures are needed to suppress these weed species. In this study, grass weed panicle cutting, chaff milling and a combination of both treatments were examined as potential control measures to reduce the entry of grass weed seeds into the soil seed bank. An untreated control and a standard herbicide application served as control treatments. Five field trials in winter wheat were carried out in 2023/2024, two with *A. myosuroides* at the University of Hohenheim (UHOH, Germany) and the Julius Kühn-Institute (JKI, Germany), two with *L. multiflorum* at UHOH and Bavarian State Research Centre for Agriculture (LfL, Germany) and one with *B. sterilis* at the Czech University of Life Sciences (CZU, Czech Republic). For the cutting treatment, panicles of the three grass weeds were cut closely above the winter wheat canopy and removed from the field two times during the vegetation period. As part of the second treatment, winter wheat chaff was collected during or after harvest and processed after harvest with a stationary impact mill. Herbicide efficacy, grass weed panicle density, grass weed seed density and seed germination rate were measured for each treatment. Grain yield was assessed at the time of winter wheat harvest. Cutting above the wheat canopy reduced panicle density of *A. myosuroides* on average by 22%, *B. sterilis* by 47% and *L. multiflorum* panicle density by 63%. At the second date of cutting, almost all panicles of *B. sterilis* were below the wheat canopy. Therefore, only one cut was performed in the field trials at CZU. Post-harvest milling destroyed on average 39% of the *A. myosuroides* seeds, 78% of the *L. multiflorum* seeds and 90% of the *B. sterilis* seeds in the chaff fraction. However, these grass weeds retain only 40%–60% of their seeds on the panicles until harvest, which impedes the efficacy of the treatments. Therefore, the combination of cutting and milling led to a reduction in weed seed density of only 10% for *A. myosuroides*, 63% for *B. sterilis* and 85% for *L. multiflorum*. In conclusion, panicle cutting and chaff milling constitute effective strategies for long-term population control of *L. multiflorum*. The data of a single, non-repeated study show that *B. sterilis* weed seed return can also be reduced with panicle cutting and chaff milling. However, both treatments did not decrease weed competition and yield losses in the year of treatment. Therefore, these measures need to be combined with other preventive and direct weed control measures.

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## 1 | Introduction

Several grass weeds including *Alopecurus myosuroides* Huds., *Lolium multiflorum* Lam. and *Bromus sterilis* L. have become increasingly abundant in European winter cereals during the last decades. This is due to an increasing percentage of winter cereal crops in crop rotations. All three grass weed species predominantly germinate in autumn when winter cereals are sown (Appleby and Brewster 1992; Blair et al. 1999; Andersson et al. 2002; Žďárková et al. 2014; Moss 2017). Spring cropping on the other hand, can reduce *A. myosuroides* densities by up to 88% (Lutman et al. 2013). But already a delayed sowing of winter cereals in late October and November reduced the density of *A. myosuroides* by 43% because some seeds enter dormancy at the end of autumn (Gerhards et al. 2022). The three grass weeds can occur at densities of far more than 100 plants $m^{-2}$ and are therefore highly dominant weeds in winter wheat (Petersen 2006; Lutman et al. 2013; Sønderskov et al. 2020; Zeller et al. 2021). All three grass weed species also favour reduced tillage operations (Massa et al. 2013). Mouldboard ploughing depleted the soil seed bank of winter annual grass weeds and reduced grass weed density by 69% (Renton and Flower 2015; Zeller et al. 2021). Yield losses amount to 60% (Cousens et al. 1988; Zeller et al. 2021). Grass weeds cause additional costs for harvesting due to lodging of the cereal crop. After harvest, cereal grain in infested fields often needs to be dried and cleaned (Stone et al. 1999; Lutman et al. 2013). Many populations of these grass weeds are resistant to one or more herbicide modes of action in Europe (Heap 2025). In addition, stricter pesticide regulations in the European Union have resulted in a lower number of active ingredients being available for chemical control of these grass weed species, further impeding grass weed control and accelerating resistance development. Seeds are often spread by combine harvesters (Gerhards et al. 2022). Therefore, additional preventive and curative measures are needed for sustainable control of these weed species (Riemens et al. 2022).

Besides the above-mentioned preventive methods, mechanical weeding including harrowing and hoeing is the most promising alternative control measure (Rasmussen et al. 2008; Brandsaeter et al. 2012; Gerhards et al. 2020). However, harrowing is less effective against grass weeds and perennial weeds than against annual broadleaved weeds (Melander et al. 2003). Another potential strategy of integrated weed management targets the weed seed return into the soil seed bank (Riemens et al. 2022; Akhter et al. 2023). Panicle cutting and harvest weed seed control theoretically aim to prevent weed seed replenishment of weeds that have not been controlled before because of, for example, the development of herbicide resistance or inefficient direct weed control (Walsh et al. 2013). These methods aim at reducing weed entry into the soil seed bank but do not directly reduce weed competition within the current crop. Those technologies have successfully been implemented and applied in Australian farming systems but have only been partly adapted by European farmers (Walsh et al. 2018; Walsh et al. 2021; Akhter et al. 2023). As part of harvest weed seed control methods, chaff containing the weed seeds is either collected and removed from the field or destroyed by heat or milling during or after combine harvesting (Akhter et al. 2023). These control methods have been shown to be very efficient against weed species that have erect stems and retain high amounts of their seeds until crop harvest such as *Lolium rigidum* Gaudin (Blanco-Moreno et al. 2004) and *Galium aparine* L. (Glasner et al. 2019). Another option for preventing weed seed entry into the soil seed bank is cutting the weed panicles above the crop canopy before seed shatter. This strategy requires an even crop canopy height and that most weed seed panicles are above the crop canopy (Akhter et al. 2023). If a critical amount of weed biomass is removed by the cutting, panicle cutting potentially can also reduce weed competition during the growing season. Different machinery is available for cutting weed panicles above the crop canopy, focusing either on cutting the weeds (e.g., Combcut, Lyckegard; LOP 120, Meneguzzo; Biocut, DHM Engineering) or combining the cutting with the removal of panicles from the fields (e.g., Top Cut Collect, Zürn). Those technologies can provide options for the control of tall growing weeds such as *Lolium* species (Akhter et al. 2023) and *Cirsium arvense* (L.) Scop. (Tavaziva et al. 2019). In Canadian spring wheat and canola, early panicle cutting at panicle emergence reduced seed return of wild oat (*Avena fatua* L.) more than late cutting at the initiation of seed shed (Tidemann et al. 2021). However, little research has been conducted on the response of other grass weeds such as *A. myosuroides* and *B. sterilis* to panicle cutting. Cutting and collecting are necessary for panicles that have already produced mature seeds or that develop mature seeds on the soil. Seeds of *A. myosuroides* and *B. sterilis* usually mature earlier than seeds of *L. multiflorum*. Preliminary field trials in the UK with multiple cutting regimes indicate that the practice can remove nearly 80% of *A. myosuroides* panicles, with efficacy varying by crop variety (Kanomanyanga et al. 2026). Cutting and collecting are necessary for panicles that have already produced mature seeds or in cases where seeds reach maturity on the soil after cutting. Seeds of *A. myosuroides* and *B. sterilis* usually mature earlier than seeds of *L. multiflorum*.

The objectives of this study were to investigate the effects of weed panicle cutting, chaff milling and a combination of both treatments on winter wheat yield and weed seed return of the grass weed species *A. myosuroides*, *L. multiflorum* and *B. sterilis*. The underlying hypotheses were that (i) panicle cutting is more efficient in preventing weed seed return into the soil seed bank than chaff milling, because chaff milling can only affect seeds that are retained on the panicles until harvest. It was further hypothesized that (ii) both treatments are less efficient against the short-growing grasses *A. myosuroides* and *B. sterilis* than against *L. multiflorum* and (iii) panicle cutting and chaff milling have no direct effect on winter wheat grain yield.

## 2 | Materials and Methods

### 2.1 | Experimental Sites

Five field trials were carried out in 2023/2024, two with *A. myosuroides* at the University of Hohenheim (UHOH, Germany) and the Julius Kühn-Institute (JKI, Germany), two with *L. multiflorum* at UHOH and Bavarian State Research Centre for Agriculture (LFL, Germany) and one with *B. sterilis* at the Czech University of Life Sciences (CZU, Czech Republic). Experimental details are given in Table 1.

**TABLE 1** | Description of the field trials including location, target weeds, winter wheat cultivar, seeding rate, experimental treatments and dates of treatments and assessments (dd-mm-yyyy).

| | UHOH | JKI | UHOH | LFL | CZU |
|---|---|---|---|---|---|
| Location | *Ihinger Hof, Renningen*, 48°44′33″ N 8°55′31.1″ E | *Heistpei Jerstedt*, 51°95′43″ N 10°39′12″ E | *Ihinger Hof, Renningen*, 48°44′33″ N 8°55′31.1″ E | *Langenbach Freising*, 48°44′81″ N 8°57′08″ E | *Prague-Suchdol*, 50°08′25″ N 14°22′25″ E |
| Target grass weed | *Alopecurus myosuroides* | *Alopecurus myosuroides* | *Lolium multiflorum* | *Lolium multiflorum* | *Bromus sterilis* |
| Cultivar winter wheat | Patras | RTG-Reform | Patras | Su Jonte | Patras |
| Seeding rate winter wheat | 350 seeds $m^{-2}$ | 390 seeds $m^{-2}$ | 350 seeds $m^{-2}$ | 380 seeds $m^{-2}$ | 360 seeds $m^{-2}$ |
| Sowing date winter wheat | 24-10-2023 | 08-12-2023 | 24-10-2023 | 20-10-2023 | 15-10-2023 |
| Treatments | 1. Untreated control (“Untreated”)<br>2. Herbicide treatment (“Herbicide”)<br>3. Panicle cutting slightly above wheat canopy (“Panicle cutting”)<br>4. Chaff collection and milling after harvest (“Chaff milling”)<br>5. Combination of treatment 3 and 4 (“Cutting + Milling”) | | | | |
| Herbicide application | 25-10-2023[a] | 27-03-2024[b] | 25-10-2023[a] | 30-10-2023[c] | 29-03-2024[d] |
| Herbicide efficacy assessment | 20-03-2024 | 23-04-2023 | 20-03-2024 | 15-03-2024 | 26-04-2024 |
| Panicle cutting | 08-05-2024<br>06-06-2024 | 28-05-2024<br>26-06-2024 | 08-05-2024<br>06-06-2024 | 27-05-2024<br>24-06-2024 | 14-05-2025 |
| Harvest | 31-07-2024 | 12-08-2024 | 31-07-2024 | 05-08-2024 | 12-08-2024 |
| Chaff collection | 31-07-2024 | 12-08-2024 | 31-07-2024 | 12-08-2024 | 23-08-2024 |
| Chaff milling | 14-11-2024 (same day for samples from all sites) | | | | |

[a] 2.5 L $ha^{-1}$ Boxer (800 g $L^{-1}$ prosulfocarb, EC, Syngenta) + 0.5 L $ha^{-1}$ Herold (400 g $L^{-1}$ flufenacet +200 g $L^{-1}$ diflufenican, SC, Bayer CropScience).
[b] 500 g $ha^{-1}$ Niantic (29.2 g $kg^{-1}$ mesosulfuron, 5.6 g $kg^{-1}$ iodosulfuron, 86.6 g $kg^{-1}$ mefenpyr, WG, Life Scientific).
[c] 1.0 L $ha^{-1}$ Quirinus (50 g $L^{-1}$ picolinafen +240 g $L^{-1}$ flufenacet, SC, BASF).
[d] 1.8 L $ha^{-1}$ Avoxa (33.3 g $L^{-1}$ pinoxaden +8.3 g $L^{-1}$ pyroxsulam + Safener, EC, Syngenta).

## 2.2 | Experimental Setup and Design

Winter wheat was sown at an inter-row distance of 12.5 cm in all experiments. Winter wheat cultivars, seeding rates and sowing dates are provided in Table 1. *A. myosuroides* at UHOH was sown together with the winter wheat at a seed rate of 5 kg $ha^{-1}$ and *L. multiflorum* was sown at a seed rate of 25 kg $ha^{-1}$ at UHOH and LFL. At JKI and CZU, the experiments were conducted on fields with natural grass weed infestations. Seedbeds were prepared after stubble tillage using a chisel plough and a rotor tiller at all experimental sites. In all experiments, one-factorial randomised complete block designs with three replicates were realised. The plots were 3 m wide and 10 m long, with the longer side in the sowing direction of the crop. The experiment contained five treatments. An untreated control (Untreated) and a standard grass weed herbicide control (Herbicide) were compared to repeated panicle cutting (Panicle cutting) after grass weed flowering, chaff collection and milling after harvest (Chaff milling), and a combination of both mechanical treatments (Cutting + Milling). Dicotyledonous weed species were controlled with selective herbicides with no activity against grass weeds. All herbicides were applied at the maximum given label rate with a plot sprayer (Schachtner-Gerätetechnik, Ludwigsburg, Germany). The sprayer was calibrated for a volume of 200 L $ha^{-1}$ and a speed of 3.6 km $h^{-1}$.

Panicles were cut twice (only once for *B. sterilis* in CZU) just above the winter wheat canopy in May and in June using a front-cutter (Duplex 275F, Seco, Austria) at UHOH and LFL. At JKI and CZU, panicles were cut by hand. Clipped panicles were collected and removed from the field simulating the use of the Top Cut Collect machine. Winter wheat was harvested with plot harvesters of the respective research stations of the four experimental sites. A strip of 1.5 m × 10 m in the centre of each plot was harvested to determine the grain yield. At UHOH and JKI, the chaff fraction was collected during harvest in a big bag fixed at the back of the combine harvester above the opening for the straw exit. At LFL and CZU, chaff was collected in the grain fraction by turning off the fan of the combine harvester

and removing the sieve for separating grain and chaff. Chaff and grain at LFL and CZU were later separated in a stationary cleaning machine in the laboratory before milling of the grass weed seeds. Chaff was stored in paper bags in a dry and cool room until it was milled.

### 2.3 | Data Collection

Grass weed densities were counted in March/April 2024 using a 0.1 $m^2$ frame. Four random positions were selected per plot for counting. Weed control efficacy (WCE%) was calculated according to Equation (1).

$$WCE\% = 100\% \left(1 - w_a / w_b\right) \quad (1)$$

where $w_a$ is the weed density 28 days after treatment and $w_b$ is the weed density before the treatment in the same plot. It was not differentiated between alive and plants damaged by the herbicide treatment and damaged plants were therefore included in the density counts.

To assess grass weed seed densities in the different treatments, the average number of seeds per panicle was estimated by counting the number of seeds from 50 individual panicles before cutting and averaged over the respective experimental site. These 50 panicles were randomly selected in each plot. Grass weed panicle densities were recorded by counting the number of panicles directly after cutting at three random positions in each plot using a 0.5 m × 0.5 m frame. Seed densities were then calculated based on the panicle densities multiplied by the average number of seeds per panicle.

At each site, 100 grass weed panicles were randomly collected from the cut panicles for a seed germination test. Four weeks after cutting, the seeds were threshed, mixed and then 100 seeds were randomly chosen for the germination test. Four times 25 seeds were placed on filter paper in petri dishes and filled with 8 mL deionised water. The petri dishes were put in the germination chamber at a temperature regime of 15°C during the day and 10°C at night with a 12-h photoperiod. The number of germinated seeds was counted after 14 days.

At winter wheat harvest, winter wheat grain moisture was measured gravimetrically on a sample of 500 g per plot. Winter wheat grain yield per plot was then calculated based on a 14% moisture content. A germination test was conducted with 100 randomly chosen weed seeds from the collected chaff.

Approximately 90 days after harvest, the samples of 500 g chaff from each chaff milling treatment plot of all five field trials (collected as described above) were milled with a stationary hammer mill at UHOH (Gruber, Gaspoltshofen, Typ SK 75, Germany) with 1.5 mm sieves. In the subsequent greenhouse germination bioassay, 50 g milled and 50 g unmilled chaff per plot were carefully distributed on 50 cm × 32 cm plates filled with soil (sandy loam) and watered daily. The germinated grass weed seeds were counted after 28 days. Equation (2) was used to determine the milling control efficacy (MCE%).

$$\mathrm{MCE}\% = 100\% \left(1 - m_a / m_b\right) \quad (2)$$

where $m_a$ is the number of germinated seeds after milling and $m_b$ is the number of germinated seeds without milling in the same plot.

Data on average seed retention rate for the three weed species was taken from different studies assessing the weed seed retention rate at crop harvest. In these studies, a mean retention rate of 33% for *A. myosuroides* seeds (Bitarafan and Andreasen 2020), 62% for *L. multiflorum* seeds (Akgun et al. 2008) and 41% for *Bromus hordeaceus* L. seeds (Glasner et al. 2019, no data were available for *B. sterilis*) were determined at crop harvest.

For the calculation of weed seed return of the chaff milling treatments, seed retention multiplied with the milling control efficacy was subtracted from the seed density.

### 2.4 | Statistical Analysis

The data of *A. myosuroides*, *L. multiflorum* and *B. sterilis* panicle and seed density $m^{-2}$ for the treatments (Untreated, Herbicide, panicle cutting, Chaff milling, Cutting + Milling) after cutting and milling as well as the grain yield data were analysed with the statistical software R (Version 4.1.2.). A linear model fitted the data in the following way:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_k + e_{ijk} \quad (3)$$

where $y_{ijk}$ denotes the observation, μ the general mean and $\alpha_i$ and $\beta_j$ represent the fixed effects of the $i$th treatment and the $j$th point in time (only for panicle cutting), as well as their interactions. The random effects of the block are denoted as $\gamma_k$. The error term $e_{ijk}$ was taken as normally distributed with a mean of zero and a variance of $\sigma^2$. Normal distribution and homogeneity of variance were assessed visually utilising residual plots (fitted vs. residual and q-q-plots) prior to performing an analysis of variance (ANOVA) to test significance of the tested factors. Data on *A. myosuroides* from UHOH and JKI was log-transformed and data on *L. multiflorum* from UHOH was log-transformed, whereas *L. multiflorum* from Freising was cubed prior to further analysis. Pairwise comparisons of treatment means within points in time were afterwards tested ($\alpha = 0.05$) using a Tukey's HSD test. Mean values and standard errors in the manuscript are displayed as back-transformed values. Each site was analysed separately because of interactions between site and treatment.

## 3 | Results

### 3.1 | Weed Density and Weed Control Efficacy

Average grass weed densities across all treatments assessed before the herbicide treatment ranged between 140–243 plants $m^{-2}$ for *A. myosuroides* and 167–433 plants $m^{-2}$ for *L. multiflorum*. Infestation rates of *B. sterilis* were lower with an average of 43 plants $m^{-2}$. The herbicide treatment controlled almost all grass weeds at the experimental sites at the JKI (*A. myosuroides*) and LFL (*L. multiflorum*). Average herbicide weed control efficacy against *B. sterilis* was lower (52% ± 4.3%) than against

**TABLE 2** | Herbicide control efficacy (%), seeds per panicle, grass weed seed germination rates after first panicle cut, second panicle cut and after harvest (%) and seed mortality of chaff milling (MCE%).

| | UHOH | JKI | UHOH | LFL | CZU |
|---|---|---|---|---|---|
| **Target grass weed** | ***A. myo-suroides*** | ***A. myo-suroides*** | ***L. multi-florum*** | ***L. multi-florum*** | ***B. sterilis*** |
| Herbicide control efficacy (%) | 86 ± 4 | 100 | 79 ± 6 | 99.5 ± 1 | 52 ± 4 |
| Seeds per panicle | 85 ± 4 | 100 ± 9 | 300 ± 24 | 302 ± 26 | 128 ± 13 |
| Seed germination after first cut (%) | 0 | 0 | 0 | 0 | 0 |
| Seed germination rate after second cut (%) | 0 | 0 | 0 | 54 ± 10 | n.a. |
| Seed germination rate after harvest (%) | 95 ± 8 | > 95 | 95 ± 4 | 94 ± 7 | > 95 |
| Seed mortality of chaff milling (MCE%) | 55 ± 6 | 22.5 ± 4 | 84 ± 7 | 72 ± 8 | 89.5 ± 7 |

*L. multiflorum* (89% ± 7.6%) and *A. myosuroides* (93% ± 3.8%) (Table 2).

### 3.2 | Panicle Density and Seed Germination

Cutting significantly affected panicle densities ($p < 0.001$). At UHOH and JKI, cutting decreased panicle density of *A. myosuroides* by 55% compared to the untreated control (Figure 1a,b). An increase in panicle densities for *A. myosuroides* of 17% was observed between the first and second cut at JKI, whereas panicle density in the untreated control decreased by 22% (Figure 1b). At LFL, 51% of the *L. multiflorum* panicles were removed after the first cut (Figure 1d). while at UHOH, up to 71% of the panicles were removed. It seems there was not much incremental benefit to the second cut for *L. multiflorum* (Figure 1c, Table 2). At CZU, panicles of *B. sterilis* were only cut once at the early date in May. This treatment removed 44% of the panicles (Figure 1e). Later in June, almost all panicles of *B. sterilis* were below the winter wheat ears. In some spots of the plots, *B. sterilis* caused lodging of winter wheat and *B. sterilis*.

On average, 85 seeds of *A. myosuroides* were counted per panicle at UHOH and 100 seeds per panicle at JKI. *L. multiflorum* panicles contained 300 seeds at UHOH and 302 seeds at LFL. For *B. sterilis*, 52 seeds were counted per panicle at CZU.

In the germination tests, none of the seeds of the four grass weed species collected from the first cut of the four experimental sites germinated. After the second cut, 54% of the *L. multiflorum* seeds collected at LFL germinated. Seeds of *A. myosuroides* (JKI and UHOH) and *L. multiflorum* (UHOH) also did not germinate after the second cut. When collected at the time of crop harvest, the majority (> 95%) of the weed seeds were viable (Table 2). With the long period between harvest and the germination test with the chaff, primary dormancy was expected to be broken.

### 3.3 | Weed Seed Return

Weed seed return data illustrated in Figure 2 consider the number of seeds per panicle, the germination rate of seeds after cutting, the seed mortality of chaff milling and the seed retention rate at the time of harvest for each grass weed species separately. Chaff milling destroyed on average 39% of the *A. myosuroides* seeds, 78% of the *L. multiflorum* seeds and 89.5% of the *Bromus sterilis* seeds (Table 2). However, panicle cutting and chaff milling did not significantly reduce *A. myosuroides* seed density compared to the untreated control at UHOH and JKI (Figure 2a,b). On average, weed seed return after panicle cutting and chaff milling was only 10% lower than in the untreated control. Only the herbicide treatment significantly reduced *A. myosuroides* weed seed return at both sites. In contrast, weed seed return of *B. sterilis* was significantly lower after panicle cutting, chaff milling and the combination of panicle cutting and chaff milling compared to the untreated control and in the same range as the herbicide treatment (Figure 2e). However, those conclusions on *B. sterilis* are not robust because data originate from a single non-repeated field trial. The combination of panicle cutting and chaff milling reduced the weed seed return by 63% compared to the untreated control. *L. multiflorum* showed the strongest effect of panicle cutting and chaff milling on weed seed return. The combination of both treatments on average reduced the weed seed return by 85% (Figure 2c–e). Chaff milling was more effective against *L. multiflorum* than panicle cutting at LFL. At UHOH, both treatments had a similar effect on weed seed return of *L. multiflorum*. The combination of panicle cutting and chaff milling was more effective in reducing weed seed return than each treatment alone at both sites. At UHOH, the combination of cutting and milling resulted in similar weed seed return as the herbicide treatment. At LFL, the herbicide treatment showed the lowest weed seed return. It was observed that most of the seeds of *L. multiflorum* collected in the chaff in the combined treatment originated from re-grown panicles, whereas seeds of *A. myosuroides* and *B. sterilis* in the chaff originated mostly from panicles that were below the canopy of winter wheat. However, it was assumed that seed number per panicle and seed retention were always equal for clipped and unclipped panicles.

### 3.4 | Winter Wheat Grain Yield

The yield of winter wheat remained unaffected by panicle cutting and chaff milling at all sites. The herbicide treatments

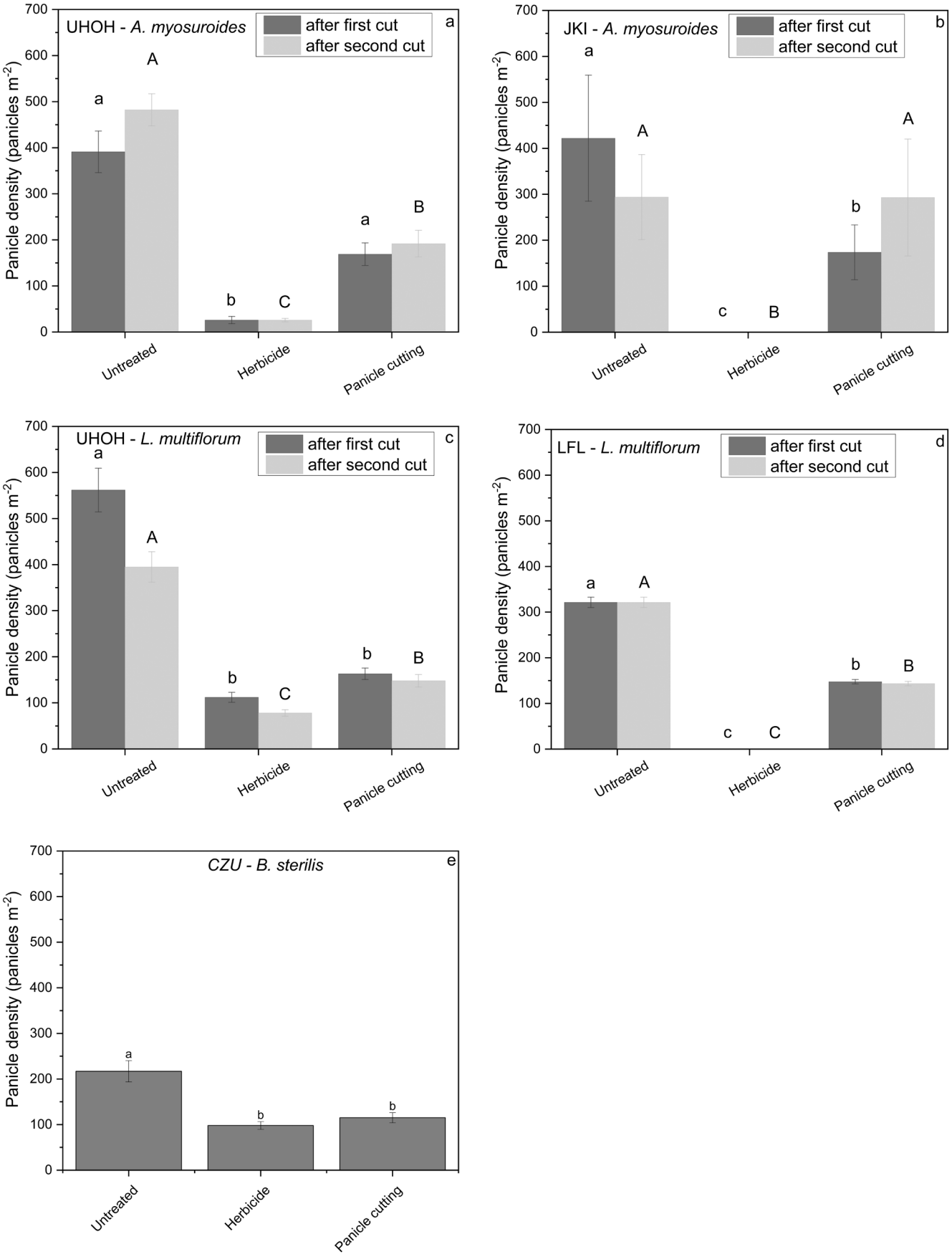



**FIGURE 1** | Grass weed panicle density (panicles $m^{-2}$) of *A. myosuroides* and *L. multiflorum* after the first and second panicle cut. At CZU, *B. sterilis* panicles were cut only once. Means with the same letter are not significantly different according to Tukey HSD-test at $p \leq 0.05$. Small letters indicate differences after the first cut. Capital letters represent differences after the second cut. Bars represent the standard error of the mean.

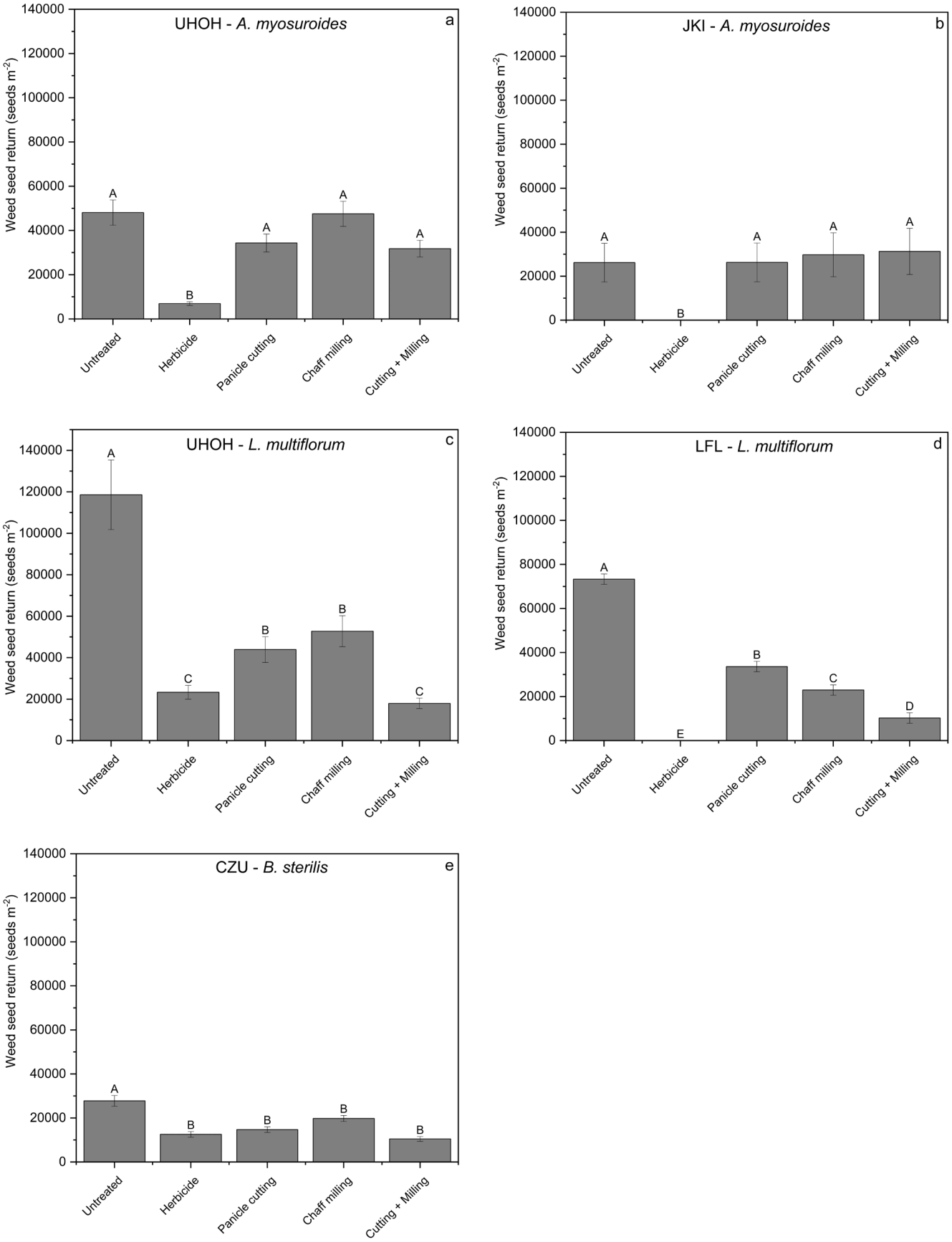



**FIGURE 2** | Weed seed return (seeds $m^{-2}$) after herbicide treatment, panicle cutting, chaff milling and a combination of cutting and milling. Means with the same letter are not significantly different according to Tukey HSD test at $p \leq 0.05$. Bars represent the standard error of the mean.

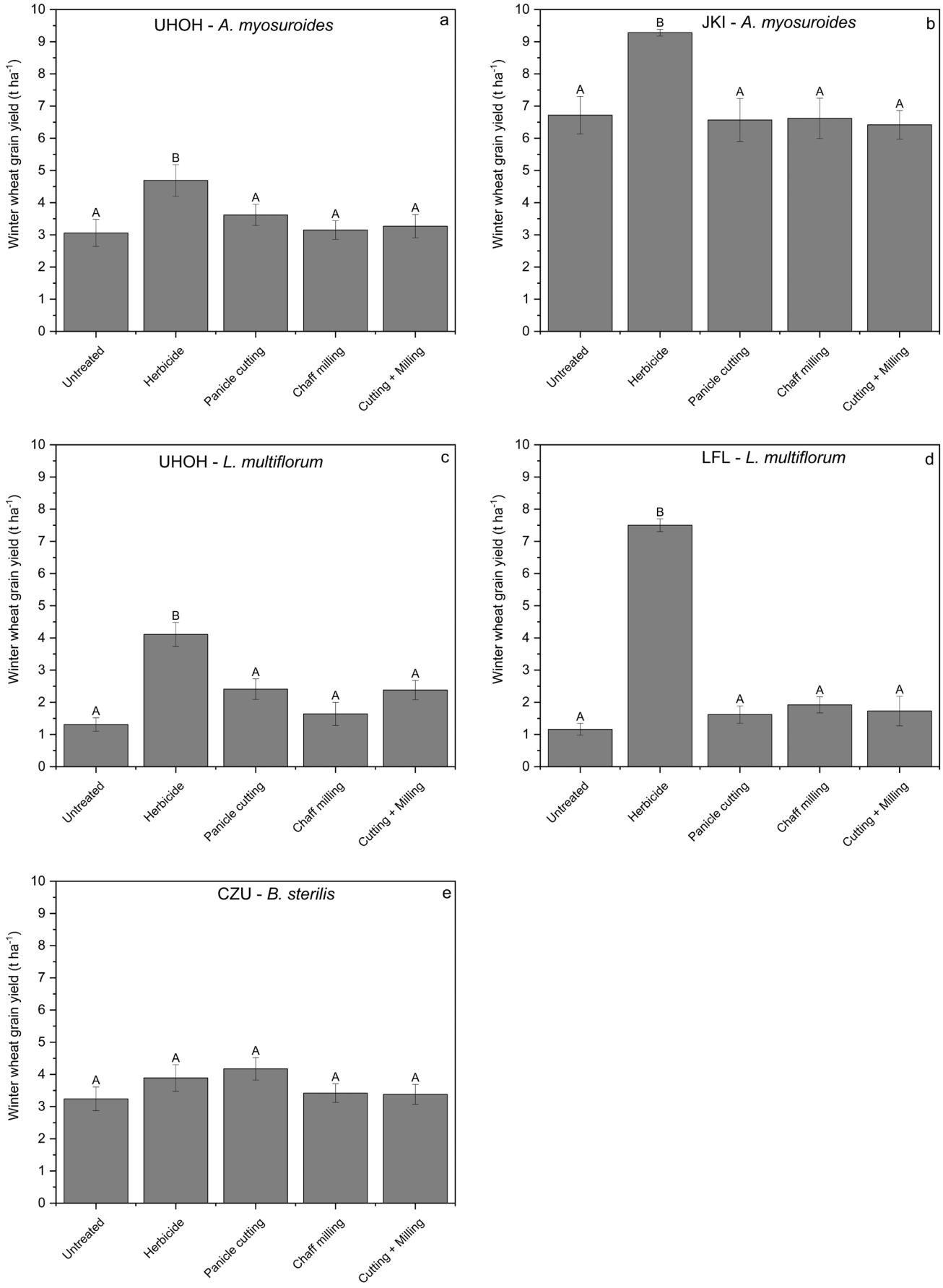



**FIGURE 3** | Winter wheat grain yield ($t\,ha^{-1}$) after herbicide treatment, panicle cutting, chaff milling and a combination of both. Means with the same letter are not significantly different according to Tukey HSD test at $p \leq 0.05$. Bars represent the standard error of the mean.

resulted in a significantly higher grain yield ($p < 0.01$) compared to the untreated control at four of the five experimental sites (Figure 3a–e). Herbicides saved between 1.1 t ha$^{-1}$ grain yield at UHOH (Figure 3a) and 5.8 t ha$^{-1}$ at LFL (Figure 3d) indicating the strong competitive effects of *A. myosuroides* and *L. multiflorum*. At CZU, the herbicide treatment did not result in a higher winter wheat yield than in the untreated control probably due to low weed control efficacy (Figure 3e).

## 4 | Discussion

Panicle cutting and chaff milling were shown to be very effective for controlling the weed seed return of the grass weed species *L. multiflorum*. In a single, non-repeated experiment, both treatments were also effective against *B. sterilis*. Panicle cutting and chaff milling were less effective in reducing the seed return of *A. myosuroides*. Differences in the weed species response to cutting can be explained by the morphological characteristics of the three grass weed species. *L. multiflorum* is the tallest growing grass weed of all three weeds tested with erect blades and ears growing much taller than winter wheat (Hanf 1985; Appleby and Brewster 1992; Sønderskov et al. 2020; Akhter et al. 2023). *L. multiflorum* seems to have less capability to produce new panicles after cutting than *A. myosuroides*. It was observed that the panicle density of *A. myosuroides* was higher at the second cut compared to the first cut.

In this study, chaff milling was most effective against *L. multiflorum*. This can be explained by 50%–62% seed retention of *L. multiflorum* until harvest (Akgun et al. 2008; San Martin et al. 2021; Akhter et al. 2023) compared to 33% seed retention for *A. myosuroides* (Bitarafan and Andreasen 2020). Therefore, more seeds of *L. multiflorum* are collected in the chaff fraction than those of *A. myosuroides*. It was assumed that seed retention of new panicles after clipping of *A. myosuroides* was equal to that of unclipped panicles. However, this needs to be examined in further studies. Moreover, chaff milling destroyed more seeds of *L. multiflorum* and *B. sterilis* than of *A. myosuroides*, which can be explained by the smaller seed size and bigger seed coat of *A. myosuroides* compared to the other two grass weeds (Hanf 1985; Akhter et al. 2023).

Plants of *B. sterilis* were difficult to control with herbicides at the CZU site. Low efficacy of herbicides against *B. sterilis* in winter cereals was also reported by Petersen (2006). ALS inhibitors are often the only mode of action that can be used and several populations of *B. sterilis* show resistance to this mode of action of herbicide (Petersen 2006). The blades of *B. sterilis* are less erect than the blades of the other two grass weeds. Heavy seed weight is causing lodging of the plants and panicles move below the winter wheat canopy (Žďárková et al. 2014). This limits the period for selective panicle cutting to very early applications, when panicles possibly have the capacity to regrow. However, chaff milling caused a very high mortality of *B. sterilis* seeds although typically more than half of the *Bromus* species seeds are already scattered at the time of harvest (Glasner et al. 2019). Therefore, chaff milling and the combination of panicle cutting and chaff milling resulted in the highest weed seed reduction of *B. sterilis* of all four treatments tested. We failed to reject the null hypothesis that panicle cutting and chaff milling would result in different weed seed return ($p = 0.478$). This is likely due to challenges with lodging and re-tillering of grass weeds, ultimately limiting the number of seeds that can be targeted by panicle cutting. In the present study, seeds did not germinate in four out of five experiments after panicles were cut even though the germination tests were conducted 4 weeks after cutting to allow the seeds for breaking primary dormancy (Bewley and Black 1983). A tetrazolium test (Witty 2012) at UHOH approved that seeds of *L. multiflorum* and *A. myosuroides* were not viable (data not shown). If the seeds are viable after cutting as it was the case with *L. multiflorum* at LFL, it would be possible to remove the panicles simultaneously with cutting using the Top Cut-Collect technology.

Panicle cutting and chaff milling are currently not widely used in European cropping systems. However, the increase in multiple herbicide-resistant weeds, a decrease in the number of available herbicide modes of action and EU political initiatives to reduce pesticide use might result in an increased demand for alternative non-chemical options. In particular, grass weed control in Europe requires alternative approaches to ensure long-term control of grass weed densities. Our results indicate that panicle cutting and chaff milling are promising weed control methods in integrated weed management strategies, at least for *L. multiflorum*. This study proves that both treatments were less efficient against *A. myosuroides* and *B. sterilis* than against *L. multiflorum*.

Panicle cutting and chaff milling provide additional weed control tactics targeting maturing weed plants and preventing weed seed return into the soil seed bank (Walsh et al. 2013; Walsh et al. 2018). Those tactics are extremely useful for problematic weed species such as herbicide-resistant grass weeds. Tavaziva et al. (2019) observed that selective shoot cutting significantly reduced seed production of *C. arvense* in spring barley. This perennial weed species is also very problematic mainly in organic farms and conservation tillage systems (Pekrun et al. 2023). However, these strategies mainly focus on reducing the entry of weed seeds into the soil and therefore must be regarded as a long-term weed management strategy. Like in an earlier study with *A. fatua* (Tidemann et al. 2021) panicle cutting was not effective in reducing grass weed competition in the current crop. Because the soil seed bank buffers the weed community response to management (Shergill et al. 2020), it may take multiple crop growing seasons before weed densities in the crop can be reduced. Therefore, the weed seed bank of grass weeds including *A. myosuroides* and *B. sterilis* should also be reduced by preventive methods such as false seedbed, rotating winter annual crops with spring crops, and occasional ploughing (Lutman et al. 2013; Zeller et al. 2021).

## 5 | Conclusions

The present study underlines the benefits of using panicle cutting and chaff milling against *L. multiflorum* to prevent weed seed return into the soil seed bank. However, this technology was less suitable for *A. myosuroides*. The data from one single field experiment with *B. sterilis* do not allow a clear conclusion on the effect of panicle cutting and chaff milling against this grass weed species. It was further observed that both methods did not reduce weed competition in the current year. Therefore, panicle cutting and chaff milling should be combined with other preventive and curative weed control methods to suppress weeds.

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## Conflicts of Interest

The authors declare no conflicts of interest.

## Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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