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The potential of glyphosate-alternatives like electrophysical weeding in the stale seedbed method for *Alopecurus myosuroides* (Huds.) control

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Abstract: Changing political demands requires the search for alternatives to glyphosate, which has often been used in the stale seedbed method. In three field trials between 2020 and 2023, three electrophysical treatments (XPower System, Zasso®) differing in speed, three mechanical treatments (disc harrow, rotary harrow, cultivator) and three chemical treatments (glyphosate, maleic hydrazide, pelargonic acid + maleic hydrazide) were evaluated concerning the efficacy and economic performance in stale seedbed method in *Alopecurus myosuroides* control. Process costs for each treatment were calculated. Furthermore, the maximum investment costs for the XPower system were calculated to be on the same level as the other treatments. In all treatments, the density of *A. myosuroides* in autumn was significantly lower than in the control. In general, the fewest plants and heads were found in the chemical treatments. Despite the lower plant density, the electrophysical method did not show a significant difference in the number of heads compared to the untreated control, especially at higher speeds. Calculated process costs ranged between 40 €/ha (glyphosate) and 430 €/ha (pelargonic acid + maleic hydrazide). To be economically comparable with the other treatments, the investment of the XPower should be at maximum between – 219 000 € (glyphosate) and 300 000 € (pelargonic acid + maleic acid), depending on the driving speed. In a holistic view, electrophysical control, as well as pelargonic acid and maleic hydrazide as glyphosate alternatives in the stale seedbed method, are not suitable. A stale seedbed with mechanical control of *A. myosuroides* is recommended.

Keywords: blackgrass; integrated weed management; non-chemical weed control; pelargonic acid; maleic hydrazide

The Green Revolution increased the global crop productivity since the 1960s, which was highly associated with higher food security. This was made possible by considerable advances in plant breeding and the use of agrochemicals such as fertilisers and synthetic pesticides (Pingali 2012). Synthetic pesticides still play a crucial role in current crop systems, especially on sites with high-yield potential. However, the decreasing acceptance of the use of synthetic pesticides in the society poses a challenge to policy (Saleh et al. 2021). EU directives such as the "sustainable use regulation" (SUR) are intended to reduce the use and risk of chemical pesticides by 50% until 2030, in line with the EU's Farm to Fork and Biodiversity strategies (European Commission 2023). In addition to political directives, resistance in all crop-damaging organism groups (weeds, pathogens, and insects) also restricts the use of pesticides (Hawkins et al. 2019). Integrated pest management (IPM), which is demanded at the political level, is coming more into focus than before. IPM requires strategies, that exhaust all possible non-chemical measurements combined with the situation-appropriate use of pesticides to control the crop-damaging organism. In Europe, the resistance of weed grasses like *Alopecurus myosuroides* (Huds.) causes high economic losses at the farm (Gerhards et al. 2016) as well as at the country level (Varah et al. 2019). A sequence of non-chemical measures combined with still effective herbicides

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are needed to control resistance *A. myosuroides* biotypes (Klauk and Petersen 2023). Therefore, the stale seedbed method is an effective technique to remove sprouted weed plants before (delayed) crop sowing. This technique showed a 25% reduction in *A. myosuroides* infestation (Menegat and Nilsson 2019). The stale seedbed method uses non-selective herbicides such as glyphosate (Heatherly et al. 1993). However, the use of glyphosate will prospectively be restricted if not prohibited in the EU. Replacing glyphosate with mechanical methods is an alternative that carries a higher risk of germination of further weed seeds through soil movement (Riemens et al. 2007). Further options in non-selective herbicides are rare in the EU, especially in Germany. Besides glyphosate, only a few herbicides with non-selective performance are currently approved. One option could be pelargonic acid, a bioherbicide which penetrates the cuticle and destroys the cell membranes of the epidermis of the target plant (Cirminna et al. 2019). A further option could be maleic hydrazide. This is often used in vegetables to regulate growth or as a sprout inhibitor, e.g., in potatoes (Lee et al. 2001). Another non-selective method without soil movement represents the electrophysical vegetation control. Early records showed the use of electricity to control weeds as early as 1901 (Timmons 2005). In the 1980s, experiments were carried out with electricity to control bolters of sugar beet with promising success (Diprose et al. 1985). Recent developments, like the Electroherb™ technology from the company Zasso®, offer further opportunities in weed control. In 2020, the prototypes of the XPower system, which contains the Electroherb™ technology, were supplied and tested. The XPower system includes a generator unit and an application unit. The generator, connected at the rear of the tractor, supplies 230 V alternating current and converts it to 700 to 8 000 V direct current by rectifier circuits mounted on the applicator. The applicator consists of three rows of electrodes (positive and negative) that touch the plants during application (Koch et al. 2020). However, there is a lack of knowledge of how a perspective omission of glyphosate in the application of the stale seedbed method could be compensated for in the control of *A. myosuroides*. This study aimed to compare the efficacy and economic performance of different methods that combat in different ways against *A. myosuroides*. The Electroherb™ Technology was included in the trial alongside mechanical and chemical methods. The mechanical treatments included rotating, slicing and mixing operations. The following hypotheses were tested:

1. Electrophysical control in the stale seedbed method significantly reduces the density of *A. myosuroides* compared to the untreated control.
2. Mechanical removal of seedlings stimulates late germination of *A. myosuroides* seeds. Consequently, the density of *A. myosuroides* is higher with mechanical methods than with electrophysical or chemical methods.
3. Electrophysical control is an economic alternative to the mechanical/chemical control options.

MATERIAL AND METHODS

Experimental setup. Three field trials were conducted between the winter cereal growing periods 2020/2021 and 2022/2023 at the Bingen site (49°58'N, 7°54'E), Germany. The fields were differently infested with *A. myosuroides* (Table 1). In the second and third trial years, approximately 1 500 *A. myosuroides* seeds per m^2 were sown in September to increase and homogenise the natural infestation level. After sowing the weed seeds with the plot seeder, the seeds were mixed with a cultivator in the 0–15 cm layer. The seedbed of all fields was prepared by a rotary harrow (0–5 cm) in September.

Table 1. Characteristics of the fields in Bingen as well as dates of sowing *Alopecurus myosuroides* (ALOMY), seedbed preparation and combat of the seedlings

Period	Soil type	Clay content (weight. %)	Previous crop	Natural Infestation ALOMY[1]	Sowing ALOMY	Seedbed preparation	ALOMY control[2]
2020/21	Loam	30	winter wheat	yes	–	28th Sep	20th Oct
2021/22	Loam	25	lupine	no	9th Sep	20th Sep	8th Nov
2022/23	Loamy Sand	17	maize	slightly	1st Sep	10th Sep	11th Oct

[1]Before the trial period; [2]sowing wheat one day after ALOMY control

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Table 2. Description of all treatments included in all trial years (2020–2023) in Bingen

Treatment	Type of stale seedbed method	Device	Speed (km/h)	Working width (m)	Working depth (cm)	Active ingredient(s)	Dose of active ingredients (g/ha)
1	control	–	–		–	–	–
2	electrophysical	XPower	1	3	–	–	–
3	electrophysical	Xpower	3	3	–	–	–
4	electrophysical	Xpower	6	3	–	–	–
5	chemical	sprayer[1]	4.5	2.5	–	glyphosate[2]	1 080
6	chemical	sprayer[1]	4.5	2.5	–	maleic hydrazide[3]	6 000
7	chemical	sprayer[1]	4.5	2.5	–	pelargonic acid[4] + maleic hydrazide[3]	13 600 + 3 000
8	mechanical	cultivator[5]	10	5	5	–	–
9	mechanical	disc harrow[6]	12	2.5	7	–	–
10	mechanical	rotary harrow[7]	6	2.5	10	–	–

[1]one-wheel sprayer; air mix 120–025 flat fan nozzle, spray pressure 210 kPa, spray volume 200 L/ha; [2]RoundUp® Powerflex; 480 g glyphosate/L; water soluble concentrate; supplier: Bayer CropScience; [3]Himalaya®; 600 g maleic hydrazide/kg; water dispersal granulate; supplier: Belchim Crop Protection; [4]Beloukha®; 680 g pelargonic acid/L; emulsion concentrate; supplier: Belchim Crop Protection; [5]Super Maxx® Bio, Güttler® GmbH, Germany; [6]Powerdisc, Bremer® Maschinenbau GmbH, Germany; [7]DC Classic, Maschio® Deutschland GmbH, Germany

After reaching the BBCH 10–12 of *A. myosuroides* (Meier 2018), the density of the germinated seedlings in each plot was counted with a counting frame bordering an area of 0.25 m^2. Subsequently, all treatments included in this trial (Table 2) were conducted on the same day in each trial year. The treatments differed in the way they combated the seedlings. All mechanical devices and the XPower device were driven by a 106-kW tractor (nominal power). The cultivator was endowed with a following harrow, the disc harrow, and the rotary harrow with a packer. The doses for pelargonic acid and maleic hydrazide were determined within a prior field test in 2020 (data not shown).

The three trial years they differed in weather conditions (Figure 1). The first trial year, 2020, was characterised by less precipitation and higher averaged temperatures compared to 2021, with the highest precipitation in 2022, especially in autumn. The weather conditions during the period of the treatments also differed (Table 3).

After controlling the *A. myosuroides* seedlings, winter wheat (cv. RGT Reform, 350 seeds/m^2) was sown (3 cm depth) by a plot seeder. To extend the IPM approach, cinmethylin, a benzyl-ether with high efficacy against ACCase and ALS-resistant *A. myosuroides* biotypes (Klauk and Petersen 2023), was applied in pre-emergence (0.66 L/ha Luxinum®; 750 g cinmethylin/L; HRAC: 30; emulsion concentrate; supplier: BASF SE). 67.5 g/ha Pico® (750 g picolinafen/kg; HRAC: 12; water-dispersible granulate; supplier: BASF SE) was added to control dicotyledonous weeds. Both 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, speed 4.5 km/h) with a working width of 2.5 m. Randomly selected areas were covered with a 1 m^2 panel before pre-emergence herbicide application on each plot to determine the treatment-specific efficacy with and without herbicide. The plot size was adapted to the working width. The size of the plot was 2.5 × 16 m for the treatments "control", "disc harrow", "rotary harrow", and all chemical treatments. Here, four areas were covered with panels before herbicide application. For the electrophysical treatments as well as for the cultivator, the size of the plot was 5 × 16 m, and eight areas were covered. A strip of 1 m width was treated twice due to the working width of 3 m of the XPower, but this was not used for any data evaluation. The treatments were organised in a randomised block design, whereby each treatment was replicated four times.

Data collection. The *A. myosuroides* plants were counted after sprouting to determine the level of infestation for each plot before treatments were carried out. Four and eight places were randomly

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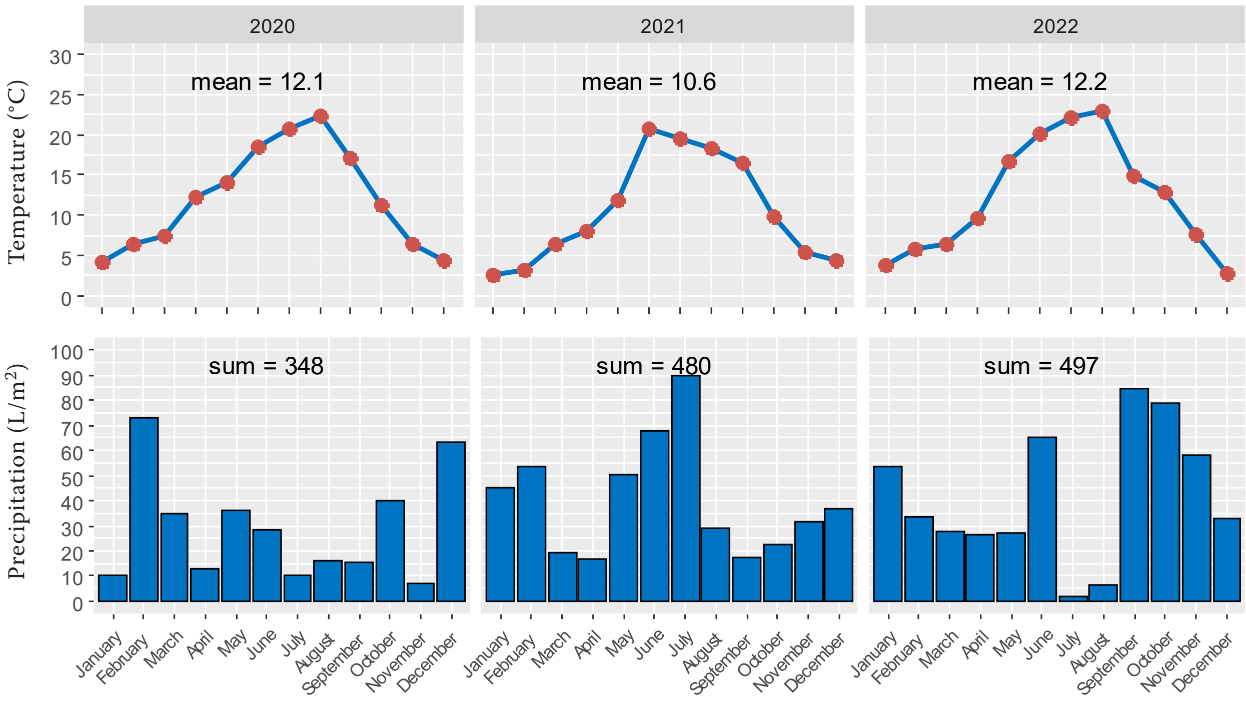

Figure 1. Temperature and precipitation for each month for the trial years 2020–2022 in Bingen (Data: weather station Bingen-Gaulsheim)

selected for infestation assessment on 2.5 m and 5 m wide plots, respectively. The counting was repeated after 14 to 21 days of treatment. Here, densities were counted at four places (2.5 m wide plots) and eight places (5 m wide plots) for both herbicide-treated and untreated areas. The head density of *A. myosuroides* and winter wheat was determined after flowering in spring at the same places as in autumn. Counting was conducted by using a quadratic counting frame bordering an area of 0.25 m^2. The winter wheat yield was assessed for one core plot in 2.5 wide plots and two core plots in 5 m wide plots, whereby a core plot comprised an area 1.5 m wide and 16 m long. A representative sample was taken from each plot to determine the yield at 14% moisture content.

Economical analysis. The costs for the mechanical and chemical treatments were taken from the KTBL database (2023), which is a federal institution within the Ministry of Agriculture in Germany. The database offers setting options for tractor power, working width for the selected measure, field size, and the distance between the field and the farm. Tractor power was set at 102 kW for all mechanical measures, with the treatment-specific working width selected. For the chemical treatments, a tractor power of 54 kW and a working width of 15 m were specified, which was considered a typical constellation. For all mechanical and chemical treatments, a distance between field and farm of 1 km and a field size of 1 ha was assumed. For the herbicides, market averaged prices from 2020 to 2022 were taken (RoundUp® Powerflex: 8.36 €/L, Beloukha®: 14.52 €/L, Himalaya®: 23.65 €/L). No data for process costs was available for electrophysical processes. The

Table 3. Temperature and precipitation 30 days before and 30 days after treatments for the trial years 2020–2022 in Bingen (Data: weather station Bingen-Gaulsheim)

Year	30 days before treatments		30 days after treatments	
	average temperature (°C)	precipitation (L/m^2)	average temperature (°C)	precipitation (L/m^2)
2020	12.0	34.5	9.8	24.8
2021	8.5	33.8	4.5	26.0
2022	12.4	78.6	12.0	70.5

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calculated process costs included diesel and wage costs per ha. Costs for maintenance could not be considered due to a lack of experience with the few prototypes built and tested so far. The speed-specific area performance was calculated by multiplying the 3 m working width with the speed, where a turning time of 16% was assumed. The 106-kW tractor consumed an average of 32 L/h diesel in the electrophysical treatments, which at an assumed diesel price of 0.85 €/L (KTBL) costs 27.2 €/h. Wage costs of 40 €/h were supposed for all treatments. The resulting 67.2 €/h for electrophysical treatments was divided by the speed-specific area performance to calculate the speed-dependent process costs per ha. Due to the non-existent investment costs for the XPower system, the speed-dependent process costs for the electrophysical treatments were compared with the costs for the mechanical as well as the chemical treatments. The annual cost benefit of the electrophysical treatments was calculated with the following Eq. 1:

$$\text{annual cost-benefit} = (A - B) \times C \qquad (1)$$

where: A – the cost of mechanical or chemical treatment; B – calculated process cost of electrophysical treatment; C – area treated per year, set at 100 ha/a for this calculation. The maximum investment cost (MIC) for the XPower system was calculated individually for each mechanical and chemical treatment by multiplying the specific annual cost-benefit and the present value interest factor of the annuity (PVIFA), which can be obtained with the following Eq. 2:

$$\text{PVIFA} = \frac{(1+D)^{(E-1)}}{(1+D)^{(D \times E)}} \qquad (2)$$

where: D – interest in % (here 4%); E – duration of use (here 10 a), resulting in a PVIFA of 8.11. The product of the treatment-specific annual cost-benefit and the PVIFA of 8.11

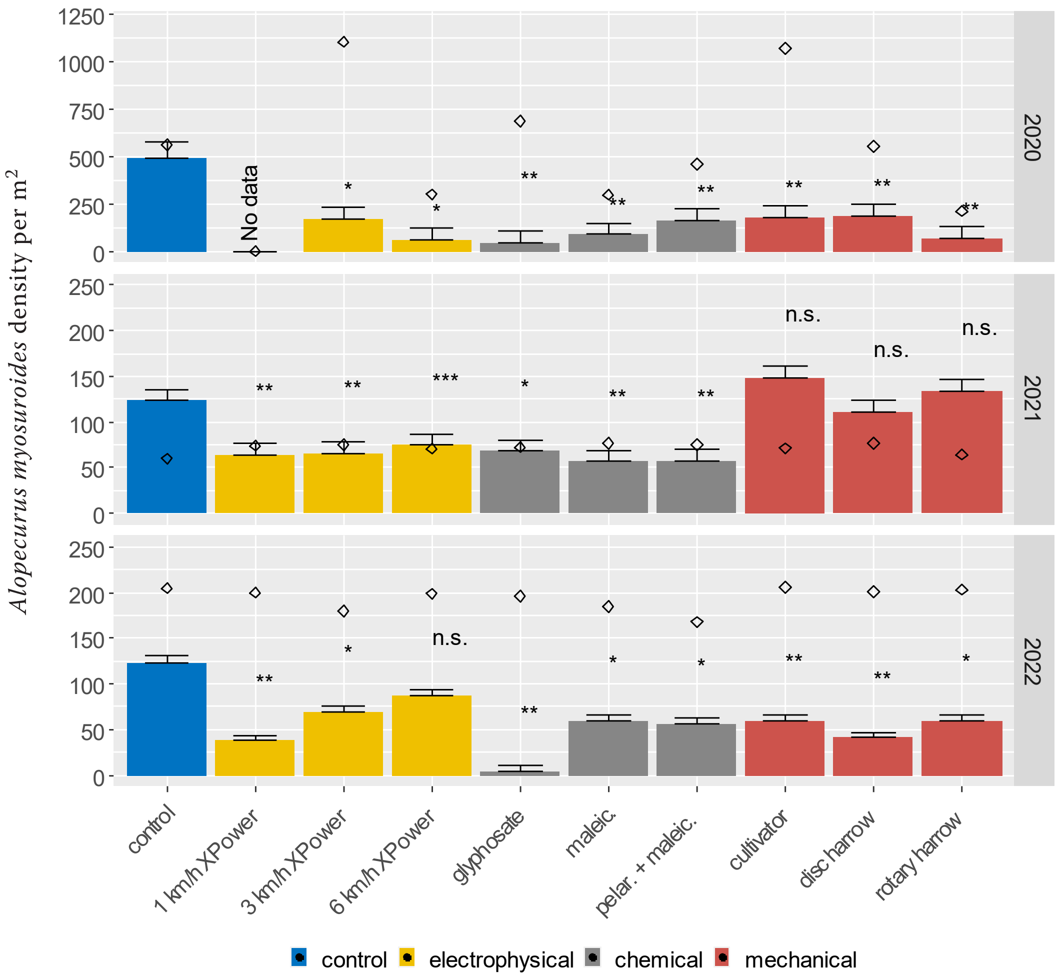

Figure 2. Comparison of *Alopecurus myosuroides* density before (rhombus) and after treatment (bars) in autumn in 2020, 2021 and 2022 at the Bingen site (error bars: ± standard error; ns – not significant; **P*-value ≤ 0.05; ***P*-value ≤ 0.01; ****P*-value ≤ 0.001, separately for each year, Dunnett's test, reference group: control)

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form the maximum investment costs for the XPower system. Consequently, with this investment cost of the XPower system, the electrophysical treatment would incur the exact process costs as the respective mechanical or chemical treatment.

Statistical analysis. Statistical analysis was conducted with R (version 4.2.3) (R Core Team 2023). All data were tested for normal distribution (Shapiro-Wilk test) and variance homogeneity (Levene test) using the R package *car* (Fox and Weisberg 2019). Subsequently, linear mixed effect models (LMM) were used to explore the responsible variables density of *A. myosuroides* in autumn and spring and winter wheat heads in spring in the pre-emergence herbicide treated and untreated area and the winter wheat yield. Each year was analysed separately. The treatments were included as a fixed factor, and the repetition (nested design) as a random factor. The package *lmerTest* was used for the LMM (Kuznetsova et al. 2017). After the LMM, Tukey's honestly significant difference (HSD) post hoc test (α ≤ 0.05) was conducted by using the package *emmeans* (Lenth 2023). For the comparison of the density of *A. myosuroides* before and after treatment, the Dunnett test was applied after the LMM, comparing all treatments with the "control" treatment.

RESULTS

Comparison *A. myosuroides* density before and after treatment. In two out of three years, a significant density reduction was observed in all treatments compared to the control (Figure 2). The highest levels were observed for glyphosate and 1 km/h XPower. In contrast, more *A. myosuroides* plants were ascertained after treatment than before in the second trial year, especially for the mechanical treatments. Here, the mechanical treatments did not significantly differ from the control about the development of the *A. myosuroides* density.

The lowest densities of *A. myosuroides* in the areas without pre-emergence herbicides (plants and heads) were perceived in the chemical-treated plots (especially for glyphosate) compared to the other treatments (Figure 3). More heads were counted for the electrophysical as well as the mechanical treatments in all years.

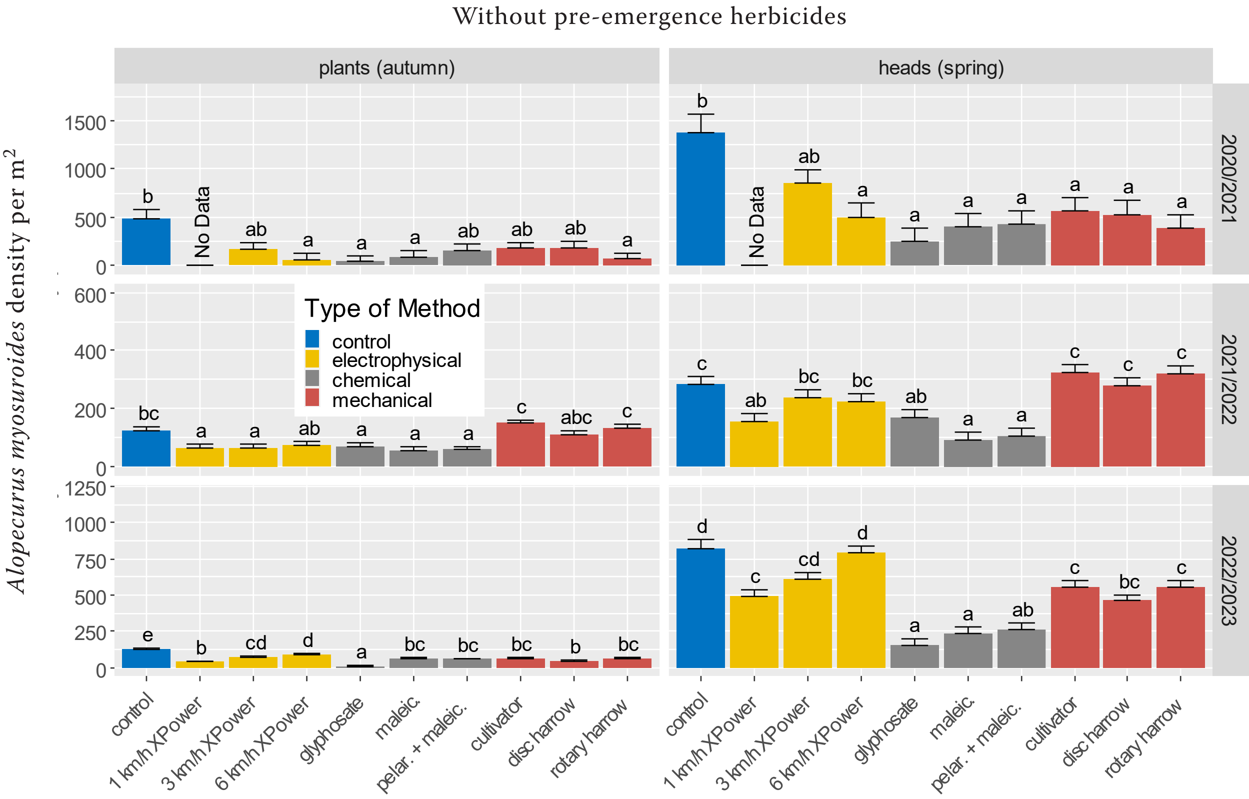

Figure 3. *Alopecurus myosuroides* plants and heads per m^2 (without application of pre-emergence herbicides) depending on the treatment for stale seedbed in 2020/21, 2021/22 and 2022/23 at Bingen site (error bars: standard error; different letters indicate significant differences between categories, $P \leq 0.05$, Tukey's HSD (honestly significant difference) test; glyphosate: 1 080 g glyphosate/ha; maleic.: 6 000 g maleic hydrazide/ha; pelar. + maleic.: 13 600 g pelargonic acid + 3 000 g maleic hydrazide/ha)

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A. myosuroides densities were lower when the stale seedbed method was combined with the application of pre-emergence herbicides (Figure 4). However, the number of heads in the electrophysical treatment was only significantly lower than in the control at 1 km/h speed.

Wheat yield. Compared to the control, a higher wheat yield was mostly harvested when a stale seedbed was established (Figure 5). Yields tended to be higher for both the chemical and mechanical treatments compared to the electrophysical treatments. Overall, the highest wheat yield was achieved with glyphosate application.

Economical analysis. The process costs were lowest for the glyphosate application compared to the other techniques (Table 4). The most cost-intensive treatments were applying pelargonic acid combined with maleic hydrazide and 1 km/h XPower at 430 €/ha and 305 €/ha, respectively. The acquisition of the XPower system would be economical only compared to the two chemical treatments, pelargonic acid plus maleic hydrazide and maleic hydrazide solo. The maximum investment costs for the XPower system should be low or even negative to be economically comparable to glyphosate or mechanical treatments.

DISCUSSION

This study aimed to evaluate the potential of electrophysical vegetation control and other techniques as glyphosate alternatives for use in stale seedbed methods against *A. myosuroides*. Compared to the control, the stale seedbed method with electrophysical control significantly reduced *A. myosuroides* infestation in autumn, but the density of heads in spring was significantly lower only at 1 km/h speed. Therefore, the first hypothesis needs to be rejected. Two aspects must be considered for an electrophysical control of *A. myosuroides* in stale seedbed method: (1) the efficacy of the electrophysical control is closely related to

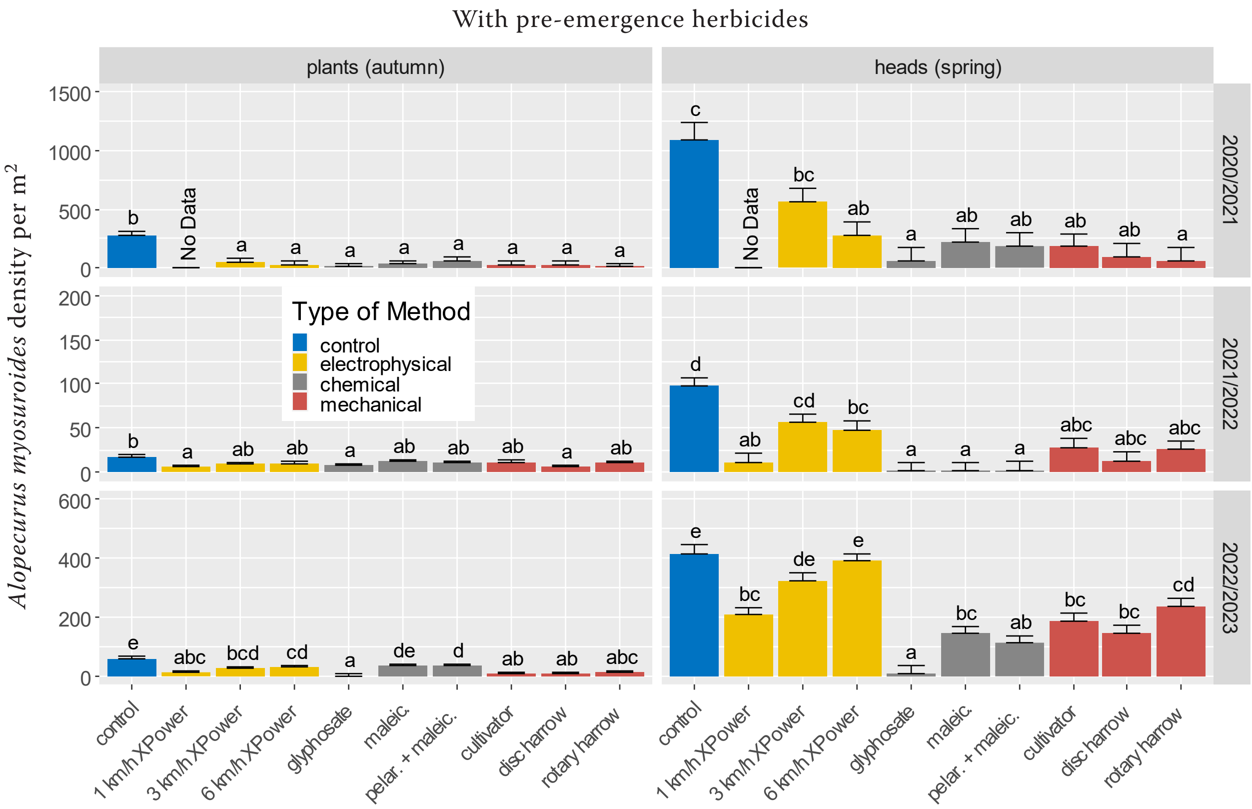

Figure 4. *Alopecurus myosuroides* plants and heads per m^2 (area with application of pre-emergence herbicides) depending on the treatment for stale seedbed in 2020/21, 2021/22 and 2022/23 at Bingen site (error bars: standard error; different letters indicate significant differences between categories, $P \leq 0.05$, Tukey's HSD (honestly significant difference) test; glyphosate: 1 080 g glyphosate/ha; maleic.: 6 000 g maleic hydrazide/ha; pelar. + maleic.: 13 600 g pelargonic acid + 3 000 g maleic hydrazide/ha)

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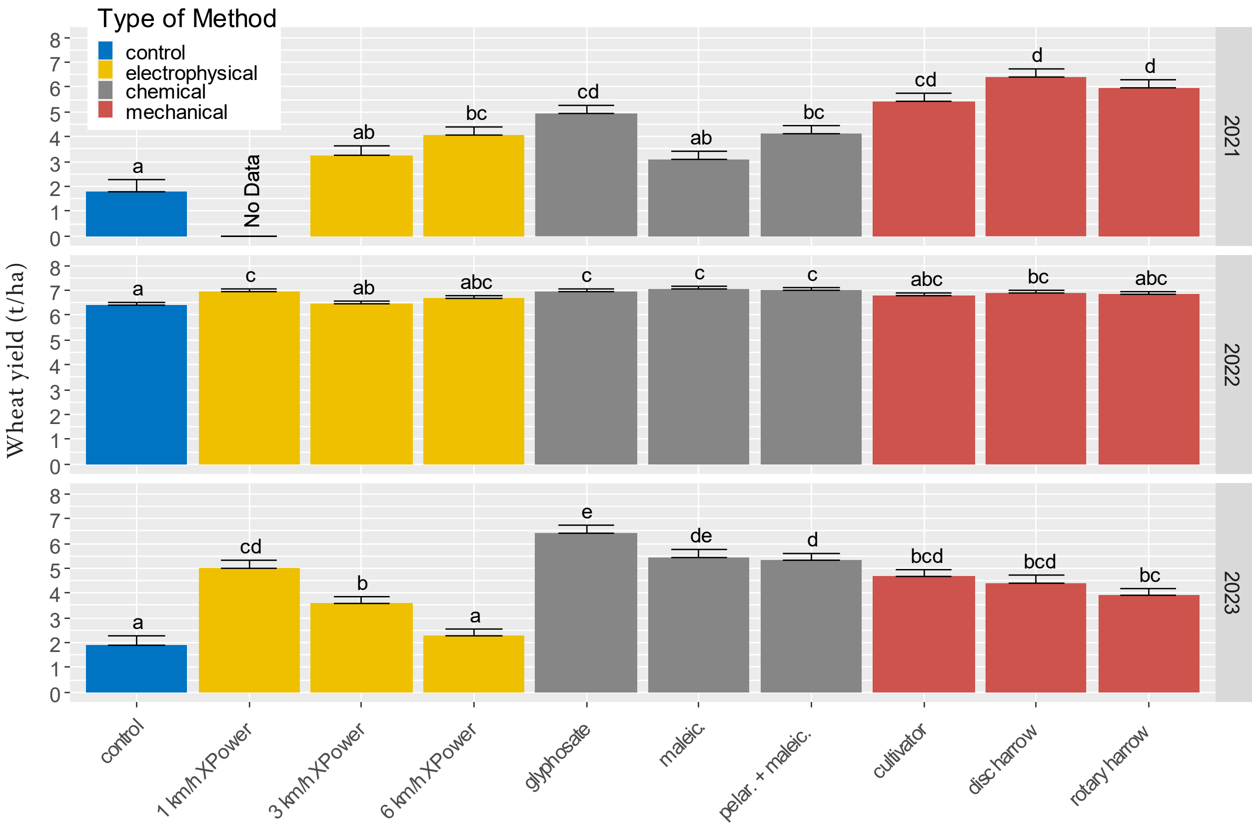

Figure 5. Wheat yield depending on the treatment for stale seedbed in 2021, 2022 and 2023 at Bingen sites (error bars: standard error; different letters indicate significant differences between categories; $P \leq 0.05$, Tukey's HSD (honestly significant difference) test; glyphosate: 1 080 g glyphosate/ha; maleic.: 6 000 g maleic hydrazide/ha; pelar. + maleic.: 13 600 g pelargonic acid + 3 000 g maleic hydrazide/ha)

the amount of straw residue or other aboveground biomass that covered the narrow-leaved *A. myosuroides* plants during application. For this purpose, all residue plant material needs to be incorporated deep into the soil after harvesting, which could be hampered by dry post-harvest soil conditions in conservation tillage. (2) the heavy weight of the XPower equipment (both the application and generator unit > 2 t) compresses the soil, especially in wet soil conditions, which are usually within the time frame of performing the stale-seedbed method when controlling *A. myosuroides*. The resulting compact soil structure

Table 4. Process cost of the stale seedbed treatments (€/ha) and the resulting maximal investment costs for XPower (€) compared to the chemical and mechanical treatments

Treatment	Process costs (€/ha)	Electrophysical treatments		
		1 km/h	3 km/h	6 km/h
		305.45	101.82	50.91
		maximal investment costs XPower (€)		
Glyphosate	39.27	–215 903	–50 735	–9 443
Pelargonic acid + maleic hydrazide	429.11	100 293	265 460	306 752
Maleic hydrazide	256.96	–39 336	125 831	167 123
Cultivator (5 m)	52.48	–205 182	–40 014	1 277
Disc harrow (2.5 m)	65.84	–194 352	–29 184	12 107
Rotary harrow (2.5 m)	103.76	–163 589	1 578	42 870

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led to unfavourable germination conditions for the crop seeds. Furthermore, the risk of crop damage was increased when using pre-emergence herbicides. The lower competitiveness of the crop against the remaining seedlings and germinating seeds allowed a higher tillering rate of *A. myosuroides*. Increasing the seeding rate of wheat, a common cultural practice to control *A. myosuroides* (Lutman et al. 2013), would not significantly improve the competitiveness of the crop under these soil conditions.

The hypothesis that a mechanical removal of *A. myosuroides* stimulates the germination of further seeds and is less effective compared to chemical and electrophysical methods needs to be rejected. In general, a potential 25% reduction of *A. myosuroides* infestation (Menegat and Nilsson 2019) and up to 70% (Zeller et al. 2021) were reported for a mechanical-based stale seedbed method in *A. myosuroides* control. Our results showed even higher potential in two out of three years. In 2021, more *A. myosuroides* plants were observed after the mechanical removal than before. This suggests a higher dormancy of the sown *A. myosuroides* seeds in 2021. Generally, *A. myosuroides* seeds are more dormant during seed maturation in moist and cool conditions (Swain et al. 2006). Therefore, the time of any cultivation needs to be adapted to the seasonally varying dormancy (Anderson and Åkerblom Espeby 2009). Especially in years when low dormancy of *A. myosuroides* seeds is expected, the stimulating effect of tillage on the germination of further *A. myosuroides* seeds could be used. Several tillage applications before sowing would reduce the soil seed reserve, a key point in *A. myosuroides* control (Klauk and Petersen 2023). Additionally, the mechanical-based stale seedbed method significantly improved the performance of the pre-emergence herbicides, which is demonstrated by low densities of plants and heads of *A. myosuroides*.

The economic evaluation of the tested methods showed a large discrepancy in economic performance between the electrophysical and the other methods. To keep an economic competitiveness, high variable costs due to high fuel input limited the possible maximum investment costs for the tested XPower system (especially at 1 km/h speed). Consequently, the third hypothesis needs to be rejected. Electrophysical methods seem to be too energy-intensive for broadcast weed control. In general, all techniques for thermal weed control are characterised by a high energy input and require specialised equipment (Coleman et al. 2019). The authors of Coleman et al. (2019) estimated high reduced energy consumption of up to 99% for point-specific approaches (i.e., non-target area will not be affected). Such an approach does not seem feasible at this stage of *A. myosuroides* control. Site-specific weed control with this system is conceivable for broadleaf weeds, which require a lower lethal energy dose in thermal weed control (Coleman et al. 2019) and emerge in the fields in clusters.

Pelargonic acid and maleic hydrazide performed comparably to glyphosate in terms of efficacy and thus to the *A. myosuroides* control. In soybeans, the weed control performance in the stale seedbed method of pelargonic acid was also similar to that of glyphosate (Kanatas et al. 2020). However, the five-to-nine-fold higher costs compared to the glyphosate application reduce the economic viability of maleic hydrazide and pelargonic acid in the stale seedbed method. The crops in which *A. myosuroides* mainly occur (winter cereals, winter oilseed rape) are characterised by lower proceeds. Hence, when costs exceed 250 € per ha, cheaper mechanical alternatives, such as cultivators with high area performance, will be preferred.

The stale seedbed method, embedded in an integrated weed management strategy, can significantly improve *A. myosuroides* control and, thus, economic profit (Zeller et al. 2021). In a holistic view, all non-soil-disturbing methods included in this study, such as electrophysical weeding and other herbicides, proved to be unsuitable alternatives to glyphosate in the stale seedbed method for *A. myosuroides*. The mechanically based stale seedbed method characterised by an adapted timing (seedbed preparation and combat) significantly reduces the infestation of *A. myosuroides*.

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REFERENCES

Andersson L., Åkerblom Espeby L. (2009): Variation in seed dormancy and light sensitivity in *Alopecurus myosuroides* and *Apera spica-venti*. Weed Research, 49: 261–270.

Ciriminna R., Fidalgo A., Ilharco L.M., Pagliaro M. (2019): Herbicides based on pelargonic acid: herbicides of the bioeconomy. Biofuels, Bioproducts and Biorefining, 13: 1476–1482.

Coleman G.R.Y., Stead A., Rigter M.P., Xu Z., Johnson D., Brooker G.M., Sukkarieh S., Walsh M.J. (2019): Using energy requirements to compare the suitability of alternative methods for

https://doi.org/10.17221/386/2023-PSE

broadcast and site-specific weed control. Weed Technology, 33: 633–650.

Diprose M.F., Fletcher R., Longden P.C., Champion M.J. (1985): Use of electricity to control bolters in sugar beet (*Beta vulgaris* L.): a comparison of the electrothermal with chemical and mechanical cutting methods. Weed Research, 25: 53–60.

European Commission (2023): Sustainable Use of Pesticide. Available at: https://food.ec.europa.eu/plants/pesticides/sustainable-use-pesticides_en (accessed 30. 6. 2023)

Fox J., Weisberg S. (2019): An R Companion to Applied Regression. 3rd Edition. Sage, Thousand Oaks.

Gerhards R., Dentler J., Gutjahr C., Auburger S., Bahrs E. (2016): An approach to investigate the costs of herbicide-resistant *Alopecurus myosuroides*. Weed Research, 56: 407–414.

Hawkins N.J., Bass C., Dixon A., Neve P. (2019): The evolutionary origins of pesticide resistance. Biological Review, 94: 135–155.

Heatherly L.G., Wesley R.A., Elmore C.D., Spurlock S.R. (1993): Net returns from stale seedbed soybean plantings (*Glycine max*) on clay soil. Weed Technology, 7: 972–980.

Kanatas P., Travlos I., Papastylianou P., Gazoulis I., Kakabouki I., Tsekoura A. (2020): Yield, quality and weed control in soybean crop as affected by several cultural and weed management practices. Notulae Botanicae Horti Agrobotanici Cluj-Napoca, 48: 329–341.

Klauk B., Petersen J. (2023): Evaluation of different weed management strategies including non-chemical tools and cinmethylin for control of multiple herbicide-resistant *Alopecurus myosuroides*. Weed Research, 63: 246–260.

Koch M., Tholen T., Drießen P., Ergas B. (2020): The ElectroherbTM technology – a new technique supporting modern weed management. In: Nordmeyer H., Ulber L. (eds.): Proceedings 29th German Conference on Weed Biology and Weed Control, Braunschweig Germany, 3.3–5.3, 261–263.

KTBL (2023): KTBL-Feldarbeitsrechner. Available at: https://daten.ktbl.de/feldarbeit/entry.html (accessed: 15. 7. 2023)

Kuznetsova A., Brockhoff P.B., Christensen R.H.B. (2017): lmerTest Package: test in linear mixed effects models. Journal of Statistical Software, 82: 1–26.

Lee W.-C., Li T.-L., Chang P.-C., Chou S.-S. (2001): High performance liquid chromatographic determination of maleic hydrazide residue in potatoes. Journal of Food and Drug Analysis, 9: 167–172.

Lenth R. (2023): Emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.8.5, https://CRAN.R-project.org/package=emmeans (accessed: 23. 7. 2023)

Lutman P.J.W., Moss S.R., Cook S., Welham S.J. (2013): A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*. Weed Research, 53: 299–313.

Meier U. (2018): Growth stages of mono- and dicotyledonous plants: BBCH Monograph. Quedlinburg, Open Agrar Repositorium.

Menegat A., Nilsson A.T.S. (2019): Interaction of preventive, cultural, and direct methods for integrated weed management in winter wheat. Agronomy, 9: 564.

Pingali P.L. (2012): Green Revolution: impacts, limits, and the path ahead. Proceedings of the National Academy of Sciences, 109: 12302–12308.

R Core Team (2023): R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/ (accessed 23. 7. 2023)

Riemens M., Van Der Weide R., Bleeker P., Lotz L. (2007): Effect of stale seedbed preparations and subsequent weed control in lettuce (cv. Iceboll) on weed densities. Weed Research, 47: 149–156.

Saleh R., Bearth A., Siegrist M. (2021): How chemophobia affects public acceptance of pesticide use and biotechnology in agriculture. Food Quality and Preference, 91: 104197.

Swain A.J., Hughes Z.S., Cook S.K., Moss S.R. (2006): Quantifying the dormancy of *Alopecurus myosuroides* seeds produced by plants exposed to different soil moisture and temperature regimes. Weed Research, 46: 470–479.

Timmons F.L. (2005): A history of weed control in the United States and Canada. Weed Science, 53: 748–761.

Varah A., Ahodo K., Coutts S.R., Hicks H.L., Comont D., Crook L., Hull R., Neve P., Childs D.Z., Freckleton R.P., Norris K. (2019): The costs of human-induced evolution in an agricultural system. Nature Sustainability, 3: 63–71.

Zeller A.K., Zeller Y.I., Gerhards R. (2021): A long-term study of crop rotations, herbicide strategies and tillage practices: effects on *Alopecurus myosuroides* Huds. abundance and contribution margins of the cropping systems. Crop Protection, 145: 105613.

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