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Evaluation of mechanical and combined chemical with mechanical weeding in maize (*Zea mays* L.), soybean (*Glycine max* (L.) Merr. and winter wheat (*Triticum aestivum* L.)

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Abstract: Joint field experiments were established in Southwestern Germany to investigate the potential of herbicide savings on-farm sites with high densities of problematic weed species. From 2020 until 2024, 21 field studies were conducted in maize, soybean and winter wheat, all realised as randomised complete block designs with four replications. Mechanical weeding and two combined chemical with mechanical weeding methods were compared to conventional broadcast pre- and post-emergence herbicide spraying and an untreated control. Weed density, herbicide savings, greenhouse gas emissions and crop yield were determined for all treatments. On average, 142 weeds/m^2 were counted in the untreated plots. The most frequent weed species were *Chenopodium album*, *Echinochloa crus-galli*, *Solanum nigrum*, *Stellaria media*, and *Veronica persica*. Combined chemical with mechanical weed control in soybean and winter wheat was more effective than chemical and mechanical weed control alone. In maize, the combination of hoeing and herbicide application achieved equal weed control efficacy (WCE) as chemical weeding alone. Hoeing removed less intra-row weeds than inter-row weeds. Hoeing and harrowing had low WCE against *Chenopodium album* and perennial weed species. Combined treatments reduced herbicide use by 24–60% in relation to conventional herbicide treatments. Mechanical and combined weed control achieved equal yield as the conventional herbicide treatment. This study underlines the potential for herbicide savings by integrating mechanical weed control methods.

Keywords: weed competition; band-spraying; integrated weed management

Most European farmers are under strong pressure to reduce their dependence on pesticides in agriculture. The European Commission aims to reduce pesticide use in the EU by 50% by 2030 (European Commission 2019, 2020a,b). Rapid resistance development to herbicides and the loss of active ingredients force farmers to apply alternative weed control methods (Andert and Ziesemer 2022).

Mechanical weeding is the predominant alternative to herbicides as a direct weed control method. Melander et al. (2005) described the positive effects and limitations of pre- and post-emergence harrowing, inter-row and intra-row hoeing in sown and transplanted crops. Pre-emergence harrowing controls weeds that have germinated in the upper soil layer. If pre-emergence harrowing is carried out

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at the right time, it can also delay weed emergence relative to the crop (Panacci et al. 2017). This delay increases the selectivity of post-emergence harrowing and hoeing (Rasmussen 1991, Rueda-Ayala et al. 2011). Annual dicotyledonous weeds are easier to control mechanically than grass weeds and perennials. While weed control efficacy (WCE) of inter-row hoeing is often equal to herbicides, intra-row WCE is rather poor or causes crop damage (Gerhards et al. 2020). For high selectivity of mechanical in-row weed control with tools such as finger weeders, torsion weeders, and ridging elements, weeds need to be smaller than the crop (Rueda-Ayala et al. 2011). All mechanical weeding tools require relatively dry soil conditions. Therefore, the WCE of mechanical weeding strongly depends on weather conditions (Melander et al. 2005).

Great improvements were made in mechanical weed control to increase WCE and selectivity, reduce crop damage and make application more efficient and easier (Van der Weide et al. 2008, Rueda-Ayala et al. 2015). Those improvements include row guiding systems with cameras for crop row detection in combination with hydraulic side-shift control of hoeing blades (e.g. KULT-Vision Control®, Kürnbach, Germany) in row-weeders using relatively simple imaging algorithms for crop detection (e.g. Stekete IC®, KULTi-Select®, Kürnbach, Germany) and completely autonomous hoeing robots using artificial intelligence (AI) for plant species classification (e.g. Farming GT®, Donzdorf, Germany) (Gerhards et al. 2024).

Wide parts of Baden-Wuerttemberg agriculture are dominated by narrow rotations of winter cereals and winter oil-seed rape. Winter oil-seed rape is sown in late August, and cereals are sown sometimes already in September. Therefore, this rotation cannot include preventive weed control methods such as false seedbeds and cover crops. Broadcast applications of pre- and post-emergence herbicides are often the only possible weed management tactics. This monotonous cropping system has selected a few problematic weed species, including *Stellaria media* (L.) Vill., *Veronica persica* Poir., *Galium aparine* L. and *Alopecurus myosuroides* Huds. with very high population densities and herbicide resistance, mainly in winter annual grass-weeds (Gerhards et al. 2022). In other areas of Baden-Wuerttemberg along the Rhine Valley, monocultures of maize or simple rotations of maize and soybean are often practised. Those fields often have high population densities of *Chenopodium album* L. and *Echinochloa crus-galli* (L.) Pal. Beauv. and *Amaranthus retroflexus* L. (Keller et al. 2014). Such fields with high weed infestations were selected for this study. Combined weeding (herbicide + mechanical or mechanical + herbicide band application) and purely mechanical weeding were compared to conventional broadcast herbicide treatments and untreated control. The objectives of this study were to evaluate those weed management systems regarding weed control efficacy, crop yield and greenhouse gas emissions. WCE was assessed per weed species to highlight species with lower and higher WCE than the mean for the weed management strategies. The hypotheses were that (*i*) combined chemical and mechanical weed control strategies provide higher weed control efficacy than each of the single treatments; (*ii*) intra-row WCE of mechanical weeding is lower than inter-row weed control; (*iii*) greenhouse gas emissions are higher for mechanical and combined weed control strategies than for chemical weed control, and (*iv*) crop yield is higher for combined weed control strategies compared to mechanical and chemical weeding alone.

MATERIAL AND METHODS

Study sites. The study is based on four field experiments in winter wheat, 10 experiments in maize and 7 experiments in soybean from 2020 until 2023. All experiments were set up in a randomised complete block design with four replicate blocks. Each plot had a length of 20 m and a width of 3 m. Two combined chemical and mechanical weed control strategies were tested against mechanical and chemical weed control alone. Combined weed control strategies included only one herbicide treatment, either pre-emergence (No. 4) or post-emergence herbicide (No. 5) combined with mechanical weeding. An untreated control was included in all experiments. Treatment 5 in soybean included post-emergent herbicide application in a 20 cm wide band over the crop row combined with inter-row hoeing (Tables 1 and 2).

Maize and soybean were sown with single-grain seeding technology at the end of April. The row spacing for soybean was 50 cm, and for maize, 75 cm. On average, 9 maize seeds/m^2 and 55 soybean seeds/m^2 were sown. Winter wheat was sown in October with 300 seeds/m^2 using drill seeding technology. The row spacing for winter wheat was 15 cm. Reduced tillage was practised at all locations, usually with one pass of the cultivator and one pass of rotary harrow before sowing.

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Table 1. Treatments tested in the field experiments

No.	Treatment	Shortcut
1	untreated control	control
2	combination of pre- and post-emergence herbicide application	herbicide
3	pre- and post-emergence harrowing and interrow hoeing	mechanical
4	pre-emergence herbicide followed by interrow hoeing	pre-herb + mech
5*	harrowing and hoeing followed by post-emergence herbicide	mech + post-herb
5**	inter-row hoeing combined with intra-row band-spraying	mech + herb-band

*in maize and winter wheat; **in soybean

Herbicides were applied with a plot sprayer (e.g. Schachtner-Gerätetechnik, Ludwigsburg, Germany) with a 3 m wide boom. The sprayer was calibrated for a volume of 200 L/ha and a speed of 3.6 km/h. Nozzles with a spray rate of 0.8 L/min at 3 bar pressure were used. The nozzle distance was 50 cm. Special nozzles with uniform distribution (Lechler, E 8002 (60 M)) at a pressure of 2.4 bar and a speed up to 4.5 km/h were used for band-spraying. Harrowing in winter wheat was conducted with a flex tine harrow (Einböck, Aerostar Classic, Dorf an der Pram, Austria). Post-emergence harrowing was applied when winter wheat had at least 3 leaves. Inter-row hoeing was done with goosefoot blades at a 5 km/h driving speed. Hoeing blades were guided through the inter-row area with a 5 cm distance to the crop row in maize and soybean and 3 cm in winter wheat. Post-emergence hoeing started when winter wheat had 3 leaves, maize 2 leaves and soybean one trifolium. Mechanical weeding was only applied under dry conditions with at least three consecutive days without rainfall were forecasted after the treatment.

Data collection. Weed density by species was counted before and after weeding using a 0.5 m^2 frame. Four counts were made per plot. The sampling frame was divided into a 0.4 m^2 inter-row area and a 0.1 m^2 intra-row area. This allowed us to assess inter-row and intra-row weed density separately. The efficacy of mechanical weeding was assessed immediately after treatment. The efficacy of the herbicide treatments was assessed 14 days after the application using the same method as before and immediately after weeding. All green weeds were classified as survivors. Weed control efficacy for inter- and intra-row was calculated according to Eq. (1).

$$\text{WCE (\%)} = 100\% \; (1 - w_a/w_b) \tag{1}$$

where: w_a – weed density after treatment; w_b – weed density before the treatment.

Winter wheat and soybean yield was obtained in an area of 2 m × 20 m in the centre of each plot using a plot combine harvester (Zürn 150, Westernhausen, Germany). Grain yield was recalculated for grain moisture at 14%. In the maize experiments, the two middle rows in each plot were harvested with Kemper Häcksler® (Maschinenfabrik KEMPER GmbH & Co. KG Stadtlohn, Germany) to determine fresh silage maize yield. Fresh biomass was dried for 48 h at 80 °C to determine dry biomass (t/ha).

Data analysis. The data were analysed using the statistical software RStudio (Version 3.4.1, R Foundation for Statistical Computing, Vienna, Austria). Figures were created with OriginPro 2022b (OriginLab Corporation, Northampton, USA). Homogeneity of variance and normal distribution of residuals were approved using residual plots and a quantile-quantile plot. An analysis of variance (ANOVA) was performed with treatment as a fixed effect and location/year as a random effect. The means of the fixed effects were compared with Tukey's *HSD* (honestly significant difference) test at $\alpha \leq 0.05$.

RESULTS AND DISCUSSION

Weed species composition, weed density and weed control efficacy. The dominant weed species in maize and soybean were *Chenopodium album*, *Echinochloa crus-galli*, *Polygonum lapathifolium* L., *Solanum nigrum* L. and *Amanthus retroflexus*. *Stellaria media*, *Veronica persica*, *Lamium purpureum* L. and *C. album* were the dominant weed species in winter wheat.

Locations (P = 0.37) and interactions of locations and treatments (P = 0.29) were not significant. Therefore, data were pooled over locations. Treatments had a significant effect on weed density and WCE (P < 0.01).

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Table 2. Experimental details of the field experiments

No.	Location	Crop/ cultivar	Year	Sowing date	Herbicide treatments (rates in L or kg/ha)	Mechanical treatments
1	Böblingen	maize, cv. Charleen	2020	24/04/20	1.5 MaisTer Power[1] (2*), 0.25 Adengo[2] (5), 2.5 Spectrum Plus[3] (2, 4)	2 × hoe (3–5*)
2	Calw	soybean, cv. SY Livius	2020	26/04/20	0.2 Centium 36 CS[4] + 0.8 Spectrum[6] (2), 0.3 Sencor Liquid[5] (2, 4), 1.0 Clearfield Clentiga[7] + additive (5)	3 × hoe (3), 1 × hoe (4, 5)
3	Hohen-heim	winter wheat, cv. Apostel	2021	20/11/20	3.0 Herold[8] (2, 4), 0.6 Broadway[9] (2, 5)	1 × hoe (3, 4, 5)
4	Böblingen	maize, cv. LG31238	2021	27/04/21	1.5 MaisTer Power[1] (2*), 0.25 Adengo[2] (5), 2.5 Spectrum Plus[3] (2, 4)	1 × hoe (3, 4, 5)
5	LTZ	maize, cv. DKC4908	2021	24/04/21	1.5 MaisTer Power (2, 5), 2.5 Spectrum Plus (2, 4)	1 × hoe (3, 4, 5)
6	Emmen-dingen	maize, cv. P9757	2021	31/05/21	1.0 MaisTer Power (2, 5), 2.5 Spectrum Plus (4)	1 × hoe (3, 4, 5)
7	Calw	soybean, cv. Achillea	2021	15/05/21	0.2 Centium 36 CS + 0.3 Sencor Liquid (2, 4), 0.8 Spectrum (2), 1.0 Clearfield Clentiga + additive (5)	3 × hoe (3), 1 × hoe (4), 2 × hoe (5)
8	Tübingen	soybean, cv. Coraline	2021	23/04/21	2.0 Artist[10] (2), 0.3 Sencor Liquid + 0.2 Centium 36 CS (4), 1.0 Clearfield Clentiga + additive (5)	1 × hoe (3,4, 5)
9	Hohen-heim	winter wheat, cv. Apostel	2022	22/10/21	2.5 Herold (2, 4), 0.5 Broadway (2, 5)	1 × pre-emergence harrow (3, 4), 3 × post-emergence harrow (3), 1 × post-emergence harrow (5)
10	LTZ	winter wheat, cv. Ramses	2022	28/10/21	2.5 Herold (2 ,4), 0.5 Broadway (2, 5)	1 × hoe (3, 4), 1 × post-emergence harrow (3, 5)
11	Hohen-heim	maize, cv. Crosbey	2022	02/05/22	1.0 MaisTer Power (2, 5), 2.5 Spectrum Plus (2), 0.25 Adengo (4)	1 × stale seedbed (3, 4, 5), 3 × hoe (3, 4), 2 × hoe (3)
12	LTZ	maize, cv. LG 369	2022	11/05/22	2.0 Laudis[11] (2, 5) 2.0 Spectrum Plus (2, 4)	1 × hoe (4, 5)
13	Böblingen	maize, cv. LG 31253	2022	03/05/22	1.0 MaisTer Power (2, 5), 0.25 Adengo (2, 4)	1 × hoe (3–5)
14	Tübingen	soybean, cv. Achillea	2022	23/04/22	2.0 Artist (2), 0.3 Sencor Liquid + 0.2 Centium 36 CS (4), 1.0 Clearfield Clentiga + additive (5)	2 × hoe (3–5)
15	Hohen-heim	soybean, cv. Achillea	2022	09/05/22	2.0 Artist (2), 0.3 Sencor Liquid + 0.2 Centium 36 CS (4), 1.0 Clearfield Clentiga + additive (5)	2 × hoe (3–5)
16	Hohen-heim	winter wheat, cv. Patras	2023	3/11/22	2.5 Herold (2, 4), 0.5 Broadway (2, 5)	2 × post-emergence harrow (3, 4, 5)
17	Hohen-heim	maize, cv. Jakleen	2023	03/05/23	1.0 MaisTer Power (2, 5), 2.5 Spectrum Plus (2), 0.25 Adengo (4)	2 × hoe (3, 5), 1 × hoe (4)
18	Reutlingen	maize, cv. Belami CS	2023	20/05/23	1.5 MaisTer Power (2), 1.0 MaisTer Power (5), 2.5 Spectrum Plus (4)	1 × hoe (3, 4, 5)
19	Böblingen	maize, cv. Jakleen	2023	22/05/23	1.5 MaisTer Power (2, 5), 2.0 Stomp Aqua[12] (4)	1 × hoe (3, 4, 5)
20	Hohen-heim	soybean, cv. Amidala	2023	03/05/23	0.2 Centium 36 CS[4] + 0.8 Spectrum[6] (2), 0.3 Sencor Liquid[5] (2, 4), 1.0 Clearfield Clentiga[7] + additive (5)	3 × hoe (3, 5), 1 × hoe (4)
21	Tübingen	soybean, cv. Regina	2023	05/05/23	0.2 Centium 36 CS[4] + 0.8 Spectrum[6] (2), 0.3 Sencor Liquid[5] (2, 4), 1.0 Clearfield Clentiga[7] + additive (5)	1 × hoe (3–5)

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*Treatment number: [1]30 g/L foramsulfuron, 9.8 g/L thiencarbazone, 0.85 g/L iodosulfuron, 15 g/L cyprosulfamide (sfener) OD, Bayer CropScience; [2]225 g/L isoxaflutole, 86.8 g/L thiencarbazone, 150 g/L cyprosulfamide (safener), EC, Bayer CropScience; [3]250 g/L pendimethalin, 213 g/L dimethenamid-P, EC, BASF; [4]360 g/L clomazone, CS, FMC; [5]600 g/L metribuzin, SC, Bayer CropScience; [6]720 g/L dimethenamid-P; [7]12.5 g/L imazamox, 250 g/L quinmerac, SC, BASF; [8]400 g/L flufenacet, 200 g/L diflufenican, SC, Adama; [9]68 g/kg pyroxsulam, 22.8 g/kg florasulam, 68.3 g/kg cloquintocet-mexyl (safener), SD, Corteva; [10]240 g/kg flufenacet, 175 g/kg metribuzin, WG, Bayer CropScience; [11]44 g/L tembotrione, 22 g/L isoxadifen-ethyl (safener), OD, Bayer CropScience; [12]455 g/L pendimethalin, CS, BASF

In maize, an average of 143 weeds/m^2 were counted in the untreated control. Mechanical weeding reduced inter-row weed density to the same extent as herbicides and combined chemical and mechanical weeding. However, intra-row weed density after mechanical weeding was significantly higher than in the herbicide treatment and the combination of hoeing and post-emergence herbicide application (Figure 1A).

The average WCE did not exceed 83% in any of the treatments. Mechanical weeding achieved the lowest WCE with 50% inter-row WCE and 36% intra-row

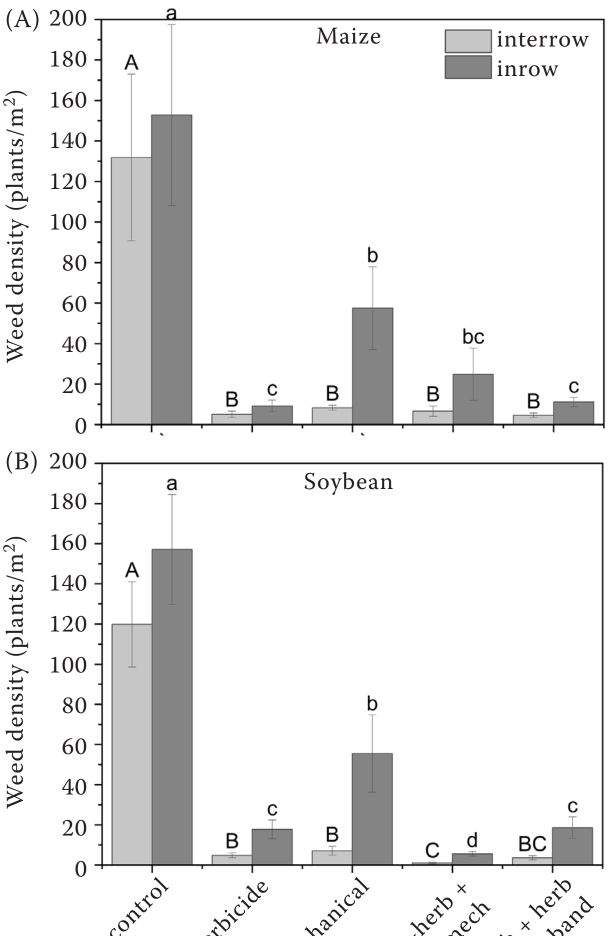

Figure 1. Effect of weed control strategies on weed density in (A) 10 maize and (B) 7 soybean experiments in Baden-Württemberg from 2020 until 2023. Weed density was measured after all treatments had been completed. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean

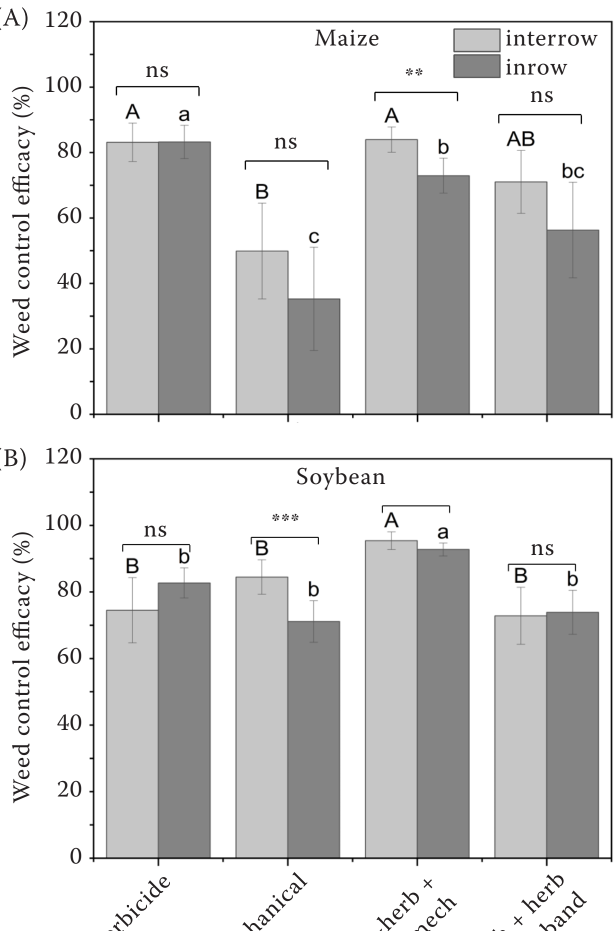

Figure 2. Weed control efficacy (WCE) in (A) 10 maize and (B) 7 soybean experiments in Baden-Württemberg from 2020 until 2023. WCE was measured after all treatments had been completed. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean. ns – not significant; $^{**}P \leq 0.01$; $^{***}P \leq 0.001$

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WCE. Inter-row WCE and intra-row WCE were equal in the conventional chemical weeding plots. Intra-row WCE in the conventional herbicide treatment was higher than in all other treatments. However, inter-row WCE was equal in the chemical and combined treatments (Figure 2A). WCE against perennial weed species such as *Cirsium arvense* (L.) Scop. and *Convolvulus arvensis* L. was lower than the average in all weed control treatments. Hoeing against *C. album* was less effective than the average and also lower than in the other treatments.

In soybean, treatments significantly reduced inter-row and in-row weed density weed densities compared to the untreated control with 120 inter-row weeds/m^2 and 159 inter-row weeds/m^2. Intra-row weed density was higher than inter-row weed density for all treatments. The combined weed control strategy using a pre-emergence herbicide and post-emergence hoeing resulted in the lowest densities with one inter-row weed/m^2 and 7 intra-row weeds/m^2 (Figure 1B).

Weed control efficacy was highest in the combined treatment with a pre-emergence herbicide followed by interrow hoeing (95% WCE). All other treatments achieved only around 80% WCE. For mechanical weeding, it was observed that inter-row WCE was higher than intra-row WCE (Figure 2B).

In winter wheat, 143 inter-row weeds/m^2 and 151 inter-row weeds/m^2 were counted in the untreated control. All treatments significantly reduced weed density. Mechanical weeding combined with post-emergence herbicide application resulted in the lowest intra-row weed density and highest inter-row WCE (Figures 3 and 4).

Mechanical weeding could only partly compensate for chemical weed control. In-row weed control efficacy of mechanical weeding was significantly lower than inter-row WCE. While mechanical in-row weeding can be very efficient in transplanted crops (Tillett et al. 2008) and in cereals using a harrow (Rasmussen 1991, Cirujeda et al. 2003), selective in-row hoeing in annual crops is very difficult. Weeds within crop rows were only buried by soil but not up-rooted as the inter-row weeds. In-row weeding using torsion weeders or finger weeders was not used in the present study. They can be implemented in conventional inter-row hoes (Van der Weide et al. 2008, Pannacci and Tei 2014). However, their efficacy was rather low if weeds emerged earlier or simultaneously with the crop (Van der Weide et al. 2008, Pannacci and Tei 2014, Gerhards et al. 2020). In-row weeding tools also increase the risk of crop damage and reduce the driving speed (Gerhards et al.

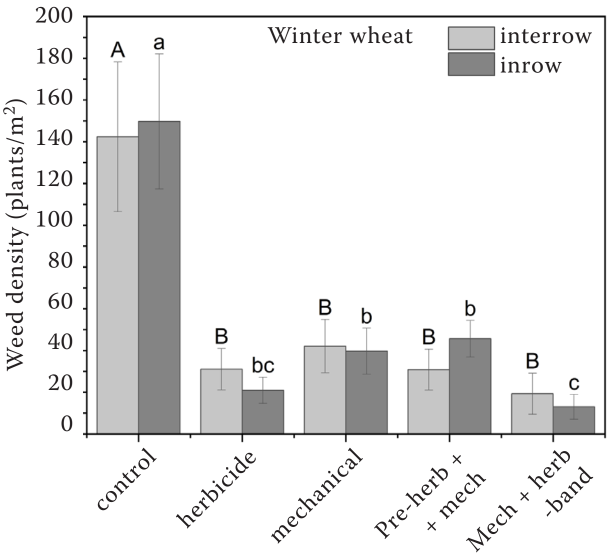

Figure 3. Effect of weed control strategies on weed density in four winter wheat experiments in Baden-Württemberg from 2020 until 2023. Weed density was measured after all treatments had been completed. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean

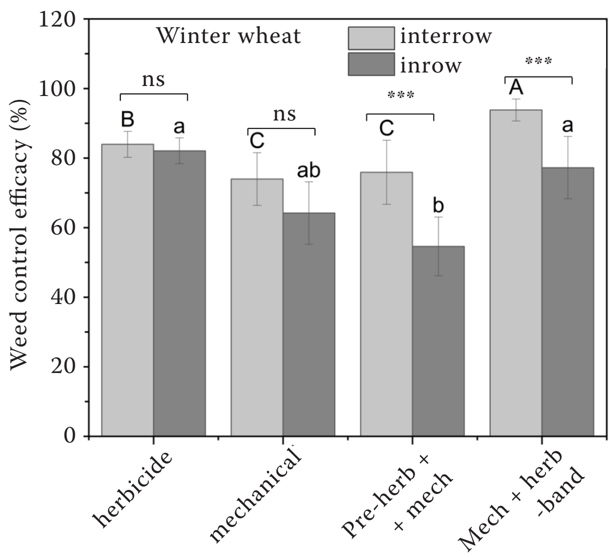

Figure 4. Weed control efficacy (WCE) in four winter wheat experiments in Baden-Württemberg from 2020 until 2023. WCE was measured after all treatments had been completed. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean. ns – not significant; ***$P \leq 0.01$

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2024). In-row mechanical weeding can be improved by camera-guided hoes with automatic hydraulic side-shift control (Kunz et al. 2018) or robotic in-row weeding (Gerhards et al. 2024).

The highest WCE in soybean and winter wheat was achieved with a combination of mechanical weeding and reduced herbicide rate. In maize, combining herbicide and hoeing and the conventional herbicide treatment resulted in equal WCE. Those results support the benefit of multiple tactics in weed management (Riemens et al. 2022). Integrated weed management (IWM) combines preventive with curative methods of weed control. Preventive methods such as cover cropping, living mulches, delayed sowing of winter cereals and stale seedbed could provide additional weed control to curative methods (Mortensen et al. 2012, Lutman et al. 2013, Zeller et al. 2021, Gerhards et al. 2022, Riemens et al. 2022). However, preventive methods were mostly missing in this study. The focus was to test if herbicides can be replaced by mechanical weeding. The relatively low average WCE of 80% of overall treatments in the present study can be explained by the missing preventive weed control tactics, which were extremely important in managing high densities of problematic weed species in other studies (Melander et al. 2005, Lutman et al. 2013, Riemens et al. 2022).

Crop yield. Mechanical weeding and combinations of chemical and mechanical weeding saved the crop yield as good as conventional herbicide treatments. The dry biomass yield of maize was significantly higher in the herbicide treatment and the combination of mechanical weeding and post-emergence herbicide compared to the untreated control (P = 0.0127). Despite lower WCE, mechanical weeding had equal yield compared to all other treatments. Soybean yield was relatively low, with a maximum of 2.6 t/ha in the herbicide treatment and combining inter-row hoeing with intra-row band-spraying. Yield differed only between those two treatments and the untreated control. Grain yield in winter wheat was equal in all treatments, with approximately 8 t/ha (Figure 5).

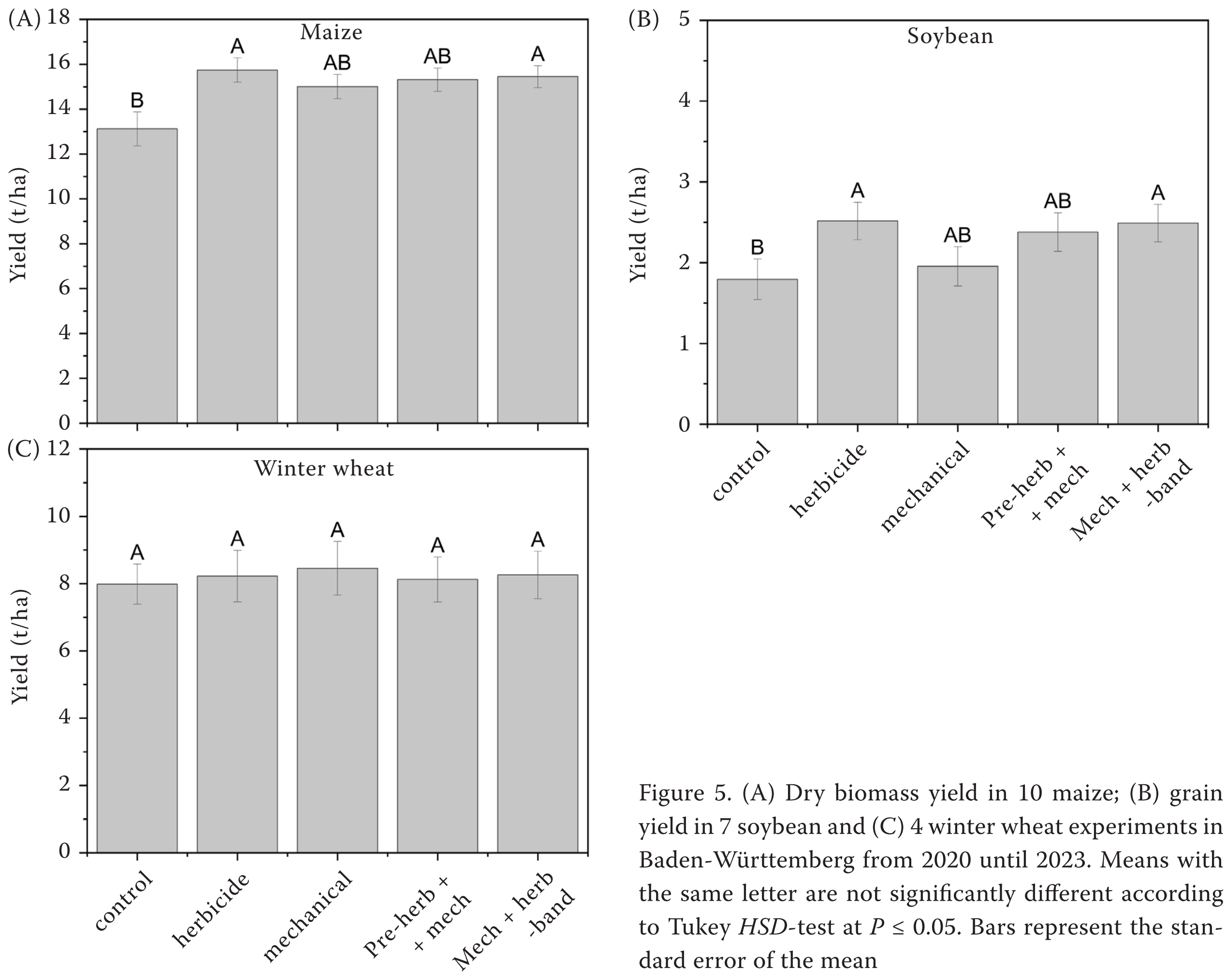

Figure 5. (A) Dry biomass yield in 10 maize; (B) grain yield in 7 soybean and (C) 4 winter wheat experiments in Baden-Württemberg from 2020 until 2023. Means with the same letter are not significantly different according to Tukey *HSD*-test at $P \leq 0.05$. Bars represent the standard error of the mean

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Table 3. Average herbicide savings of combined weed management strategies in maize (10 experiments), soybean (7 experiments) and winter wheat (4 experiments)

Treatment	Maize	Soybean	Winter wheat
Pre-herb + mech	40	24	50
Mech + post-herb or band-herb	43	60	50

Herbicide savings. Herbicide savings in the combined weed control strategies amounted to 24–60%. Savings were defined as the relative untreated area compared to the conventional chemical treatments with pre- and post-emergence herbicides. The highest savings (60%) were achieved with band-spraying in soybeans. The same herbicide at an equal rate was used as in the conventional broadcast herbicide treatment, but only in a 20 cm band over the top of each crop row was sprayed. All other savings resulted from fewer herbicide applications compared to the broadcast herbicide treatment, with usually two applications (pre- and post-emergence). In all four winter wheat experiments, herbicides were applied in autumn and spring in the chemical treatment. In the combined treatments, only one herbicide was applied (Table 3). This is clear evidence that the targets of the EU Commission for reducing pesticides in agriculture (European Commission 2019, 2020a,b) can be met with the current technologies for mechanical weed control and band-spraying. Despite many improvements made in mechanical weeding, several limitations will remain. Mechanical weeding requires dry soil conditions in the early growth stage of the weeds for acceptable weed control efficacy. Hoeing and harrowing perform better in light and loose soils than soils with higher clay and stone contents. It must also be considered that conventional mechanical weeding takes more working time than chemical weed control because of lower driving speed and lower working width (Machleb et al. 2020, Xiang et al. 2024).

This study highlights the potential for saving herbicides by combining mechanical and chemical weeding in arable fields with high infestations of problematic weed species.

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