Weed Technology

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Research Article

Cite this article: Alagbo OO, Saile M, Spaeth M, Schumacher M, Sökefeld M, Gerhards R (2025) Evaluation of different precision hoeing methods and soil physical properties of re-compacted ridge tillage systems in corn. Weed Technol. **39**(e79), 1–12. doi: 10.1017/wet.2025.10027

Received: 6 February 2025
Revised: 8 May 2025
Accepted: 24 May 2025

Associate Editor:
Kevin Bradley, University of Missouri

Nomenclature:
Corn; *Zea mays* L.

Keywords:
Conservation tillage; herbicide; living mulch; mechanical weed control; ridge cultivator; precision agriculture; soil moisture; soil temperature

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Evaluation of different precision hoeing methods and soil physical properties of re-compacted ridge tillage systems in corn

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Abstract

This study aimed to evaluate different precision hoeing methods on re-compacted ridges. It also aimed to evaluate the impact of ridge re-compaction on soil temperature and moisture retention. Five weeding trials were conducted in corn fields from 2022 to 2024 using two different ridge cultivators, Glühfosator and Damm Profi. The treatments included hoeing (HOE-2), hoeing combined with band herbicide spraying (HOE-1), hoeing combined with living mulch sown in the ridge valleys (HOE-3), and hoeing combined with postemergence harrow (HOE-4). Nontreated control and broadcast herbicide plots were included as controls. Soil moisture and temperature were recorded at 20-min intervals from May to September. Weed species composition, weed biomass, and corn silage yield were measured. Broadleaf weeds were the dominant weed species observed in all corn trials. In most trials, the hoeing treatments were not significantly different from that of applying a broadcast herbicide. Interrow areas treated with side-cut knives and ridge re-builders (HOE-1, HOE-2, and HOE-3) produced a significantly reduced weed biomass (4 to 55 g m^{-2}) and exhibited high (80% to 96% weed control efficacy (WCE) across all trials. Intrarow-treated areas (i.e., tops of ridges) with a band herbicide (HOE-1), no-till sweeps (HOE-2, HOE-3), and postemergence harrow (HOE-4) resulted in 88% to 100%, 30% to 63%, and 17% WCE, respectively. Depending on corn cultivar and ridge cultivator, the HOE-1, HOE-4, and HOE-2 treatments resulted in corn silage yield that was similar to or greater than that of a broadcast herbicide. Yield was increased by 2000 to 9000 kg ha^{-1} after the HOE-1 treatment, by 2000 to 5000 kg ha^{-1} after the HOE-4 treatment, and by 3000 to 6000 kg ha^{-1}, after the HOE-2 treatment. When rainfall was limited, re-compacted ridges demonstrated moisture conservation, which resulted in higher day-warming and lower night-cooling of ridge valleys (compared to ridge areas and flat-tilled beds), whereas when rain is heavy, ridges drained moisture and exhibited higher day-warming and lower night-cooling of ridge areas. These results suggest that precision hoeing on ridges could alternate broadcast herbicide use, while re-compacted ridges prove resilient to extreme rainfall events.

Introduction

Ridge tillage (RT) is a conservation practice that entails using raised seedbeds to optimize crop establishment and to obtain better yield outcomes (Alagbo et al. 2022). Ridges provide higher soil temperature, lower soil penetration resistance for roots, and enhanced nutrient mineralization, which all help to optimize crop growth and development (Benjamin et al. 1990; Liu et al. 2018; Shi et al. 2012). More importantly, re-compacting ridges can optimize water capillary movement (Alagbo et al. 2022, 2024). At the early growth stage of the crop, ridges often enhance crop competitiveness against weeds and can equally enhance the crop's tolerance to mechanical weeding due to better root establishment (Alagbo et al. 2022). Despite these merits, there are limitations in adopting RT systems for the cultivation of all field crops. Depending on the row-width configuration of ridges, specialized cultivators may be required for mechanical weeding and harvesting (Ditsch 1986; Klein et al. 2007). Additionally, increased weed pressure often becomes problematic in permanent RT systems in the long term (Forcella and Lindstrom 1988a; Jernigan et al. 2017; Jordan 1993) due to the nutrient-rich profile of ridges (Benjamin et al. 1990; Liu et al. 2018; Shi et al. 2012).

RT has been adopted by many farmers around the world for the cultivation of corn, soybean [*Glycine max* (L.) Merr.], tubers, and many vegetables (Alagbo et al. 2022). Broadcast herbicide application and manual weeding remain the prevalent weed management options in RT-cultivated fields (Forcella & Lindstrom, 1988a; Jernigan et al. 2017). However, the increasing population of herbicide-resistant weed species remains a concern (Klein et al. 1996; Wicks et al. 1996). Also, leaching of broadcasted herbicides into ridge valleys is inevitable due to increased soil water infiltration (Hatfield et al. 1998). The practice of manual labor to hand-pull weeds is costly in organic RT systems (Jernigan et al. 2017). Hence, precise, low-cost, and environmentally friendly weed management options are needed for RT systems.

The European Union directives for integrated pest management (European Commission 2009, 2020) recommend the integration of preventive and curative weed control approaches to lessen dependence on herbicides, thus reducing their adverse effects on the environment and averting the evolution of herbicide-resistant weed populations (Mortensen et al. 2012). Within conventional and organic farming systems, the current trends in the optimization of nonchemical weed management strategies include the use of living mulches and mechanical weeding (Alagbo et al. 2022; Bhaskar et al. 2021; Gerhards and Schappert 2020). Living mulch has been well proven to reduce erosion and leaching of nutrient resources, and to enhance weed suppression and nitrogen fixation (Bhaskar et al. 2021). In addition to early crop development on ridges (Jurik 1993), RT can combine mechanical weeding on the ridges with living mulches in the valleys to suppress weeds or herbicides sprayed in a band on the top of ridges (Alagbo et al. 2022). Weed management tactics such as these are expected to minimize weed pressure and the development of herbicide-resistant weed species.

Alagbo et al. (2024) developed and demonstrated a combined hoeing and living mulch seeding technology for re-compacted RT. Re-compacted ridges were formed with new ridging machines: Glühfosator (Frost Maschinenbau GmbH, Petershagen, Germany) and Damm Profi (Evers GmbH, Oberhausen, Germany). Both ridging elements have heavy prism rollers coupled behind that can re-compact the ridges. The soil physical properties of ridges are expected to improve when ridges are re-compacted (Alagbo et al. 2022). In addition, Damm Profi ridge cultivators loosen deep ridges (up to 0.5 to 1 m along crop rows prior to ridge forming and re-compaction) to enhance deep root penetration. In principle, straight ridges are built with RTK-GNSS (real-time kinematics global satellite navigation support system) guidance. Those straight ridges allow precise positioning and guidance of postemergence hoeing elements and autosteered seeding of living mulch using ridge furrows as a guideline. In conventional RT cropping systems, band herbicide spraying on top of ridges is expected to be combined with interrow hoeing instead of spraying herbicides on the entire ridge area. In organic-based RT cropping systems, the impact of living mulch seeding and hoeing is expected to enhance weed suppression and crop competitiveness in different crops, as an alternative to manual weeding.

The objective of this study was to evaluate the performance of different hoeing combinations on re-compacted RT systems. We further intended to evaluate the effect of ridge re-compaction on soil temperature and moisture. Several studies using flat tillage seedbeds have reported higher weed control efficacy with interrow hoeing in combination with band herbicide applications with 50% to 60% herbicide savings compared to broadcast herbicide applications (Loddo et al. 2020; Pannacci and Tei 2014). Other studies have combined interrow hoeing with intrarow torsion weeders or finger weeding using different camera sensors (Kunz et al. 2015, 2018). However, the literature contains little information on crops sown on ridges. Hence, we hypothesized that mechanical weed control combined with herbicide band spraying or living mulches could optimize weeding efficiency and increase silage yield relative to broadcast herbicide treatment in an RT system.

Materials and Methods

Experimental Site

Five corn field trials (I-2022, II-2022, III-2023, IV-2023, and V-2024) were conducted during the summer seasons of 2022, 2023, and 2024 at Ihinger-Hof, a research station of the University of Hohenheim (Table 1). Ihinger-Hof is located near Renningen (48.742361°N, 8.091972°E) in southwestern Germany, at an elevation of 475 m asl. The soil texture of Ihinger-Hof is classified as a loess loam with subsoil clay (Tschernosem-Parabraunerde). Figure 1 shows the summer rainfall and temperatures during the trial periods.

Experimental Design

The five trials were set up as randomized complete block designs with four replicates. Different weed control treatments were tested within ridges cultivated with Glühfosator or Damm Profi ridging machines. Weed control treatments in each trial (see Table 1) included an untreated control; a broadcast herbicide application; HOE-1, two hoeings (interrow) combined with band herbicide application on ridge tops (intrarow); HOE-2, two hoeings (interrow and intrarow); HOE-3, two hoeings (interrow and intrarow) combined with living mulch seeding in valleys of ridges; and HOE-4, two hoeings (interrow) combined with postemergence harrowing on ridge tops (intrarow). Control plots were left untreated throughout the entire crop cycle. The plot size was 3 m × 20 m in 2022, 3 m × 12 m in 2023, and 3 m × 15 m in 2024 with the longer sides of each plot in the sowing direction.

Agronomic Practice

In each trial location, the preceding crop was winter wheat (*Triticum aestivum* L.). Before ridging, the soil was deeply tilled with a moldboard plow (up to 30 cm deep). An RTK-GNSS guided ridging machine (Glühfosator) was used to form re-compacted ridges on May 27, 2022; January 22, 2023; and May 10, 2024. Another ridging RTK ridging machine, Damm Profi, was included in 2023 and 2024 experiments to compare both ridgers (see Figure 2). Corn variety Capuceen was sown in Trials I-2022, II-2022, and III-2023; cultivar Crowsbey was sown in Trial IV-2023; and cultivar Janeen-DSV was sown in Trial V-2024. Corn was sown with a Monosem seeding machine (Kansas City, KS) in a single row with a single corn seeder at a seeding rate of 8.8 seeds m^{-2} and 0.75-m row distance. Corn was sown on May 4, 2022; May 4, 2023; and May 10, 2024.

Treatment Applications

Hoeing Treatment Setup. Alagbo et al. (2024) developed and described a new hoeing prototype for precise postemergence hoeing on ridges built with RTK-GNSS technology. Different hoeing setups were adjusted for precise hoeing. Intrarow hoeing was performed with four pairs of no-till sweeps (8 cm wide) arranged on a 3-m hoeing frame and positioned on ridge tops with 5 cm distance from corn plants (i.e, a diameter of 10 cm around the crop was free) to prevent crop losses. Within the same setup, interrow hoeing was carried out simultaneously with four opposite pairs of down-cut side-knives (bent 130° parallel to the slopes of ridges) positioned to remove weeds within 75-cm slopes and valleys of ridges, followed by five V-shaped ridge re-builders to

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Table 1. Treatment description for different experimental trials at Ihinger-Hof in 2022, 2023, and 2024.[a]

Trial	Ridge cultivator	Weed control treatments						Corn cultivar
		CTRL	HERBI	HOE-1	HOE-2	HOE-3	HOE-4	
I-2022	Glühfosator	yes	yes	yes	yes	yes	yes	Capuceen
II-2022	Glühfosator	yes	yes	yes	yes	yes	yes	Capuceen
III-2023	Glühfosator	yes	yes	yes	yes	yes	yes	Crossbey
IV-2023	Glühfosator vs. DammProfi	yes	yes	NA	yes	yes	NA	Crossbey
V-2024	Glühfosator vs. DammProfi	yes	yes	yes	yes	yes	NA	Janeen-DSV

[a]Abbreviations: CTRL, untreated control; HERBI, broadcast herbicide; HOE-1, two hoeings combined with band herbicide application; HOE-2, two hoeings; HOE-3, two hoeings combined with living mulch application; HOE-4, two hoeings combined with postemergence harrowing; NA, treatments not applied.

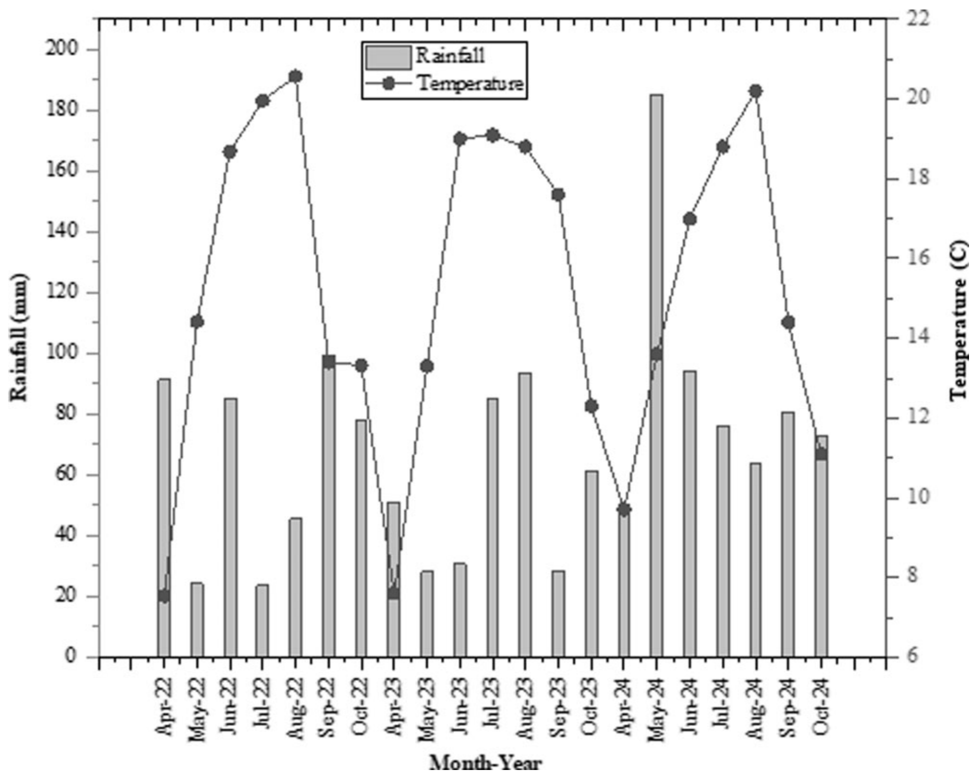

Figure 1. Rainfall (mm) and temperature (C) at Ihinger Hof during summer growing seasons (April to October) of 2022, 2023, and 2024.

reform ridges consequent to possible disruption by hoeing operation (Figure 3).

All hoeing treatments were performed at a relatively high driving speed of 5 km h^{-1} (Peruzzi et al. 2017) with a hoeing working depth of 3 to 4 cm. In all trials, the first and second hoeings were carried out at the 3- to 4-leaf and the 7- to 8-leaf stages, respectively. Two hoeing passes in corn fields occurred on May 17 and June 10, 2022; May 23 and June 16, 2023; and June 6 and July 13, 2024.

Broadcast and Band Herbicide Applications. For broadcast and band herbicide treatments, 2.5 L ha^{-1} of Spectrum Plus (BASF; 212.5 g L^{-1} dimethenamid-P + 250 g L^{-1} pendimethalin EC) and 1.0 L ha^{-1} of MaisTer Power (Bayer CropScience; 30.0 g L^{-1} foramsulfuron + 9.77 g L^{-1} thiencarbazone-methyl + 0.85 g L^{-1} iodosulfuron + 15 g L^{-1} cyprosulfamide, SC) were applied as tank-mixtures at the 3- to 4-leaf stage. All herbicides were applied with a plot sprayer (Schachtner-Fahrzeug und Gerätetechnik, Ludwigsburg, Germany). Broadcast spraying was performed with six flat-fan AD 120-02 nozzles (Lechler, St. Charles, IL; nozzle height 50 cm, band-width 25 cm) arranged with 50-cm spacing on a 3-m spraying boom. Intrarow band spraying was applied to complement hoeing, with 67% herbicide reduction in comparison to broadcast application. Band spraying was carried out on top of ridges as an intrarow treatment (covering 33% of the entire ridge area) with four 8001 E Lechler flat-fan nozzles (nozzle height 22 cm, band width 25 cm) arranged with 75-cm spacing on a 3-m spraying boom. Both broadcast and band nozzles were calibrated to deliver 200 L ha^{-1} at a pressure of 1.7 kPa and 3.6 km h^{-1} driving speed.

Living Mulch Seeding. In 2022, (Trials I and II), mixtures of ryegrass (*Lolium perenne* L.) and clover (*Trifolium subteraneum* L.) were seeded with a Lehner Ventor seeder (Lehner Maschinenbau GmbH, Westerstetten, Germany) integrated within the hoeing setup for precise broadcasting of seeds within ridge valley areas (Alagbo et al. 2024). The seeder was calibrated to deliver 10 kg ha^{-1} of *L. perenne* and 20 kg ha^{-1} of *T. subteraneum* mixtures at 660 g min^{-1} within 18 revolutions min^{-1} at 3 km h^{-1} driving speed. In the 2023 trials (III and IV), only *L. perenne* was calibrated to deliver 10 kg ha^{-1} at the same revolutions and speed as in 2022. White clover (*T. repens* L.) was broadcasted manually at 2.5 kg ha^{-1} due to

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Figure 2. Real-time kinematic global navigation satellite system (RTK-GNSS) ridgers used in the experiments. A) Glühfosator, an RTK-GNSS guided ridger for creating and re-compacting ridges (Frost Maschinenbau GmbH, Petershagen, Germany). B) DammProfi, an RTK-GNSS guided ridger for seeding, soil loosening (up to 0.5 m depth) and creating re-compacted ridges (Evers GmbH, Oberhausen, Germany).

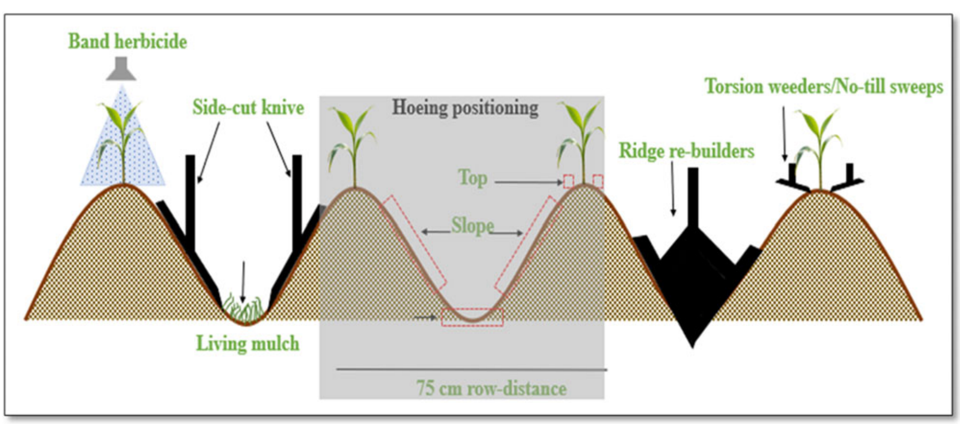

Figure 3. Schematic description of weed control in ridges showing the positioning of crops, hoeing elements (no-till sweeps), and band herbicide treatment on the top of the ridges, opposite pairs of downside-cut knives in slopes and living mulch, and ridge re-builders in valleys (adapted from Alagbo et al. 2022). Ridges made with a Glühfosator ridger is 20 cm high by 75 cm wide, while ridges made with a DammProfi ridger is 10 cm high by 75 cm width. Both ridges are 75 cm apart from the ridge center.

non-uniform seeding of living mulch mixtures in 2022. In 2024 (Trial V), only clover was sown at a rate of 40 kg ha^{-1}. All living mulch seeding was carried out on June 2, 2022; June 20, 2023; and June 26, 2024 after the second hoeing at the 7- to 8-leaf stage.

Postemergence Harrowing. Postemergence harrowing was performed on ridge tops (intrarow) with a 3-m-wide harrow (Einböck GmbH, Dorf, Germany) in a single pass. To remove weeds and prevent crop losses, harrow tines were set at the intensity 2-of-5 with a relatively low driving speed of 5 km h^{-1}. All harrowing treatments were performed on May 17 and 25, 2022, and similar treatment was performed on May 23, 2023; and June 13, 2024.

Soil Temperature and Moisture Content Determination. The TOMST® TMS (Michelska, Czech Republic) and Dragino® LSE01-LoRaWAN (Dragino Technology Co., Ltd.) data loggers were permanently installed in 2023 and 2024, respectively, on ridge-top areas, ridge valleys, and flat-tilled beds immediately after corn was sown. These sensors were used to monitor and record soil temperature and moisture on the re-compacted ridge (built with the Glühfosator) from the corn sowing date until harvest

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(May–September in all years). The sensor probes were inserted 10 cm below the ground surface, with temperature and moisture readings automatically recorded at 20-min intervals.

Data Collection

Weed Assessment. Weed species were identified, and total weed densities were counted 10–14 d immediately after the second hoeing four times per plot using a 0.05-m^2 counting frame randomly placed within the two middle rows in each plot. Weed biomass, both interrow and intrarow, was measured two times per plot toward the harvest dates using a 0.12-m^2 frame. Weed control efficacy (WCE) was estimated from weed biomass using Equation 1:

$$\mathrm{WCE}(\%) = (Bnt - Bt)/Bnt \times 100\ldots \quad [1]$$

where Bnt is the weed biomass of the nontreated control (in grams per square meter, g m^{-2}) and Bt is the weed biomass (g m^{-2}) in the treated plot.

Crop Density and Yield. Corn densities along a 1-m row were counted four times per plot after the first and second hoeing treatments. Two middle rows in each plot were harvested with Kemper Häcksler machinery (Stadtlohn, Germany) to determine fresh corn silage yield (kg ha^{-1}). Corn silage was harvested at 65% to 70% moisture content.

Data Analysis

The data were analyzed with SAS software (v.9.4; SAS Institute, Cary, NC) using a randomized complete block design (Equation 2). Raw mean values were used for the graphical illustrations displayed with OriginPro software (v.2022b; OriginLab Corporation, Northampton, MA). Before analysis, all data were checked for homogeneity of variance and normal distribution of residuals using residual plots and a quantile-quantile plot. A combined ANOVA was performed for Trials I, II, and III using a linear, one-factorial model (Equation 2):

$$Y_{ik} = \mu + a_i + b_k + e_{ik} \quad [2]$$

In Trials IV and V, a two-way factorial model was used to analyze the interaction effect of weeding and ridging elements (Equation 3):

$$Y_{ijk} = \mu + b_k + a_i + \beta_j + (a\beta)_{ij} + e_{ijk} \quad [3]$$

Observed means were compared with a least significant difference test with $\alpha = 0.05$. In Equation 2, Y_{ik} is the observed value (silage yield and weed biomass) of treatment a in block b, μ denotes the general mean, and a_i represents the fixed effects of the ith weed control treatment; while b_k and e_{ik} represent the random effects of the kth block and the residual error for each plot, respectively. In Equation 3, Y_{ijk} is the observed value (silage yield and weed biomass) of treatment a in block b, μ denotes the general mean, a_i represents the fixed effects of the ith weed control treatment, β_j represents the fixed effects of jth tillage types, $(\alpha\beta)_{ij}$ represents the interaction effect of ith weed control and jth tillage types, and b_k and e_{ijk} represent the random effects of the kth block and the residual error for each plot, respectively.

Results and Discussion

The long-term average annual rainfall at Ihinger-Hof is 654 mm and the long-term annual mean temperature is 7.9 C. In all years of trials, it was 2.8 C warmer than the long-term average. Rainfall exceeded the long-term mean by an average of 83 mm (Figure 1). Analysis of variance showed that weed control treatments varied ($P < 0.01$) across all trials. Also, there was significant interaction between ridge cultivator and weed control treatments ($P < 0.01$) in Trials IV and V.

Weed Flora Composition

Table 2 shows the weed flora and their densities in the untreated control plots. Generally, weed densities were highest in Trials III (288 weeds m^{-2}), IV (360 weeds m^{-2}), and V (1,700 weeds m^{-2}). Wild buckwheat (*Fallopian convolvulus* L.), common chickweed [*Stellaria media* (L.) Vill], black nightshade (*Solanum nigrum* L.), and common lambsquarters (*Chenopodium album* L.) were the dominant weed species in Trials I, II, III, IV, and V. Broadleaf species were more abundant on re-compacted ridges across all trials. Grasses were counted less frequently in most trials. Earlier studies have also reported that broadleaf species are more associated with ridge tillage than grasses (Forcella and Lindstrom 1988b; Jurik 1993). Moreover, broadleaf species were more diverse and abundant in corn Trials III and V compared with Trials I and II, possibly due to spatial differences in weed species richness at each trial location, because similar trials were established at different field locations in Ihinger-Hof in 2022, 2023, and 2024.

Weed Biomass Reduction

In Trials I to III combined (Figure 4A), interrow hoe-treated areas (HOE-1, HOE-2, and HOE-4) produced significantly reduced weed biomass (32–55 g m^{-2}) to levels that were similar to those after broadcast herbicide treatment, although this did not occur in the HOE-3 treatment (weed biomass, 98 g m^{-2}). The result suggests that using a side-cut knife combined with ridge rebuilding for interrow treatments was comparable to herbicide use in terms of biomass reduction. Moreover, poor germination of living mulch due to a lack of rainfall at the time seeds were broadcasted in June 2022 and 2023 could have resulted in higher weed proliferation in the HOE-3 experiment. Within intrarow areas, the HOE-1 and HOE-2 practices resulted in significantly reduced weed biomass (30 and 95 g m^{-2}, respectively), levels that were similar to those of broadcast herbicide treatment. Whereas HOE-4 provided poor biomass reduction (136 g m^{-2}), it was statistically comparable to that of a broadcast herbicide. The result implies that the use of no-till sweeps and band spraying on top of Glühfosator-constructed ridges is similar to the use of broadcast herbicides in terms of biomass reduction, whereas one pass of harrowing at a 2-of-5 intensity did not reduce intrarow weed biomass (because the treatment did not differ significantly from that of the nontreated control).

In Trials IV and V (Figures 5A and 6A), regardless of ridging cultivator used, weed biomass was significantly reduced (4–22 g m^{-2}) in interrow hoe-treated areas (HOE-1, HOE-2, and HOE-3), similar to a broadcast herbicide treatment. The latter trend is similar to interrow hoe-treated areas in Trials I–III (combined). Moreover, in intrarow treatments with either HOE-3 or HOE-2, weed biomass was higher (186 and 74 g m^{-2} respectively) in ridges made with the Damm Profi machine in contrast to similar

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Table 2. Weed flora composition and density on ridge-cultivated corn trials in 2022, 2023, and 2024.[a,b]

Common name	Scientific name	Weed flora composition — Corn trials I-2022	II-2022	III-2023	IV-2023	V-2024
		plants m^{-2}				
Common chickweed	*Stellaria media* (L.) Vill.	–	–	**101.0**	–	150
Shepherd's purse	*Capsella bursa-pastoris* (L.) Medik.	–	–	61.3	18.9	–
Black nightshade	*Solanum nigrum* L.	–	–	35.3	**227.3**	190
Lambs quarters	*Chenopodium album* L.	6.2	**7.7**	64.3	37.9	**1,175**
Purple dead-nettle	*Lamium purpurium* L.	–	–	18.4	31.6	–
Wild chamomile	*Matricaria chamomila*	–	–	7.7	31.6	185
Wild buckwheat	*Fallopia convolvulus* L.	**89.0**	6.3	–	12.6	–
	Total weed density	95.2	14	288	360	1,700

[a]A dash (–) indicates the weed was not present.
[b]Numbers in bold represent weed species with the highest density in each trial.

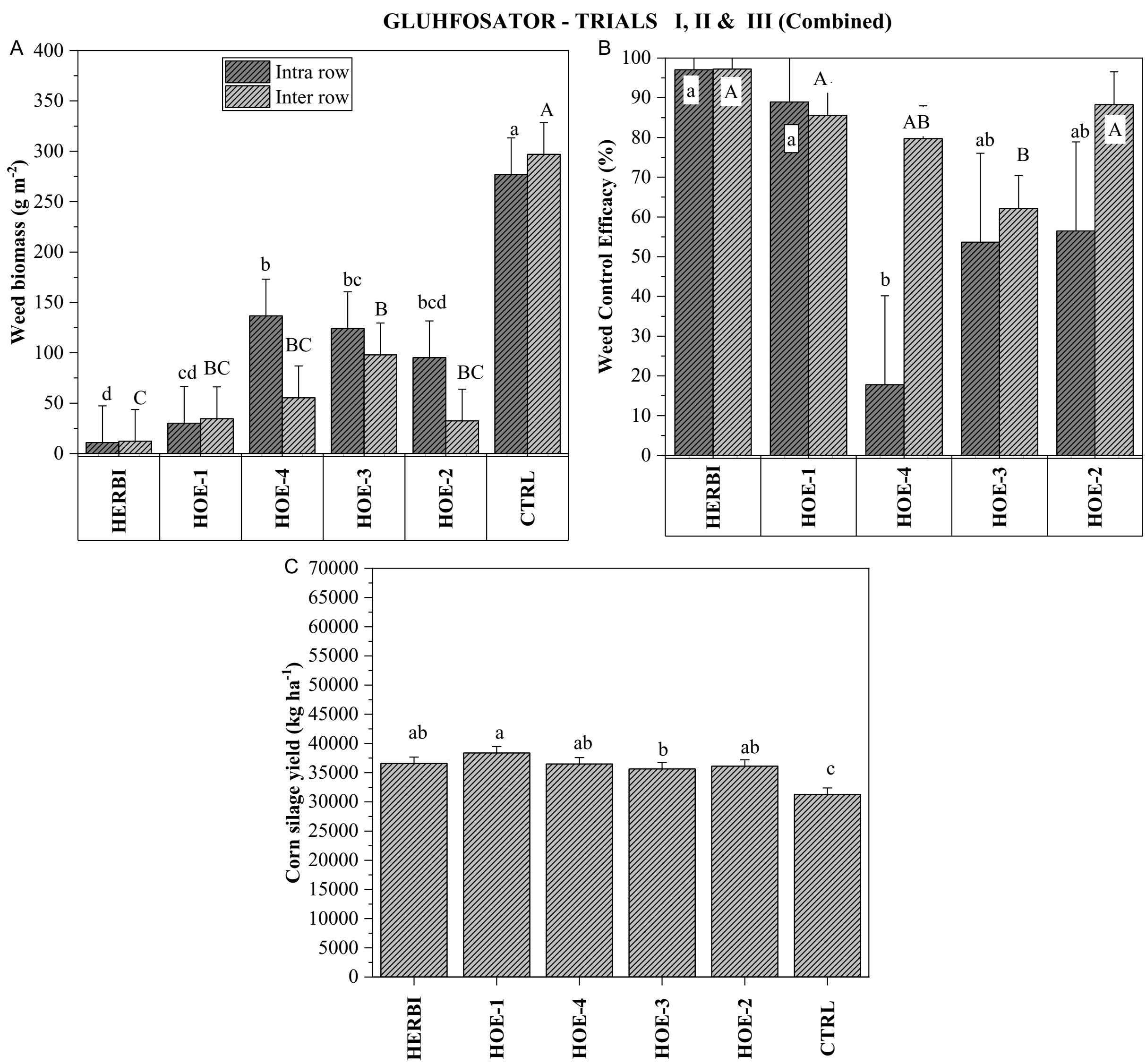

Figure 4. Effect of weed control treatments on weed biomass (A) weed control efficacy (B), and corn silage yield (C) in corn Trials I, II, and III combined (built with Glühfosator machinery). Light gray and gray bars (A and B) represent intrarow and interrow weed biomass and weed control efficacies, respectively. Abbreviations: CTRL, untreated control; HERBI, broadcast herbicide application; HOE-1, two hoeings combined with band herbicide application; HOE-2, two hoeings; HOE-3, two hoeings combined with living mulch; HOE-4, two hoeings combined with postemergence harrowing. Means with uppercase and lower case letters indicate significant differences between interrow and intrarow treatments, respectively, according to the LSD probability test (α ≤ 0.05).

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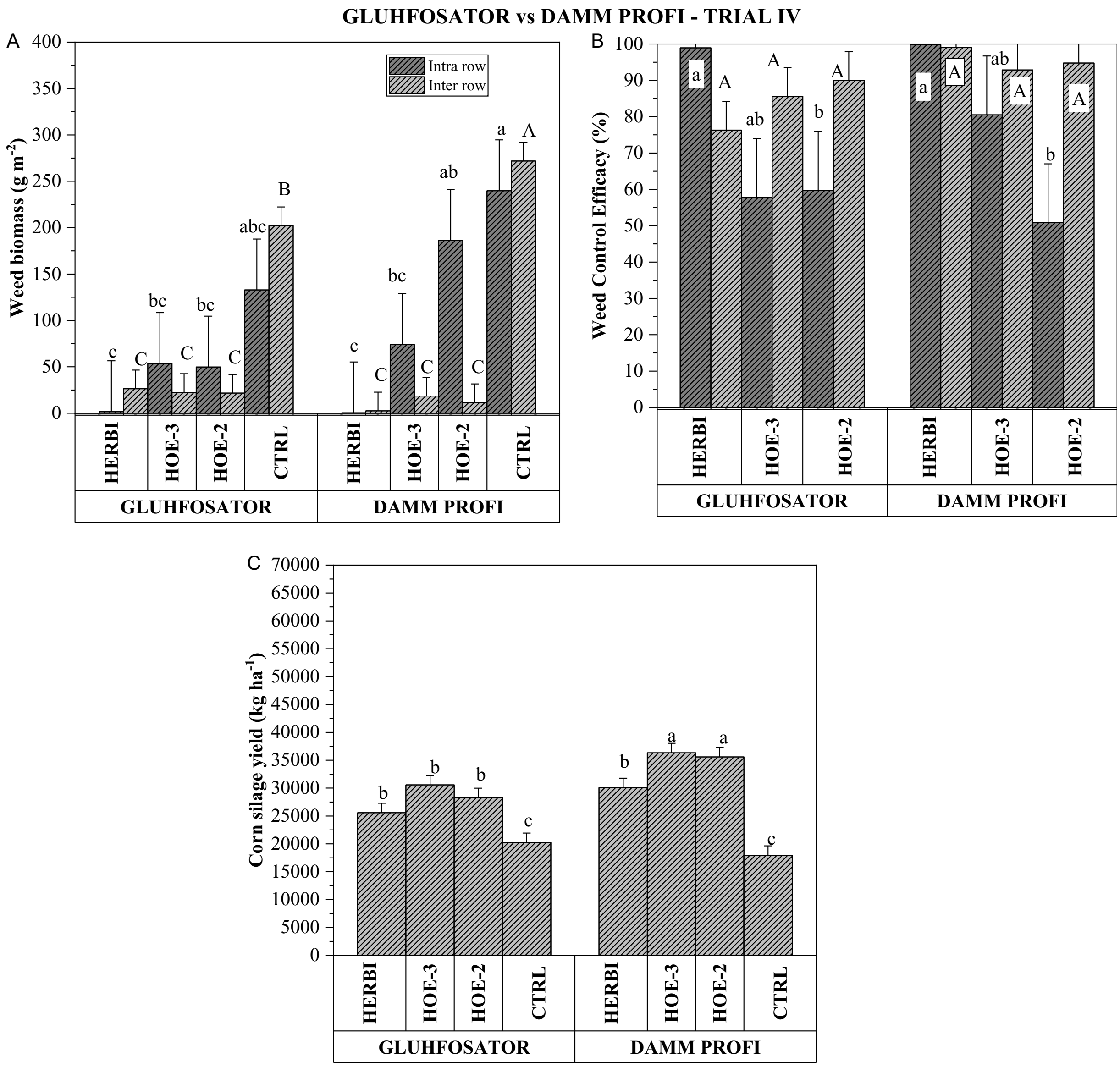

Figure 5. Effect of weed control treatments on weed biomass (A) weed control efficacy (B), and corn silage yield (C) in corn Trial IV in 2023 (built with Glühfosator and Damm Profi machinery). Light gray and gray bars (A and B) represent intrarow and interrow weed biomass and weed control efficacies, respectively. Abbreviations: CTRL, untreated control; HERBI, broadcast herbicide application; HOE-2, two hoeings; HOE-3, two hoeings combined with living mulch. Means with uppercase and lower case letters indicate significant differences between interrow and intrarow treatments, respectively, according to the LSD probability test ($\alpha \leq 0.05$).

treatments made with the Glühfosator machine (50 and 53 g m^{-2} with HOE-3 and HOE-2 treatments, respectively). A similar trend in Trial V (Figure 6A) shows that intrarow HOE-2 treatment with the Damm Profi had significantly higher weed biomass (103 g m^{-2}) in contrast to a similar treatment with a lower weed biomass (5 g m^{-2}) in ridges made with the Glühfosator. The results revealed that intrarow weeding with no-till sweeps may be preferable in ridges made with the Glühfosator rather than the Damm Profi, probably due to differences in ridge configurations between both cultivators. Glühfosator-formed ridges are 10 cm higher than Damm Profi ridges. This height enables precise fitting of no-till sweeps mounted on top of ridges close to the crops on the tops of ridges. In Trial V, the biomass reduction after band herbicide treatments (HOE-1) was similar to that of broadcast herbicide treatments regardless of ridge cultivator. Generally, differences observed in hoeing treatment performance could be attributed to variations in weed infestation levels in each trial. A similar study has shown that different field and weather conditions can lead to varying outcomes of mechanical weed control (Naruhn et al. 2021). The failure of harrow treatment to reduce weed infestation within intrarow areas shows that a single pass of harrow tines is less efficient on top of ridges. Band herbicide treatment combined with interrow hoeing (HOE-1) would be more suitable to reduce weed competition with corn on top of ridges under heavy weed pressure.

Weed Control Efficacy

In Trials I, II, and III combined (Figure 4B), interrow hoe-treated areas (HOE-1, HOE-4, and HOE-2) exhibited significantly higher WCE (80% to 88%), similar to the broadcast herbicide treatment, except that a lower WCE (62%) was observed in the HOE-3 treatment. In Trials IV and V (Figures 5B and 6B), regardless of ridge cultivator, a higher WCE (85% to 96%) was equally observed in interrow hoe-treated areas (HOE-1, HOE-3, and HOE-2). These

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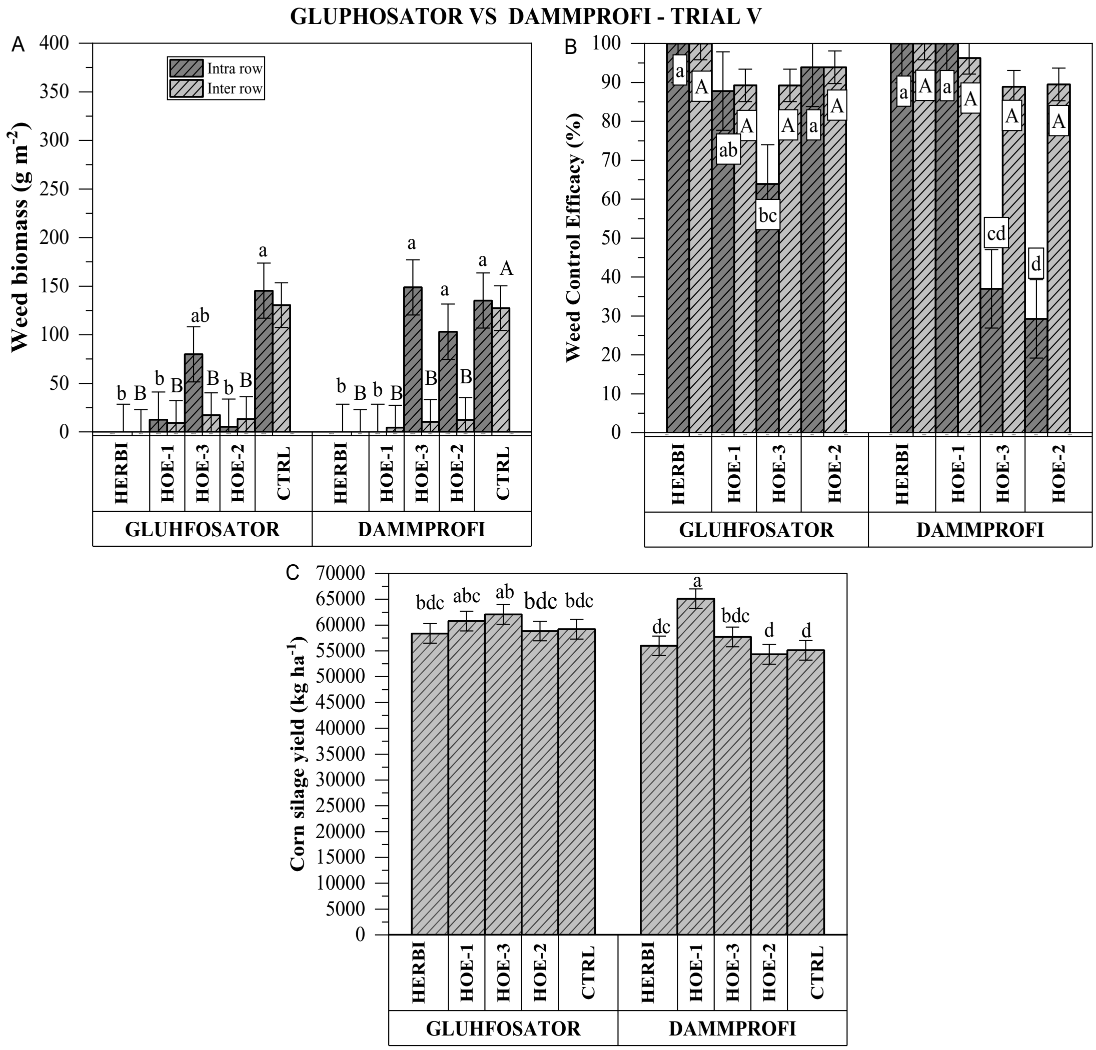

Figure 6. Effect of weed control treatments on weed biomass (A) weed control efficacy (B), and corn silage yield (C) in corn Trial V in 2024 (built with Glühfosator and Damm Profi ridgers). Light gray and gray bars (A and B) represent intrarow and interrow weed biomass and weed control efficacies, respectively. Abbreviations: CTRL, untreated control; HERBI, broadcast herbicide application; HOE-1, two hoeings combined with band herbicide; HOE-2, two hoeings; HOE-3, two hoeings combined with living mulch. Means with uppercase and lower case letters indicate significant differences between interrow and intrarow treatments, respectively, according to the LSD probability test ($\alpha \leq 0.05$).

results suggest that interrow hoeing (with side-cut knives and ridge rebuilders within slopes and valleys of re-compacted ridges) integrated with other methods can achieve a WCE that is comparable to that of a broadcast herbicide application regardless of weed pressure. Integrating tillage and band herbicide applications with other cultural practices such as the use of cover crops, is well known to improve crop competitiveness against heavy weed pressure (Abdin et al. 2000; Bhaskar et al. 2021).

Furthermore, in intrarow areas (the tops of ridges), band herbicide treatments (HOE-1) attained higher weed control efficacy (88% to 100%) regardless of the ridge cultivator. The result was consistent and statistically similar to that of a broadcast herbicide application (Figures 4B and 6B). Studies have shown that the integration of hoeing and band treatment on ridges can optimize weed control with better herbicide savings. In Italy, for example, optimal weed control with 50% to 60% herbicide reduction was realized with preemergence or postemergence band herbicide applications in combination with interrow hoeing in experiments with corn (Loddo et al. 2020). Similarly, interrow hoeing in combination with hoe-ridging or band herbicide application gave 93% to 99% WCE in corn and soybean fields with 50% to 100% herbicide reduction in Europe (Pannacci and Tei 2014; Vasileiadi et al. 2015, 2016).

Moreover, in most trials, weed control efficacy in intrarow areas treated with no-till sweeps (HOE-2 and HOE-3) ranged between poor to average in performance (30% to 63%) except HOE-3 (81% WCE in Trial IV with the Damm Profi) and HOE-2 (94% WCE in Trial V with the Glühfosator) (Figures 4B, 5B, and 6B). Also, in trials I to III combined, one pass of postemergence harrow (HOE-4) could not optimize weed control (17% WCE) on top of ridges at the present intensity (2 of 5) and working speed (5 km h^{-1}) (Figure 4B). Poor performance of no-till sweep blades and harrows on top of ridges could be attributed to a mild harrowing intensity and unrepeated passes as was established in related studies (Pannacci and Tei 2014; Saile et al. 2023). With a repeated number of harrowing at the early growth stages of weeds, better weed control and crop selectivity were observed (Fogliatto et al. 2019; Rasmussen et al. 2008). Adjusting the aggressiveness of harrow tines or speed could enhance the forceful uprooting of weeds between crop rows of deep-sown crops such as corn and soybean (Van der Weide et al. 2008).

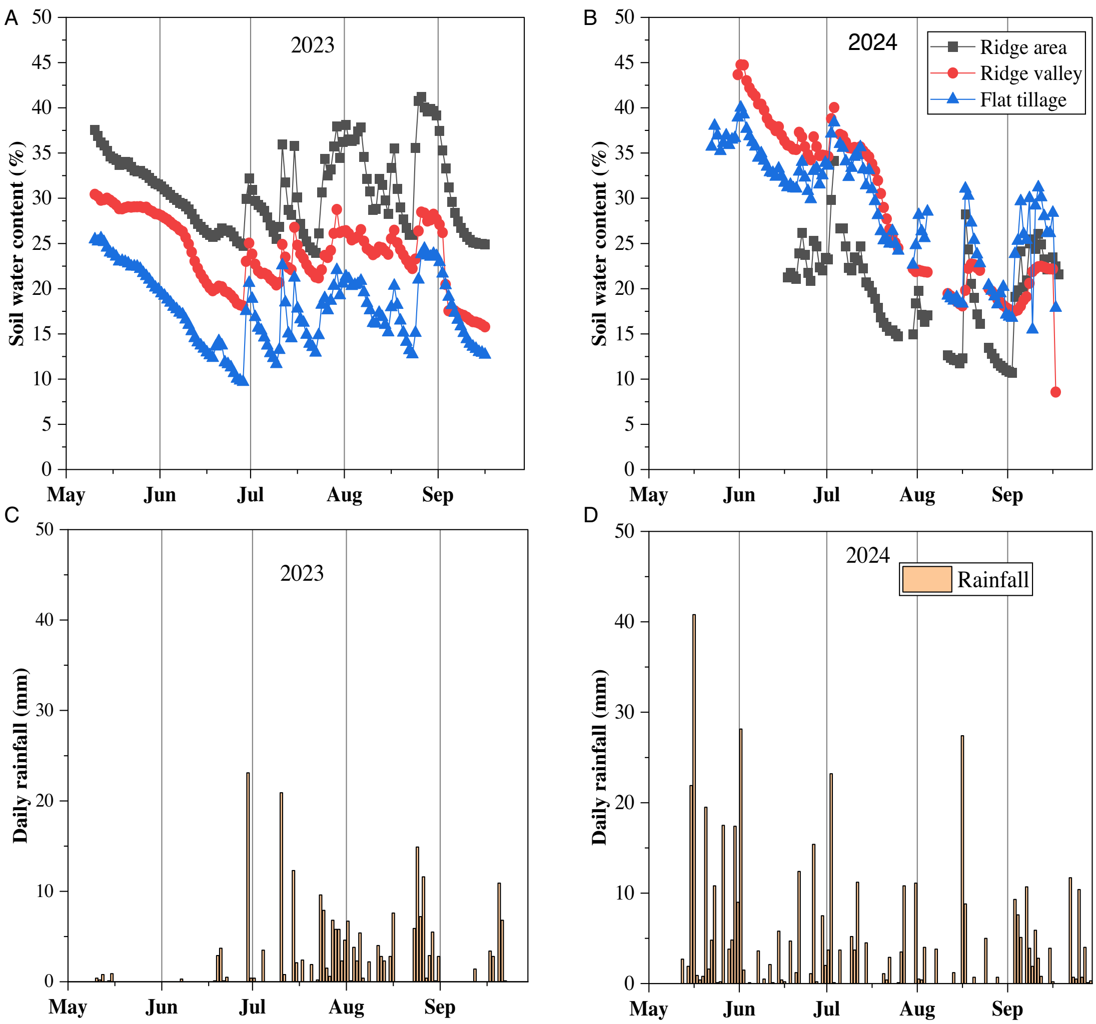

Figure 7. Scatter graphs showing distribution of soil water content (A and B) within ridge area (black), ridge valley (red) of Glühfosator-built ridges, and flat tillage (blue) as influenced by rainfall in 2023 (C) and 2024 (D) summer months. Soil water content measurements taken at 20-min intervals were cumulated into daily averages.

Corn Silage Yield

Despite inefficient weed control observed with intrarow hoeing treatments (HOE-2, HOE-3, HOE-4), corn silage yield was either increased (in number) or statistically on par with broadcast herbicide treatments across trials (Figures 4C, 5C, and 6C). In Trials I, II, and III combined, an increase of 1800 kg ha^{-1} in corn silage yield occurred after the HOE-1 treatment (Figure 4C). In Trial IV, HOE-3 and HOE-2 treatments resulted in corn silage yields of 5000 and 6000 kg ha^{-1}, respectively, in ridges made with Damm Profi machinery, and increases of 5000 and 3000 kg ha^{-1}, respectively, in ridges made with Glühfosator machinery (Figure 5C). In Trial V, corn silage yield from HOE-1 and HOE-3 treatments were increased by 9000 and 2000 kg ha^{-1}, respectively, in Damm Profi ridges and 2000 and 4000 kg ha^{-1}, respectively, in Glühfosator ridges (Figure 6C).

The increase in corn silage yield observed in this study could have resulted from the interactive influence of hoeing treatment and ridge configuration. Fogliatto et al. (2019) also observed that corn silage yield was not reduced when mechanical weeding occurred. Corn silage yield obtained with similar hoeing settings on ridges was shown to be similar to that obtained from flat seedbeds (Alagbo et al. 2024; Vasileiadis et al. 2015, 2016). Other studies have demonstrated that corn silage and soybean grain yield are optimized (comparable to broadcast herbicide treatments) with band herbicide applications combined with interrow hoeing (Fogliatto et al. 2019; Loddo et al. 2020; Pannacci and Tei 2014; Vasileiadis et al. 2015, 2016).

Soil Water Content and Temperature

Figure 7, A and B, contain scatterplots of soil water content in 2023 and 204 within ridge area, ridge valley, and flat tillage areas as influenced by rainfall (Figure 7, C and D) in summer months. Throughout the 2023 growing season, SWC rose steadily in the order of ridge area > ridge valley > flat tillage. Due to limited daily rainfall (~0.2 mm) between early May and late June 2023, a steady decline in SWC was observed on the ridge area (37%–25%), followed by the ridge valley (30%–18%), followed by flat tillage (25%–10%). In 2024, SWC declined steadily in a reverse order: ridge valley ≥ flat tillage > ridge area under persistent daily rainfall (~5 mm) throughout the growing season. However, results from both years demonstrate that SWC within the three environments (ridge area, ridge valley, and flat tilled) often varied largely with rainfall, such that moisture seems to be conserved within ridge area under limited rainfall, while moisture is drained from ridge area under persistent or heavy rainfall. Fatumah et al. (2024) reported that soil types, tillage systems, and rainfall patterns are among the

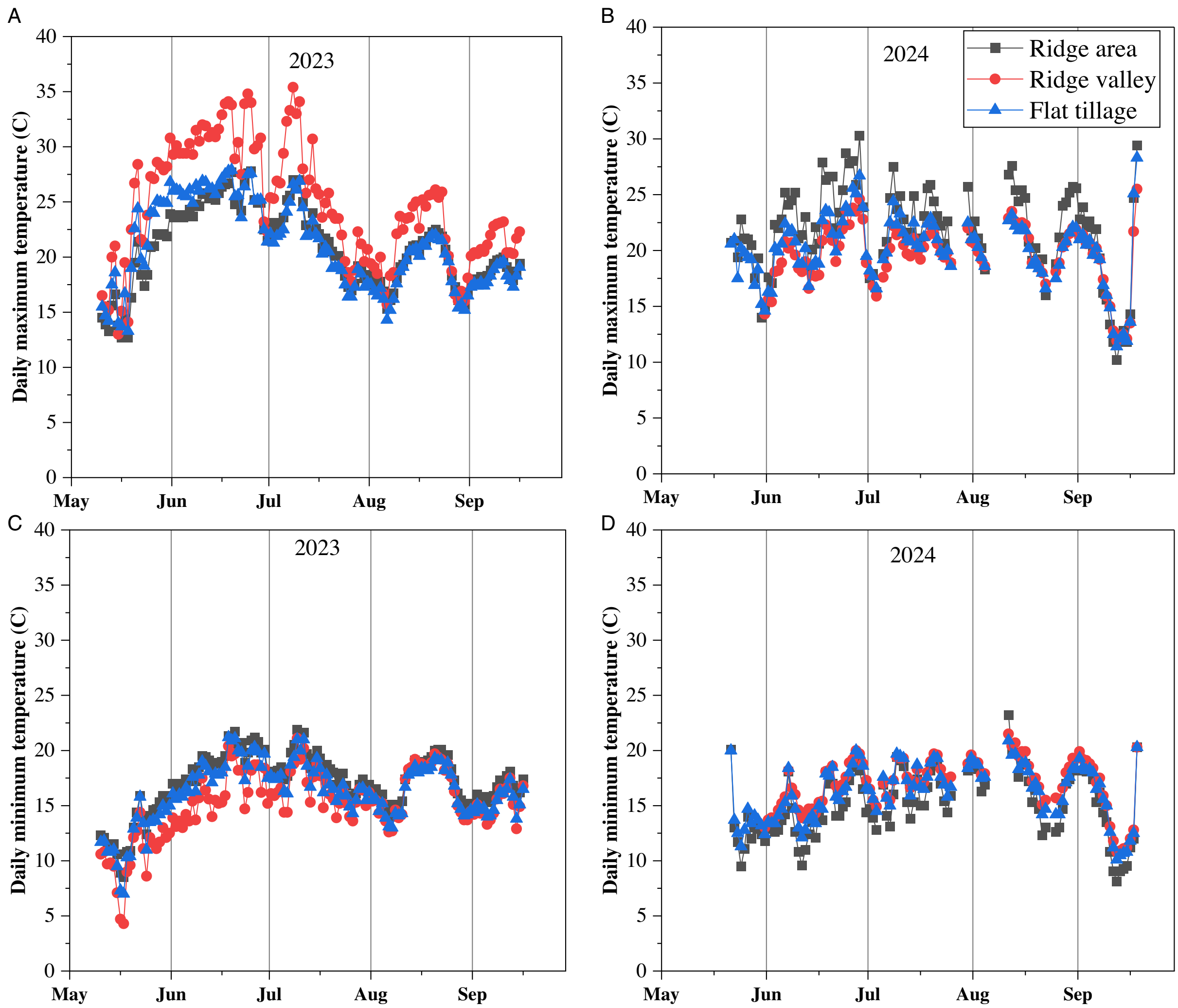

Figure 8. Scatter plots showing daily maximum (A and B) and minimum (C and D) temperature trends within ridge areas (black) and ridge valleys (red) in ridges built with a Glühfosator ridger and flat tillage (blue) in 2023 and 2024 summer months (May–September). Temperatures taken at 20-min intervals were cumulated into daily averages.

key factors that influence the magnitude of surface run-off volume in time and space.

Figure 8 shows the daily maximum and minimum temperature trends observed within three locations (ridge area, ridge valley, and flat tillage) in the 2023 and 2024 summer seasons. In 2023, daily extreme maximum and minimum temperatures were consistent within ridge valley. The highest maximum (27.8 C, 35.4 C, 28.9 C) and lowest minimum (8.5 C, 4.3 C, 7 C) temperature values were observed within ridge area, ridge valley, and flat tillage locations, respectively (Figure 8, A and C). In 2024, daily extreme maximum and minimum temperatures were consistently reached within the ridge areas. Highest maximum (30.3 C, 25.5 C, 28.3 C) and lowest minimum (8.1 C, 10.8 C, 10.1 C) values were observed within the ridge area, ridge valley, and flat tillage locations, respectively (Figure 8, B and D).

In summary, the highest (35.4 C) and lowest (4.3 C) temperatures were recorded within the ridge valley under limited rainfall (240 mm) in the summer of 2023, whereas the highest (30.3 C) and lowest (8.1 C) temperatures were recorded within the ridge area under heavy rainfall (464 mm) in the summer of 2024. Alagbo et al., (2024) recorded similar temperature dynamics within ridge areas and ridge valleys in the same study location. This suggests that when rainfall is limited, moisture is conserved within ridge areas with increased day warming and night cooling of ridge valleys occurring better than it does in ridge areas and flat-tilled beds. On the other hand, under persistent heavy rainfall, moisture is drained from ridge areas with increased day warming and night cooling of ridge areas occurring better than in ridge valleys and flat-tilled beds.

Practical Implications

This study demonstrates that straight ridges built with RTK-GNSS guidance could allow precise application of postemergence herbicides and autosteered seeding of living mulch, using ridge furrows as a guideline. Despite the varying outcomes of mechanical weed control (due to weather variation and weed pressure) from the various trials, interrow hoeing with side-cut knives and ridge re-rebuilding within slopes and valleys of re-compacted ridges (integrated with other methods) optimized WCE (80% to 96%) to levels similar to those of broadcast herbicides. Farmers can easily adopt the interrow hoeing method as a mechanical weeding option within the ridge slope and valley (furrow areas), immediately after successful hoeing, introduce living mulch seeding to suppress weeds within interrow areas. This is expected to act as a soil cover to suppress weed pressure, reduce erosion and the leaching of

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nutrient resources, and fix nitrogen back into the soil (particularly in a permanent RT system).

In addition to interrow hoeing, integration of no-till sweep blades or postemergence harrowing could optimize weed control on top of ridges. However, repeated passes of no-till blades and higher harrowing intensity (e.g., 3 of 5 or 4 of 5) at a higher speed (7 km h^{-1}) are most presumably needed to achieve better weed control efficacy. Moreover, the efficacy of no-till sweeps may be better on tall ridges than on short ridges. Furthermore, the integration of band herbicide spraying with interrow hoeing can optimize weed control on top of ridges. In summary, the integrated interrow and intrarow mechanical weeding options within the ridge profile may serve as an alternative to manual weeding in organic ridge-cultivated corn, whereas integrated interrow hoeing with band spraying on top of ridges may result in 50% to 60% herbicide savings while also reducing the development of herbicide-resistant weeds.

Under both limited and excessive rainfall conditions, alternate conservation and draining of moisture within re-compacted ridges demonstrate the benefits of ridge tillage in adapting to extreme weather events such as drought or flood. In addition, better warming and cooling of ridges could catalyze crop growth and activities of soil microbes.

Acknowledgements. We thank Sebastian Hajek, Marc Friebolin, and Sandor Knecht for setting up the experiments at Ihinger-Hof. We also thank the technical assistants in the Department of Weed Science, University of Hohenheim, for their help in collecting data. We acknowledge K.U.L.T.-Kress for providing hoeing sweeps for optimal adjustment of the ridges. We also thank Lechler GmbH for providing a specified band spraying nozzle set for this study; and HRD GmbH and FROST GmbH for making ridgers available for this experiment.

Funding. The project is funded by the DiWenkLa (Digital Value Chains for a Sustainable Small-Scale Agriculture) and ENABLE projects. DiWenkLa is supported by funds from the Federal Ministry of Food and Agriculture through grant 28DE106A18. DiWenkLa is also supported by the Ministry for Food, Rural Areas, and Consumer Protection Baden-Württemberg. The ENABLE project is funded by the Baden-Württemberg Foundation as part of the "Innovative technologies for climate resilience in agriculture and forestry" program.

Competing interests. The authors declare they have no competing interests.

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