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Evaluating Sensor-Based Mechanical Weeding Combined with Pre- and Post-Emergence Herbicides for Integrated Weed Management in Cereals

Marcus Saile *, Michael Spaeth and Roland Gerhards

Department of Weed Science, University of Hohenheim, 70593 Stuttgart, Germany; michael.spaeth@uni-hohenheim.de (M.S.); roland.gerhards@uni-hohenheim.de (R.G.)
* Correspondence: marcus.saile@uni-hohenheim.de; Tel.: +49–711-4592–2389

Abstract: Due to the increasing number of herbicide-resistant weed populations and the resulting yield losses, weed control must be given high priority to ensure food security. Integrated weed management (IWM) strategies, including reduced herbicide application, sensor-guided mechanical weed control and combinations thereof are indispensable to achieve this goal. Therefore, this study examined combinations of pre- and post-emergence herbicide applications with sensor-based harrowing and hoeing in cereals by conducting five field experiments at two locations in Southwestern Germany from 2019 to 2021. Each experiment contained an untreated control and a single post-emergence herbicide treatment as a comparison to these IWM treatments. The effects of the different IWM approaches on weed control efficacy (WCE), crop density, and grain yield were recorded. All experiments were set up in a randomized complete block design with four repetitions. Pre-emergence herbicide application combined with one-time harrowing and subsequent hoeing (Pre-Herb + Harr + Hoe) achieved the highest WCE (100%), followed by an approach of WCE (95%) for two-times hoeing. In contrast, a single pre-emergence herbicide application achieved the worst result with an average WCE of 25%. Grain yield was equal between all treatments in between 6 t ha^{-1} and 10 t ha^{-1}, except for a single pre-emergence herbicide application, which achieved a 2.5 t ha^{-1} higher grain yield in winter wheat in 2021 that averaged 11 t ha^{-1}, compared to the combination of Pre-Herb + Harr + Hoe that averaged 8.5 t ha^{-1}. The results showed that it is possible to reduce and replace herbicides while achieving equivalent yield and WCE.

Keywords: precision farming; digital farming; site-specific; camera-guided; herbicide reduction; integrated weed management

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1. Introduction

Weeds are the most important pest in wheat worldwide [1]. Previous estimates of global yield loss due to weeds were 9.8% [2] and 12.3%, respectively [3]. However, Oerke [1] estimated the global potential yield loss in wheat to be 23.0% with a range of 18% to 29%, and the actual loss to be 7.7%. Therefore, weed-related crop losses can be substantial and may be avoided, or reduced, by using chemical and mechanical plant protection measures or cultural practices.

Using herbicides has become the main strategy to control weeds in arable crops due to a high efficacy along with improved crop quality and quantity at low costs [4,5]. Herbicides account for 60% of the plant protection agents that are used worldwide [6,7]. Post-emergence herbicides (POST) are the most common and effective method of weed control in cereals [8]. Pre-emergence herbicides (PRE), on the one hand, usually have a lower control efficacy that averages 65% and sufficient soil moisture is necessary for root uptake [9–11]. On the other hand, PRE are less affected by resistance [12]. However, field studies that were carried out in Europe in winter cereals showed a weed control efficacy (WCE) in high variance from 55% to almost 100% after pre- or post-emergence herbicide application against grasses and broadleaf weeds, depending on the weed composition and the used herbicide [13,14]. Nevertheless, the continuous and repeated use of herbicides with the same mode of action, combined with changes in modern agriculture production (e.g., reduced tillage, monocultures) has led to the selection of specific herbicide-resistant weeds which are well adapted to the reduced tillage and the monotonous crop rotation [15–18]. Due to the strong increase in herbicide resistance in weed populations, the effective use of herbicides is under major risk and at the same time the acceptance for the use of herbicides in society is decreasing. The social rejection of herbicides can be attributed to potential risks for the environment, food chain contaminations, the health of end users, and loss of biodiversity in agroecosystems [19–23]. Therefore, there is a need for alternative measures and integrated management with a long-term perspective. Further, the European Commission has increased regulation due to pesticide use in the agricultural landscape. Regulations such as "Farm-to-Fork" or "Biodiversity 2030", states that farmers have to reduce pesticide use by 50% and increase biodiversity [24]. In order to reduce herbicide use in agriculture while still maintaining high yields and adequate weed control, a diverse weed control strategy is required. One of the main purposes of integrated weed management (IWM) is to suppress problematic weed species using multiple tactics of weed control (direct methods, such as mechanical or chemical, and preventive methods, such as crop rotation, including different soil tillage practices and cover crops) [23,25].

As one of the most common weed control alternatives, mechanical weeding can be used to reduce the amount of herbicides. Among physical weed control measures, harrowing and hoeing are very promising because of their high efficacy [26,27]. However, the reported WCE of both varies considerably in the literature. Field studies that were carried out in Germany and Norway showed variations in WCE from approx. 60 to 90% for harrowing and approx. 40 to 90% for hoeing [27–30]. A field study in sugar beet showed that the combination of pre- and post-emergence herbicides and the use of hoeing technology achieved equivalent WCEs of 76 to 86%, compared to multiple herbicide applications [31]. Combinations of the band application of herbicides and inter-row hoeing could achieve optimal weed reduction in maize due to a complete field herbicide application and equal yields [32]. The efficiency of mechanical weed control varies due to weather, soil and plant conditions, and incorrect implementation. [33,34]. In particular, implement steering or intensity-adjustment mistakes can substantially decrease the efficiency [35]. To avoid high variations in efficiency, sensors can be used that adjust the intensity or guide the implement automatically, thus facilitating the farmers' work. Weed hoeing or harrowing with automatic steering/adjusting technology has been shown to constantly reduce weed densities in different crops by more than 85% [27,30]. Crop damage has been observed to decrease with sensor-based steering; in addition, driving speed could be increased, e.g., for hoeing from 4 km h^{-1} up to 8 km h^{-1} [27]. Nevertheless, a single alternative measure (mechanical weeding or soil tillage) cannot replace the efficiency of chemical weed control [36]; a combination of pre- and post-emergence herbicide with sensor-guided mechanical weed control, including sensor-guided harrowing and hoeing is preferable. Mechanical weeding and soil tillage do however have the potential to be the first step in fulfilling the EU goal, reducing the amount of herbicide and maintaining a high level of weed control.

Therefore, the objectives of this study were to combine different chemicals (pre- and post-emergence herbicides) with sensor-based mechanical treatments (harrowing and hoeing) to reduce the amount of pre- and post-emergence herbicides, while maintaining high yields and adequate weed control. The first hypothesis was that a combination of two sensor-based mechanical treatments could replace the complete herbicide application, while yield and weed control remain at the original level. The second hypothesis was that an integrated approach of combining pre-emergence herbicides with hoeing could achieve similarly high WCEs and grain yield, compared to a herbicide strategy alone. The last hypothesis was that the combination of post-emergent harrowing, hoeing and herbicide application may achieve the highest WCE and grain yield.

2. Materials and Methods

2.1. Experimental Site and Design

One field experiment in spring oat (*Avena sativa*) cv. Apollon, was conducted in the season 2019/2020 in Southwestern Germany in Hohenheim (48.7° N, 9.29° E). In the season 2020/2021 three additional trials were set up; at Hohenheim, a winter wheat cv. Rgt Reform and a spring oat trial cv. Apollon were established, and one winter wheat cv. Rgt Reform trial was established at Eningen. In the two winter wheat experiments more treatments were included than in the season before. The experiments were located in Hohenheim and Eningen (48.4° N, 9.30° E) at an altitude of 400 m and 720 m above sea level, respectively. Both farms (Hohenheim and Eningen) are conventionally managed. The long-term annual rainfall for Hohenheim is 685 mm and 820 mm in Eningen. The average long-term annual temperature for Hohenheim is 10.3 °C and 6.8 °C for Eningen. In 2019/2020, Hohenheim received 180 mm more precipitation, and in 2020/2021, 40 mm less precipitation than the average; the temperature was 0.4 °C, −0.9 °C higher/lower than the long-term mean, respectively. In 2020/2021, the average rainfall at Eningen was 100 mm higher than the long-term mean, and the annual temperature was −0.3 °C lower than the mean. The soil texture at both locations was classified as a silty loam (Table 1). Cereals were sown in recommended densities and the row distance was 150 mm in all five field trials (Table 1). Fertilization and plant protection were carried out in all trials, according to good agricultural practice.

Table 1. Year, location, crop with cultivar, sowing date (YYYY-MM-DD), seed rate, crop rotation before, soil tillage before and soil texture of all five experiments.

Year	Location	Crop (cv.), Sowing Date	Seed Rate (Seeds m^{-2})	Crop Rotation	Soil Tillage	Soil Texture
2019/2020	Hohenheim	Spring oats, cv. Apollon 2020-03-20	350	Winter wheat, Cover crops	Mulching, plowing	25% clay, 5% sand, 70% silt
2020/2021	Hohenheim	Spring oats, cv. Apollon 2021–03-22	350	Winter wheat, Cover crops	Mulching, plowing	25% clay, 5% sand, 70% silt
2020/2021	Hohenheim	Winter wheat, cv. Rgt Reform 2020-10-25	300	Alfalfa	Plowing, rotary harrow	25% clay, 5% sand, 70% silt
2020/2021	Eningen	Winter wheat, cv. Rgt Reform 2020-10-22	310	Oil seed rape	Plowing, rotary harrow	43% clay, 23% sand, 35% silt

All four experiments were set up as a randomized complete block design with four repetitions. The plot size in all trials was 6 × 30 m with the longer side of the plots in the sowing direction of the crop. In 2019/2020, one experiment and in 2020/2021 one experiment contained 6 treatments; in 2020/2021, two winter wheat experiments included 12 treatments. The treatments in 2019/2020 consisted of an untreated control (Con); an herbicide control (Herb), including a pre- and post-emergence herbicide; a single hoeing pass (Hoe 1×); a single harrowing pass (Harr 1×); a combination of first harrowing with subsequent hoeing (Harr + Hoe); and a combination the other way around (Hoe + Harr). In 2020/2021, 6 treatments were added to the previous design: a single pre-emergence herbicide (Pre-Herb); a double harrowing pass (Harr 2×); a double hoeing pass (Hoe 2×); a pre-emergence herbicide combined with one-time harrowing (Pre-Herb + Harr); a pre-emergence herbicide combined with one hoeing pass (Pre-Herb + Hoe); and as a combination of all, a pre-emergence herbicide with one-pass harrowing and one-pass hoeing (Pre-Herb + Harr + Hoe). The CON plots were left untreated for the entire growing season. However, it was ensured that the untreated control also received the same number of passes with the tractor wheels as the other treatments. Harrowing and hoeing in winter wheat and spring oats was performed in one/two pass(es) shortly before the late tillering stage of the crop (BBCH 13–29) from early March to late April. Harrowing and hoeing were performed parallel to the crop rows with a driving speed of 8 km h^{-1} and 5 km h^{-1}, respectively. A medium automatic harrowing intensity (Crop Soil Cover, CSC 20%) was used for all treatments. CSC is defined as the part of the crop that is covered by soil after the treatment [37]. Flat hoeing sweeps with a width of 10 cm were used for all treatments. Mechanical weeding was performed when it was relatively dry and at least three consecutive days without rainfall were forecasted after the treatment. The pre-emergence herbicide applications were carried out shortly before the germination of the crop, and post-emergence herbicides were applied shortly before tillering at the crop growth stage BBCH 14–18. All chemical applications were carried out with a plot sprayer (Schachtner-Fahrzeug- und Gerätetechnik, Ludwigsburg, Germany) that was equipped with flat jet nozzles (Lechler, AD 130–02) at a pressure of 2.4 bar and a speed up to 4.5 km h^{-1} (see Figure 1). Different herbicides were applied for the crops and locations (see Table 2). The pre- and post-emergence herbicides were sprayed at the recommended field rates, according to the crop. At the execution of the treatments, except for Pre-Herb, the majority of the weed species had developed 2–4 true leaves.

Figure 1. From left to right: the sensor-based harrow in a winter wheat field 2020/2021; the camera-guided hoe and the plot sprayer used in a winter wheat field 2020/2021 in Eningen.

Table 2. Overview of the used Pre- and Post-emergence herbicides with their application time in days after sowing (DAS) for each crop, in both years and all locations.

Year, Location	Crop	PRE-Appl. (DAS)	Herbicide Field Rate	POST-Appl. (DAS)	Herbicide Field Rate
2019/2020, Hohenheim	Spring oats	-	-	26	[1] Biathlon® 4D (0.07 kg ha^{-1}) + Adjuvant
2020/2021, Hohenheim	Spring oats	-	-	29	[1] Biathlon® 4D (0.07 kg ha^{-1}) + Adjuvant
2020/2021, Hohenheim	Winter wheat	5	[3] Malibu® (4 L ha^{-1})	135	[1] Biathlon® 4D (0.07 kg ha^{-1}) + Adjuvant and [2] Atlantis® Flex (0.3 kg ha^{-1}) + Adjuvant
2020/2021, Eningen	Winter wheat	7	[3] Malibu® (4 L ha^{-1})	137	[1] Biathlon® 4D (0.07 kg ha^{-1}) + Adjuvant and [2] Atlantis® Flex (0.3 kg ha^{-1}) + Adjuvant

[1] Biathlon® 4D = Florasulam 54 g a.i. kg^{-1} + Tritosulfuron 714 g a.i. kg^{-1}, GR, BASF. [2] Atlantis® Flex = Propoxycarbazone 67.5 g a.i. kg^{-1} + Mesosulfuron 43.8 g a.i. kg^{-1}, GR, Bayer CropScience. [3] Malibu® = Flufenacet 60 g a.i. L^{-1} + Pendimethalin 600 g a.i. L^{-1}, EC, BASF plc.

2.2. Camera-Controlled Harrowing and Hoeing Technology

The automatic harrowing treatments were performed with a 6 m-wide harrow (Hatzenbichler, St. Andrä, Austria) with flexible tines (25 mm distance between the tines, six tine rows, tine bending 120°, 6 mm tine diameter, 380 mm tine length and protected spring winding), see Figure 1. The adjustment of the harrowing intensity was achieved by a hydraulic regulation of the tine angle. The hydraulic cylinder is regulated by a controller containing a decision support system for the continuous adjustment of the tine angle based on a pre-set CSC threshold value. The tine angle is increased if the actual CSC is lower than the threshold to increase WCE; the tine angle is decreased if the actual CSC is higher than the threshold to avoid crop damage. The CSC is measured online using two RGB (color model for red, green and blue components) cameras that are mounted in front of and behind the harrow, and from these images the crop coverage is calculated [38].

The camera-guided hoeing treatments were performed with a 3 m-wide hoe (K.U.L.T.-Kress Umweltschonende Landtechnik, Kürnbach, Germany) with 10 cm no-till sweeps, see Figure 1. Row detection is implemented in a real-time system for automatic steering of the sweeps in the inter-row with a distance of 20 mm to the crop rows. The camera is mounted at the tool bar of the hoe, scanning diagonally forward on 6 crop rows and analyzing the images by a connected controller. The images are segmented into a green (plants) and brown background (soil and mulch). In the regions of the highest green pixel densities, tracking of the cereal rows is carried out by an extended Kalman filter [39]. A hydraulic side-shift cylinder was implemented to automatically move the no-till sweeps exactly in the center between two cereal rows.

2.3. Data Collection

Data assessment was identical in all trials and in both years. Weed density, crop density and grain yield were measured in an area of 3 × 15 m in the middle of the plots to avoid edge effects. Weed density and crop losses were counted at four random locations per plot using a quadratic frame of 0.1 m^2. Plant counts were taken one day before chemical or mechanical application, immediately after the treatment and 14 days after the treatments. The weeds in the herbicide plots were only measured before and 14 days after application. The weed control efficacy (WCE) was calculated according to Rasmussen [40] where *ds* is the weed density (weeds m^{-2}) after application and *du* is the weed density in the same plot before the application.

$$\text{WCE} = 100\% - ds \ / \ (0.01 \times du) \tag{1}$$

The WCE for the herbicide application was calculated using the weed density 14 days after treatment. Additionally, the weed species spectrum was recorded during the weed density assessment. Crop density was assessed four times at random positions in each plot by using a quadratic frame of 0.1 m^2 directly and 14 days after treatment. Crop losses were calculated using data immediately before and 14 days after weed control treatments. Grain yield was recorded inside the plots on an area of 10 m × 1. 5 m using a plot combine harvester (Wintersteiger, Ried im Innkreis, Austria). All grain yield data are presented at 86% dry weight.

2.4. Data Analysis

The data were analyzed with the statistical software R (Version 3.4.1, R Foundation for Statistical Computing, Vienna, Austria). Prior to analysis, the data were tested for homogeneity of variance and normal distribution of residuals by utilizing residual plots ("residual vs predicted" plot) and a quantile–quantile plot. An analysis of variance (ANOVA) was performed, according to the following linear one factorial model.

$$\mathrm{Y_{ik}} = \mu + \mathrm{a_i} + \mathrm{b_k} + \mathrm{e_{ik}} \tag{2}$$

where $\mathrm{Y_{ik}}$ is the measured result (grain yield, crop density and WCE) of treatment a at block b. μ denotes the general mean and $\mathrm{a_i}$ represents the fixed effects of the ith treatment, while $\mathrm{b_k}$ and $\mathrm{e_{ik}}$ represent the random effects of the kth block and the residual error for each plot, respectively. Due to the significant interactions between year and treatments, and between location and treatments, the factors of year and location were analyzed separately. For each experiment (location per year), the model was then calculated separately. The means of the fixed effects were compared with Tukey's HSD test at $\alpha \leq 0.05$.

3. Results

3.1. Weed Density in Spring Oats and Winter Wheat

The highest weed density in the control treatments was measured in spring oats at Hohenheim in 2020 with an average of 36 weeds m^{-2}; the lowest weed density mean was measured in spring oats in Hohenheim in 2021 with 14.5 weeds m^{-2}. The five most abundant weed species with their frequency are listed in Table 3.

Table 3. The average weed densities and the frequencies of the five most abundant weed species in the control plots (Con) in the field experiments in Hohenheim and Eningen in winter wheat and spring oat. Means were obtained from four counts using a 0.5 m^2 estimation frame.

Number	Location	Crop	Year	Weed Density (Weeds m^{-2})	Weed Species
1	Hohenheim	Spring oats	2020	36	*Veronica persica* POIR. 31% *Lamium purpureum* (L.) 25% *Capsella bursa-pastoris* (L.) 19% *Stellaria media* (L.) 18% *Cirsium arvense* (L.) 5%
2	Hohenheim	Spring oats	2021	15	*Veronica persica* POIR. 33% *Lamium purpureum* (L.) 27% *Capsella bursa-pastoris* (L.) 19% *Stellaria media* (L.) 10% *Thlaspi arvense* (L.) 9%
3	Hohenheim	Winter wheat	2021	17	*Veronica persica* POIR. 33% *Lamium purpureum* (L.) 25% *Stellaria media* (L.) 19% *Capsella bursa-pastoris* (L.) 10% *Chenopodium album* (L.) 4%
4	Eningen	Winter wheat	2021	23	*Veronica persica* POIR. 29% *Lamium purpureum* (L.) 27% *Galium aparine* (L.) 12% *Persicaria maculosa* GRAY. 7% *Rumex crispus* (L.) 5%

3.2. Weed Control Efficacy in Spring Oats (2019/2020 and 2020/2021) in Hohenheim

There were no significant differences among the tested weed control measures within individual locations and years (WCE 75–100%). The lowest control was recorded in Con with 5–25% WCE, which was significantly lower than all the other treatments. In the spring oats experiments (Figure 2A,B) the efficacies of the mechanical treatments ranged between 75 and 85%.

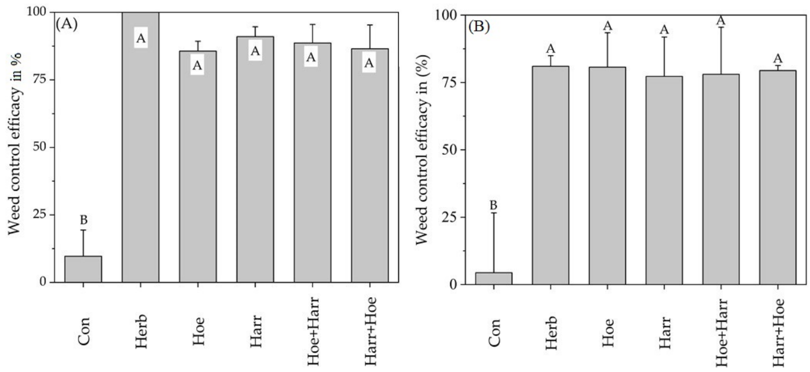

Figure 2. Weed control efficacy (WCE%) recorded in spring oats at Hohenheim in 2019/2020 (**A**) and in spring oats at Hohenheim in 2020/2021 (**B**). WCE for mechanical treatments was measured directly after treatment. Herbicide efficacy was assessed 14 days after application. Means with the same letter are not significantly different, according to an HSD-test at $\alpha \leq 0.05$. Con = untreated control, Herb = herbicide control, Hoe = one-time hoeing, Harr = one-time harrowing, Hoe + Harr = first hoeing and subsequent harrowing, and Harr + Hoe = first harrowing and subsequent hoeing.

3.3. Weed Control Efficacy in Winter Wheat (2020/2021) in Hohenheim and Eningen

The highest WCE was achieved in the Herb (WCE > 99%) and in the Pre-Herb + Harr + Hoe treatment (WCE > 98%), see Figure 3A,B. The lowest control efficacy was measured in the Con- and Pre-Herb-treatments with a WCE between 5 and 25%. No significant differences were detected between the treatments, except for Con and Pre-Herb. The average WCE of the solely mechanical treatments varied between 70 and 85% in both locations. The treatments with a double mechanical treatment (Harr 2× and Hoe 2×) achieved an average of 80% WCE; there was no significant difference due to single mechanical treatments (Harr and Hoe) which achieved 75% WCE. All treatments combining chemical and mechanical weed control achieved a WCE between 55% (Pre-Herb + Hoe) and 100% (Pre-Herb + Harr + Hoe) at both locations.

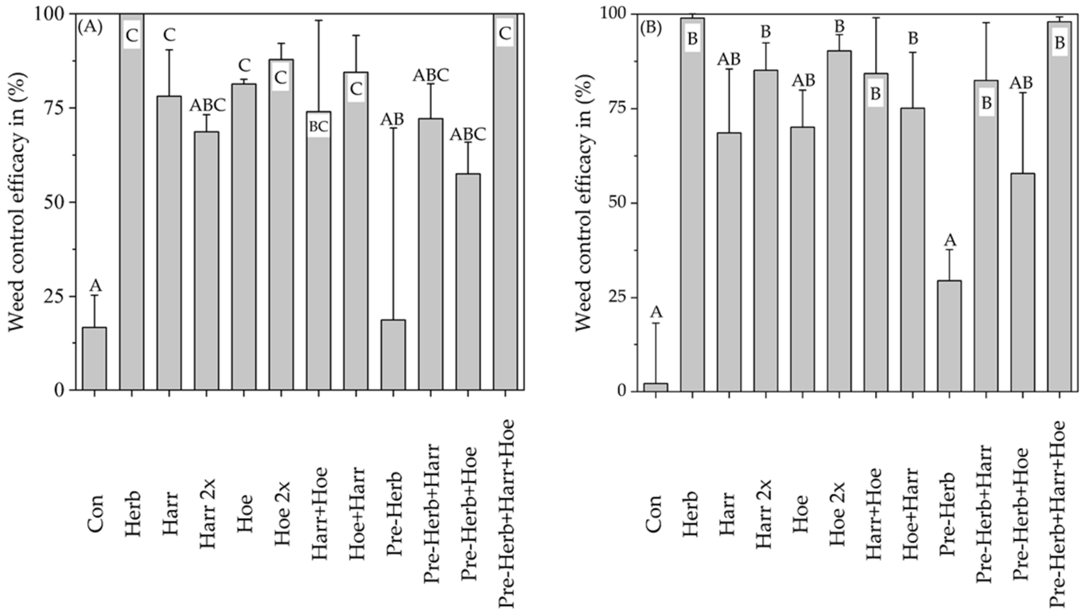

Figure 3. Weed control efficacy (WCE %) in winter wheat at Hohenheim (**A**) in 2020/2021 and Eningen (**B**) in 2020/2021. WCE for mechanical treatments was measured directly after treatment. Herbicide efficacy was assessed 14 days after application. Means with different letters (ABC) are significantly different, according to an HSD-test at $\alpha \leq 0.05$. Con = untreated control, Herb = herbicide control, Hoe = one-time hoeing, Hoe 2× = two-time hoeing, Harr = one-time harrowing, Harr 2× = two-time harrowing, Harr + Hoe = first harrowing and subsequent hoeing, Hoe + Harr = first hoeing and subsequent harrowing, Pre-Herb = pre-emergence herbicide, Pre-Herb + Harr = pre-emergence herbicide and one-time harrowing, Pre-Herb + Hoe = pre-emergence herbicide and one-time hoeing, and Pre-Herb + Harr + Hoe = pre-emergence herbicide plus once-harrowing and subsequent hoeing.

3.4. Crop Losses of Spring Oats and Winter Wheat

The highest crop losses were measured in the combined mechanical treatments Harr + Hoe (Ø 18 crops m^{-2}) and Hoe + Harr (Ø 16 crops m^{-2}), see Table 4. Similar crop damage was recorded in the Pre-Herb + Harr + Hoe treatment with an average crop loss of 14 crops m^{-2}. In the solely chemical treatments (Herb and Pre-Herb) no considerable crop losses (0–3 crops m^{-2}) appeared. Two-times the same mechanical treatment (Hoe 2× and Harr 2×) tended to damage more crops, compared to single mechanical treatments (Hoe and Harr). The combination of chemical and mechanical treatments (Pre-Herb + Hoe and Pre-Herb + Harr) achieved moderate crop damages (Ø 4–6 crops m^{-2}).

Table 4. Overview of the crop losses (crop plants m^{-2}) of the tested treatments within each location and year. Means with different letters (a,b,c,d) are significantly different, according to an HSD-test at $\alpha \leq 0.05$. Means were obtained from four counts using a 0.5 m^2 estimation frame. Con = untreated control, Herb = herbicide control, Hoe = one-time hoeing, Hoe 2× = two-time hoeing, Harr = one-time harrowing, Harr 2× = two-time harrowing, Harr + Hoe = first harrowing and subsequent hoeing, Hoe + Harr = first hoeing and subsequent harrowing, Pre-Herb = pre-emergence herbicide, Pre-Herb + Harr = pre-emergence herbicide and one-time harrowing, Pre-Herb + Hoe = pre-emergence herbicide and one-time hoeing, and Pre-Herb + Harr + Hoe = pre-emergence herbicide plus one-time harrowing and a second-time hoeing.

Treatment	Spring Oats 2019/2020 Hohenheim (Crops m^{-2})	Spring Oats 2020/2021 Hohenheim (Crops m^{-2})	Winter Wheat 2020/2021 Hohenheim (Crops m^{-2})	Winter Wheat 2020/2021 Eningen (Crops m^{-2})
Herb	1b	0c	0c	1d
Harr	6ab	6c	5abc	4bcd
Harr 2×	-	-	6abc	8abc
Hoe	3b	8c	2c	2cd
Hoe 2×	-	-	5bc	4bcd
Harr + Hoe	24a	29a	10ab	10ab
Hoe + Harr	23a	23ab	10ab	9abc
Pre-Herb	-	-	1c	3cd
Pre-Herb + Harr	-	-	6abc	6bcd
Pre-Herb + Hoe	-	-	4bc	7bcd
Pre-Herb + Harr + Hoe	-	-	12a	15a

The summer annual crop losses were twice as high (23–29 crop losses m^{-2}), compared to the winter annual crop (9–15 crop losses m^{-2}).

3.5. Grain Yield in Spring Oats in Hohenheim within the 6 Treatments 2019/2020 and 2020/2021

There were no significant differences in grain yield over both experiments and locations, see Figure 4A,B. Most mechanical treatments tended to achieve a 1 t ha^{-1} higher grain yield, compared to the Con treatment. Mechanical treatments did not differ significantly from the Herb treatment.

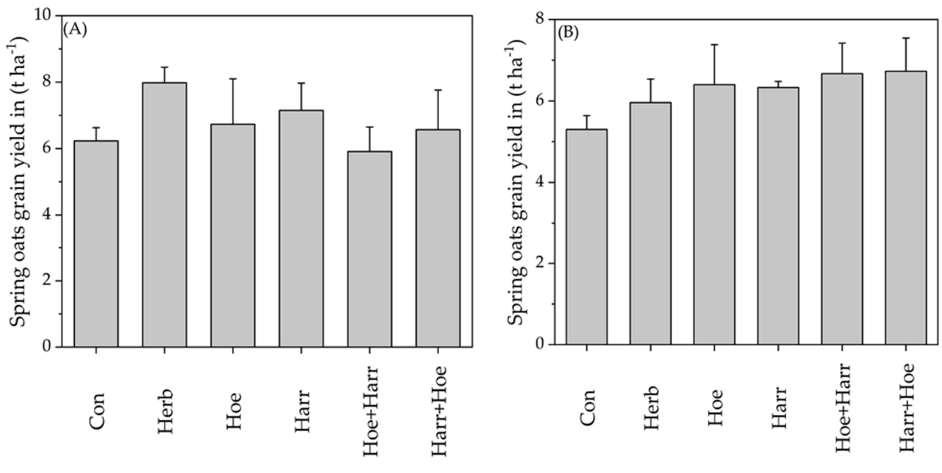

Figure 4. Grain yield in (t ha^{-1}) recorded in spring oats at Hohenheim in 2019/2020 (**A**) and 2020/2021 (**B**). Results without letters where no significant differences were detected, according to ANOVA. Con = untreated control, Herb = herbicide control, Hoe = one-time hoeing, Harr = one-time harrowing, Harr + Hoe = first harrowing and subsequent hoeing, Hoe + Harr = first hoeing and subsequent harrowing.

3.6. Grain Yield in Winter Wheat in Hohenheim and Eningen in 2020/2021

In the winter wheat experiment at Hohenheim, the highest grain yield was measured in the Pre-Herb treatment with 11 t ha^{-1}, see Figure 5A. The lowest grain yield was achieved in the combined treatment Pre-Herb + Harr + Hoe with 8.9 t ha^{-1} and was significantly lower than the Pre-Herb treatment. There were no significant differences between the remaining treatments. The grain yield for winter wheat varied between 9.1 and 10 t ha^{-1}. In the winter wheat experiment at Eningen, see Figure 5B, no significant differences between any treatments were recorded. The tendentially highest grain yield was measured at one-time harrowing (8.2 t ha^{-1}), followed by Herb (8.1 t ha^{-1}) and Pre-Herb + Harr + Hoe (8.0 t ha^{-1}). The tendentially lowest grain yield was observed in the Con (6.6 t ha^{-1}), followed by one-time hoeing (6.8 t ha^{-1}) and two-times harrowing (6.9 t ha^{-1}).

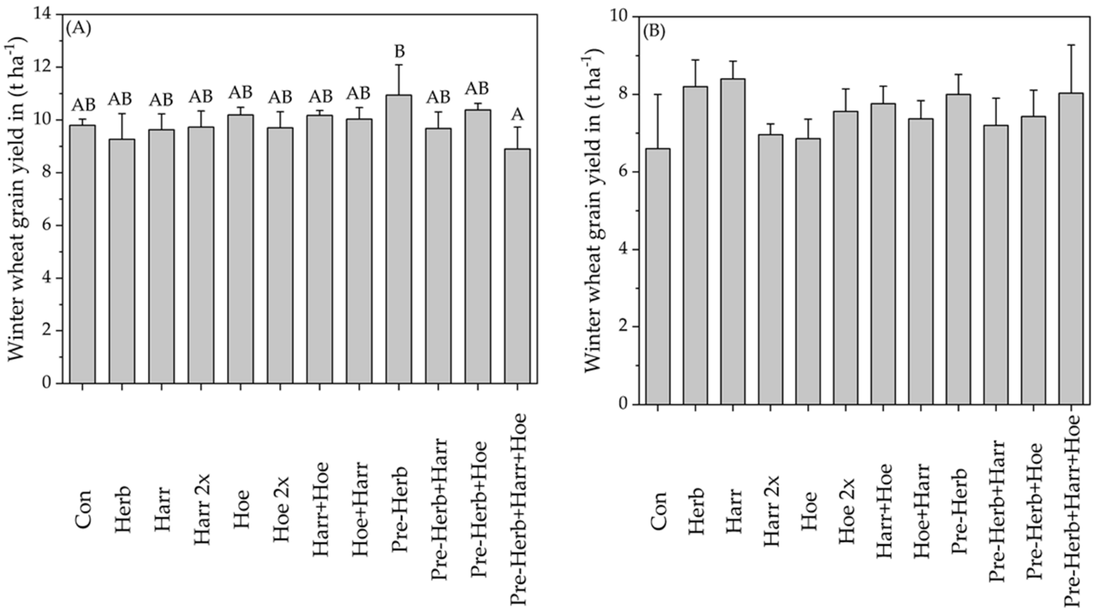

Figure 5. Grain yield in (t ha^{-1}) recorded in winter wheat at Hohenheim 2020/2021 (**A**) and in winter wheat at Eningen in 2020/2021 (**B**). Means with the same letter are not significantly different, according to an HSD-test at $\alpha \leq 0.05$. Results without letters where no significant differences were detected, according to ANOVA. Con = untreated control, Herb = herbicide control, Hoe = one-time hoeing, Hoe 2x = two-time hoeing, Harr = one-time harrowing, Harr 2x = two-time harrowing, Harr + Hoe = one-time harrowing and a second-time hoeing, Hoe + Harr = one-time hoeing and a second-time harrowing, Pre-Herb = pre-emergence herbicide, Pre-Herb + Harr = pre-emergence herbicide and one-time harrowing, Pre-Herb + Hoe = pre-emergence herbicide and one-time hoeing, and Pre-Herb + Harr + Hoe = pre-emergence herbicide plus one-time harrowing and a second-time hoeing.

4. Discussion

This study presents different IWM approaches, including single applications of pre- and post-emergence herbicides, sensor-based harrowing and hoeing, and combinations thereof. Our results showed that the sensor-based mechanical weed control can provide high WCE, reduce the amount of herbicide and achieve similar grain-yield levels, compared to the herbicide treatments. WCE in the present study was similarly high for all once or twice applied sensor-based mechanical weed control treatments (between 75 and 100%) and could replace the chemical weed control measures for the first experimental season. This can be attributed to a low average weed pressure (15–48 weeds m^{-2}), relatively dry soil conditions before and after the treatments, the fine seedbed and the optimal automatic adjustment of the intensity for a selective mechanical weed control. Dry soil and seedbed conditions are one of the most important factors for successful mechanical weed control [29,30,41,42]. Similar results of equal WCE for sensor-based mechanical treatments and conventional herbicide applications were recorded in previous studies [27,30,43]. These authors also justify their high WCE results with the exact adaptation of the sensor-based harrow/hoe to the field and weather conditions. The only difference in WCE in the present study was recorded between the summer annual and winter annual crops, with spring oats showing on average a 25% lower WCE than winter wheat. This might be due to a relatively well-established winter annual crop (vital crop and roots) at application time. Therefore, a higher automatic intensity adjustment, based on a crop soil cover (CSC) value of 20%, was realized to achieve the preset-CSC threshold value. Similar results for mechanical weed control were found for winter wheat and spring barley by Rasmussen and Svenningsen [42]. The combination of pre-emergence herbicide with a double mechanical weed control could achieve equal WCE (95–100% WCE), higher crop damages and equal grain yield, compared to pre- and post-emergence herbicide control. This is comparable to results from IWM studies in maize, sunflower and soybean from Italy. For IWM strategies, including hoeing and herbicide application, the authors showed WCE up to 100% [44]. Crops were damaged due to mechanical control measures but simultaneously the crop vitality increased. Therefore, a post-emergence herbicide application can be replaced. Pannacci and Tei [44] could reduce the amount of herbicide by 50% by combining chemical and mechanical weed control measures, by an average WCE of 99% and a similar yield, compared to a broadcast herbicide application. Winter crops, which are robust against mechanical stress, are highly competitive so that a certain level of weed density can be tolerated [42].

A single pre-emergence herbicide application showed the lowest WCE, but simultaneously achieved the highest yield in winter wheat or at least no significant yield loss. This can be an effect of the low weed densities in the experimental fields, or on areas with low weed densities, a higher crop damage can be instated by weed control measures (post-emergence herbicide application and mechanical weed control). Messelhäuser et al. [14] also recorded a significantly higher grain yield with herbicides that were applied in pre-emergence rather than post-emergence in winter annual crops, due to crop damage of the latter. The significantly lowest yield was recorded in the combination of pre-emergence herbicide including harrow and hoe, which also showed high plant losses, due to a high mechanical crop damage and the chemical crop stress. Plant losses were also quite high when harrowing and hoeing were combined (either way). This might be due to a higher weed density before weed control, because no pre-emergence herbicide was applied, and therefore a higher automatic intensity adjustment and a reduced row-guidance along the crop rows [43,45,46] were the result. However, if harrowed only once, the crop can compensate the crop damage due to the agronomical benefit of harrowing [42].

In our study, all entirely sensor-based mechanical approaches achieved grain yields that were equal to approaches involving herbicides. However, this result highly depends, just like the WCE, on optimal weather conditions, seedbed preparations, and a high accuracy of the automatic intensity adjustment of the mechanical implements [27,30,47,48]. Other studies from Pannacci and Tei [44] showed lower WCE and grain yield for mechanical weeding when intensity adjustments or row-guidance were performed manually.

5. Conclusions

The present study shows that sensor-based mechanical weed control can replace herbicide applications. Nevertheless, the efficiency of mechanical weed management practices depends a lot on the environmental conditions, meaning they cannot replace the herbicide application in each year. Therefore, a combined IWM approach using pre-emergence herbicide application and post-emergence sensor-guided mechanical weed control offers a robust weed management strategy, which may help to accomplish the targets to reduce pesticide use in the European Union. Field experiments have shown that a low level of weed infestation can be tolerated in winter wheat and spring oats, so the principle of the economic threshold of integrated crop production must also be followed for the specific weed species to prevent crop damage, by weed management practices. However, further investigations are needed to determine if the herbicide application can be further replaced by including soil tillage, crop rotation and cover cropping in an IWM approach.

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