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Smart Harrowing—Adjusting the Treatment Intensity Based on Machine Vision to Achieve a Uniform Weed Control Selectivity under Heterogeneous Field Conditions

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Abstract: Harrowing is mostly applied with a constant intensity across the whole field. Heterogeneous field conditions such as variable soil texture, different crop growth stages, variations of the weed infestation level, and weed species composition are usually not considered during the treatment. This study offers a new approach to sensor-based harrowing which addresses these field variations. Smart harrowing requires the continuous adaptation of the treatment intensity to maintain the same level of crop selectivity while ensuring a high weed control efficacy. Therefore, a harrow was equipped with a sensor-system to automatically adjust the angle of the harrow tines based on a newly developed decision algorithm. In 2020, three field experiments were conducted in winter wheat and spring oats to investigate the response of the weed control efficacy and the crop to different harrowing intensities, in Southwest Germany. In all experiments, six levels of crop soil cover (CSC) were tested. The CSC determines the balance between crop damage and weed removal. Each experiment contained an untreated control and an herbicide treatment as a comparison to the harrowing treatments. The results showed an increase in the weed control efficacy (WCE) with an increasing CSC threshold. Difficult-to-control weed species such as *Cirsium arvense* L. and *Galium aparine* L. were best controlled with a CSC threshold of 70%. However, 70% CSC caused up to 50% crop biomass loss and up to 2 t·ha^{-1} of grain yield reduction. With a CSC threshold of 20% it was possible to control up to 98% of *Thlaspi arvense* L. The highest crop biomass, grain yield, and selectivity were achieved with an CSC threshold of 20–25% at all locations. With this harrowing intensity, grain yields were higher than in the herbicide plots and a WCE of 68–98% was achieved. Due to the rapid adjustment of tine angle, the new sensor-based harrow allows users to apply the most selective harrowing intensity in every location of the field. Therefore, it can achieve equal weed control efficacies as using herbicide applications.

Keywords: digital farming; digital image analysis; mechanical weeding; precision farming

1. Introduction

Concerns about negative side-effects of herbicides on ground and surface water, biodiversity, human health and residues in the food chain, and the increasing problem of herbicide resistant weed species, are major factors for an increasing interest in non-chemical weed control methods [1,2]. Mechanical weed control methods such as harrowing and hoeing, are highly promising alternatives to chemical weed control. However, the success of mechanical weeding highly depends on the crop, the present weed species composition, the growth stages of the weeds, and soil and weather conditions. Harrowing can achieve 80–90% weed control efficacy (WCE) against mostly annual broad-leaved weeds in spring cereals (spring barley, oat, and triticale) [3–5]. Inter-row hoeing with no-till sweeps and goosefoot blades controls up to 89% of the weeds in spring barley [6]. Under favorable soil conditions, mechanical weeding can achieve almost the same weed control efficacy as herbicides. Sensor-based weed control can improve the aforementioned efficacies resulting in outcomes that are comparable to those of herbicide treatments. Light and friable soils combined with dry and sunny weather are ideal conditions for harrowing [7]. Wet soil is less favorable for harrowing and weeds have better chances to recover [8].

Harrowing mainly uproots and buries weeds with soil [8]. Only a small proportion (less than 10%) of weeds are pulled out of the soil [8]. It is most efficient if the weeds have developed only cotyledons and the first true leaves [4].

Selectivity is a suitable parameter to determine the success of weed harrowing. It is defined as the percentage ratio of WCE and crop soil cover (CSC) [3]. CSC is the percentage of the crop canopy which is covered by soil immediately after harrowing [3]. Harrowing intensity can be regulated by changing the tine angle in relation to the field surface, the pressure of the tines onto the soil, the tractor driving speed, and the number of passes [9,10]. Hereby, the treatment intensity must be suitable for the crop development. Crop plants in the early development stages (e.g., winter wheat in the three-leaf stage) should be harrowed with a lower intensity than crops in more advanced development stages during tillering to avoid excessive crop plant losses [11]. It must be considered that harrowing results in physical stress for the plants and the frost tolerance of the crop plants can be decreased for a limited time [12]. However, in addition to weed control, harrowing might have several positive effects on the crop including soil loosening, aeration of the soil, increasing soil temperatures and water infiltration, mineral nitrogen content, and induction of tillering [13].

In practical farming, treatment intensity is mostly set by visual assessment of the harrowing effect on the crop and weeds in a test stripe. Then, a constant treatment intensity is applied throughout the entire field. The treatment is usually not adjusted during the application unless severe crop damage or failure of weed control efficacy becomes very obvious [5,14]. A constant treatment intensity of the harrow would damage the crop in areas with very light soil and at the retarded crop growth stage. It would reduce WCE in areas with well-developed crops and high weed infestation levels. Site-specific harrowing with a camera-controlled adjustment of tine angle automatically increases intensity at locations with high density, weed patches, and high crop coverage. It reduces the intensity of harrowing in areas with poor crop development and low weed density [15]. To increase the selectivity of harrowing, a balance between crop damage and weed control must be established. Thus, the variability in soil coverage and weed control must be constantly adjusted. For this study, the selectivity was defined as the relationship between the percentage of weed control and CSC directly after harrowing [3]. New emergence of weeds was not considered after the treatment. Crops with a low competitiveness against weeds should be cultivated repeatedly [4].

In recent decades, different sensor-based harrow developments were undertaken by [15–21]. In a previous study, [18] developed a sensor-based harrow that used a photo-optical sensor to detect the weed density in front of the tractor. A camera measured the actual value and compared it to a preset threshold. A quantitative determination was performed between the weed density and soil. Afterwards the harrow adapted automatically to the previously recorded field conditions. Other systems, such as [20], developed a sensor-based harrow and measured the weed density before application using a bi-spectral camera. In a different study, [15] showed the possibilities of automatically adjusted depth control of the tines. For our approach, [21] demonstrated the possibilities of sensor-based harrowing by simultaneously controlling several parameters, such as weed density, soil conditions, and driving speed, by only measuring the burial before and after the treatment. This simplicity of the system offers a great advantage compared to others.

The objective of this study was to test different harrowing intensities based on preset CSC thresholds in the decision algorithm of the sensor-based harrow. The influence of different CSC values on WCE, crop biomass, grain yield, and selectivity were measured. The sensor-based harrow was capable of realizing a constant CSC in a heterogenous field by constantly adjusting the tine angle with a hydraulic control system. The aim was to find the optimum CSC corresponding to the highest selectivity and yield in two spring oats fields and one winter wheat field. It was first hypothesized that maximum WCE was already reached at CSC of less than 30% and higher CSC did not further increase WCE. The second hypothesis was that strong harrowing intensities causing 70% CSC could control difficult-to-control weed species, patches of species such as *Cirsium arvense* and *Galium aparine*, which usually survive post-emergence harrowing. The third hypothesis was that highest grain yields were achieved with medium CSC thresholds.

2. Materials and Methods

2.1. Experimental Sites and Details

In 2020, three field experiments were conducted in winter wheat and spring oats at two locations of the University of Hohenheim in Southwest Germany to test the sensor-based harrow under heterogeneous field conditions. The first location, Oberer Lindenhof (48.47° N, 9.30° E), is a conventional farm, situated near Eningen, at an altitude of 720 m above sea level. The second location is a conventional farm at Hirrlingen (48.41° N, 8.89° E) with an elevation of 423 m above sea level. The average annual rainfall for both research locations was similar with 790 mm in Eningen and 796 mm in Hirrlingen. During the vegetation period, average temperatures were 1.5 °C higher than average and 80 mm less precipitation was recorded at both locations. Two experiments were carried out in Hirrlingen, one in winter wheat (*Triticum aestivum* L., cv. Patras) and one in spring oats (*Avena sativa* L., cv. Armani). Sowing density was 300 viable seeds m^{-2} in winter wheat and 350 viable seeds m^{-2} in oats. Winter wheat was sown on 10 October 2019 and oats on 15 March 2020. The third field trial near Eningen was sown with 350 viable seeds m^{-2} in oats. (*A. sativa*, cv. Armani) on 24 March 2020. The row distance was 150 mm in all three experiments. The soil texture was a silty loam at both locations. Details of the experiments are presented in Table 1.

Table 1. Details of harrowing experiments in Hirrlingen and Eningen with different mechanical and herbicide treatments in 2020.

Details	Hirrlingen (48.41° N, 8.89° E) Winter Wheat	Hirrlingen (48.41° N, 8.89° E) Spring Oats	Eningen (48.47° N, 9.30° E) Spring Oats
Sea level	423 m	423 m	720 m
Long-term average Precipitation	790 mm	790 mm	796 mm
Long-term average temperature	7.8 °C	7.8 °C	8.5 °C
Soil composition	Clay 53%, Sand 7%, Silt 40%	Clay 56%, Sand 11%, Silt 33%	Clay 43%, Sand 23%, Silt 35%
Crop variety	cv. Patras	cv. Armani	cv. Armani
Sowing	10 October 2019	15 March 2020	24 March 2020
Seed density	300 seeds·m^{-2}	350 seeds·m^{-2}	350 seeds·m^{-2}
Mechanical application	19 March 2020	6 May 2020	8 May 2020
Herbicide application	16 March 2020	16 May 2020	19 May 2020
Harrow driving speed	8 km h^{-1}	8 km h^{-1}	8 km·h^{-1}
Harvesting	3 August 2020	03 August 2020	28 August 2020

All three trials were set up as a randomized complete block design with four repetitions and six treatment intensities, one untreated control, and an herbicide treatment across the entire plot. The plot size was 6 × 25 m. Table 2 provides an overview of the treatments and their respective descriptions.

Table 2. Treatment descriptions, time of treatment, and crop growth stage of the field trials at Hirrlingen and Eningen in 2020. CSC means crop soil cover, defined as the percentage of the crop canopy that is covered by soil immediately after harrowing. WW-H, SO-H means Winter Wheat-Hirrlingen, Spring Oats-Hirrlingen, respectively, and SO-E means Spring Oats Eningen.

Treatment	Treatment Acronym	Time of Treatment (DAS *)	Crop Growth Stage (BBCH **)
Untreated control	CON	-	-
Herbicide	HERB	WW-H 158, SO-H 63, SO-E 56	BBCH 14
Crop soil cover of 5%	CSC_5%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 15%	CSC_15%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 20%	CSC_20%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 25%	CSC_25%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 45%	CSC_45%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 70%	CSC_70%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24

* DAS = Day After Sowing, ** BBCH = Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie.

In the herbicide treatment, Concert SX (Cheminova Deutschland GmbH, metsulfuron 38.4 g/kg a.i. and thifensulfuron 384.5 g/kg a.i.) was applied with a plot sprayer in oats at Hirrlingen and Eningen at crop stage Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) 14. In winter wheat Atlantis Flex + Biathlon 4D (Bayer CropScience Deutschland GmbH, propoxycarbazone 67.5 g/kg a.i. and mesosulfuron 43.8 g/kg a.i. + BASF SE, tritosulfuron 714 g/kg a.i., and florasulam 54 g/kg a.i.) was also applied with a plot sprayer. The mechanical treatments were performed at crop stage BBCH 21–24. Due to the high clay content, it was important to have ideal soil moisture and friable soil conditions for the mechanical cultivation with the harrow. In the untreated control, no weed control method was carried out. The untreated plots were driven by the tractor in the same manner as for all mechanical treatments but with the harrow raised. Harrowing was performed parallel to the crop rows with a driving speed of 8 km·h^{-1}.

2.2. *Description of the Sensor-Based Harrow (SenHa)*

The 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 maximum force that each tine could apply was 50 newtons, with a decrease of 0.67 newtons degree^{-1}. The automatic adjustment of the harrowing intensity was achieved by controlling the hydraulic cylinders responsible for changing the tine angle and using digital image analysis, as described in [21]. The harrow was composed of four 1.5 m sections. All the sections received the same signal that was calculated based on the digital image analysis method. Thus, the tine angle was always equal for each harrow section. A gear divider ensured an even distribution of the oil flow to all four hydraulic cylinders. The main function of the machine vision elements was to continuously measure the plant soil cover in front and behind the harrow. Weeds were removed from the images using a morphological filter of object size. Then, crop coverage was calculated. The difference in crop soil coverage between the front camera (before harrowing) and the row camera (after harrowing) is defined as crop soil cover (CSC). CSC was continuously measured during harrowing. The actual CSC value was then compared with a preset threshold value in the image analysis software (IRS). If the actual CSC was higher than the preset threshold, the tine angle was decreased to avoid crop damage. If the CSC was lower than the preset threshold, the tine angle was increased to achieve a higher weed control efficacy. The concept and the importance of the harrow tine angle is depicted in Figure 1. The angle α describes the angle of each harrow tine during the treatments. Reducing alpha results in a less intense (reduced pressure on tine) treatment, whereas an increase in alpha causes a more aggressive (increased pressure on tine) treatment. The pressure on the tine working part is a linear response equal to the change of alpha. It is important to note that alpha is always measured in relation to the harrow and not in relation to the ground; see Figure 2.

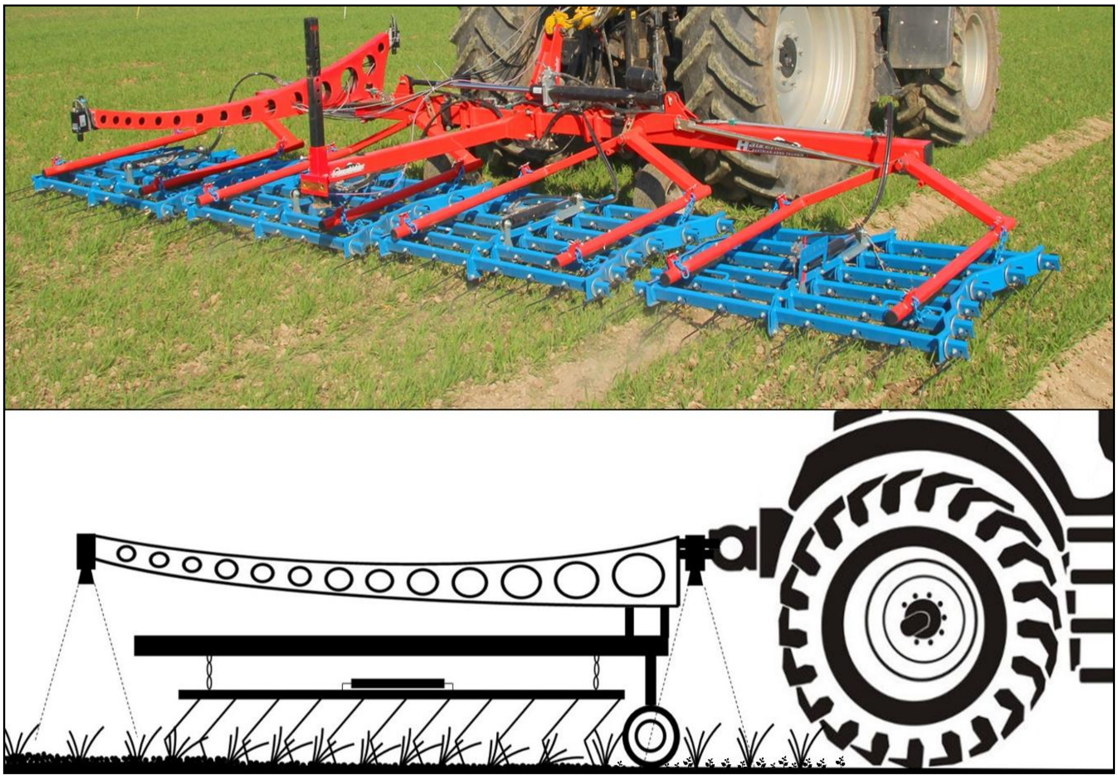

Figure 1. In the top image, the sensor-based harrow used in winter wheat in spring 2020. The design of the harrow with the field of view from both cameras, containing the automatic adjustment of the tine angle, in the bottom image.

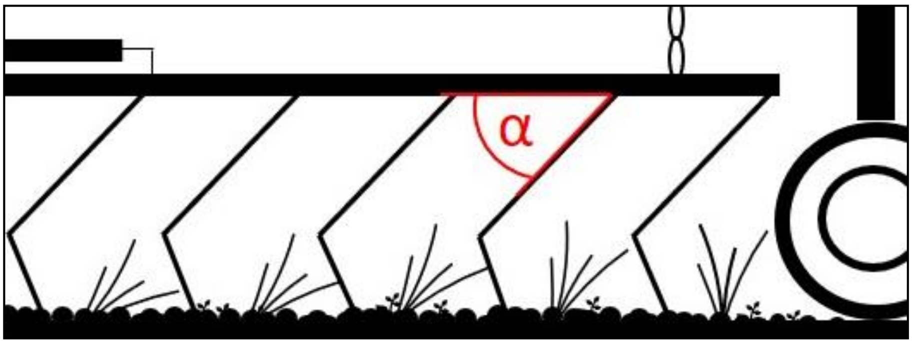

Figure 2. The concept of adjusting the harrow tine angle α based on the image analysis software (IRS). α is always measured in relation to the harrow, not to the ground.

2.3. Data Collection

All measurements, the biomass cut, and the harvesting of grains was performed only in the 10 center rows to reduce possible border effects. At the time of harrowing, the weed species were in the 2–6-leaf stage. All field measurements and agronomic operations were performed identically. At both research locations, weed plants per m^{-2} were counted for each plot three days prior to harrowing and the herbicide application. Three days after harrowing, weed plants were counted again for the mechanical treatments at Eningen and Hirrlingen. After a waiting period of two weeks, weed plants were also counted for the herbicide treatment in all trails. Weed counts were conducted using a frame of 1/10 m^2. Four random counts were performed in each plot. The percentage of weed control efficiency was calculated in each plot separately, because of the heterogeneity of the trial. An above ground biomass cut of 1 m^2 was performed at BBCH 49 in the spring oats at Eningen and Hirrlingen, and in the winter wheat at Hirrlingen at BBCH 59. The plant matter was separated into weed and crop plants. The fresh crop weight was measured shortly after taking the biomass cuts (data not shown). The plant material was then placed in a drying chamber for 48 h at 80 °C. After the drying process, the dry mass of the crop and weed plants was weighed and recorded for each plot. To assess the grain yield (t·ha^{-1}), each plot was harvested at a size of 10 m × 1.25 m. Marginal effects were excluded by a core harvest. The harvest was undertaken using plot combine harvesters (Wintersteiger, Ried im Innkreis, Austria). The oat and winter wheat plots were harvested on 3 August 2020 at Hirrlingen and the spring oats on 26 August 2020 at Eningen.

2.4. Data Analysis

The data were analyzed with the R Studio software (Version 1.0.136, RStudio Team, Boston, MA, USA). Prior to the analysis, the data were tested for homogeneity of variance and normal distribution of the residues. An analysis of variance (ANOVA) was performed, and the means of each observation were compared with a Tukey-Honest Significant Difference (HSD) test at $\alpha \leq 0.05$. The model used was the following:

$$Y_{ik} = \mu + a_i + b_k + e_{ik} \tag{1}$$

where Y_{ik} is the result (e.g., grain yield) of treatment i at block k. μ is the general mean, a_i is the yield attributed to treatment i, while b_k is the block effect of block k, and e_{ik} is the residual error of that specific plot. *CSC* (%) was calculated in accordance with Rasmussen et al. [10] as:

$$CSC = \frac{100 \cdot (L_0 - L)}{L_0} \tag{2}$$

where L_0 represents crop coverage before harrowing and L is the crop coverage measured after harrowing. The weed control efficacy (*WCE*) was calculated according to Rasmussen, J. [22] as:

$$WCE = 100\% - \frac{ds}{0.01 \cdot du} \tag{3}$$

where ds is the weed density (weeds m^{-2}) after application of the treatments and du is the weed density (weeds m^{-2}) in the same treatment plot before the application.

3. Results

3.1. Weed Density and the Five Most Common Weed Species in Each Trial

The highest weed density before harrowing was measured in spring oats in Eningen with 140 weeds m^{-2}, followed by spring oats in Hirrlingen with 110 weeds m^{-2} and winter wheat in Hirrlingen with 70 weeds m^{-2}. The five most abundant weed species before harrowing with their frequency are listed in Table 3. In general, there were more difficult-to-control weed species in Hirrlingen including *Galium aparine* in winter wheat with a frequency of 29% and *Cirsium arvense* in spring oats with a frequency of 28%. In spring oats in Eningen, the most problematic weed species was *Polygonum aviculare L.* with a frequency of 17%.

Table 3. The average weed densities and the frequencies of the five most abundant weed species in the field experiments in Hirrlingen and Eningen.

Location	Crop	Weed Density Weeds m^{-2}	Weed Species
Eningen	Spring oats	140	*Thlaspi arvense* L. (field pennycress) 33% *Veronica persica POIR.* (birdeye speedwell) 23% *Polygonum aviculare* L. (common knotgrass) 17% *Chenopodium album* L. (lamb's quarters) 10% *Capsella bursa-pastoris* L. (shepherd's purse) 7%
Hirrlingen	Winter wheat	70	*Galium aparine.* (cleavers) 29% *Veronica persica POIR.* (birdeye speedwell) 21% *Lamium purpureum* L. (red dead-nettle) 12% *Capsella bursa-pastoris* L. (shepherd's purse) 11% *Stellaria media* L. (chickweed) 9%
Hirrlingen	Spring oats	110	*Cirsium arvense* (creeping thistle) 28% *Polygonum aviculare* (common knotgrass) 19% *Thlaspi arvense* L. (field pennycress) 18% *Chenopodium album* L. (lamb's quarters) 14% *Veronica persica POIR.* (birdeye speedwell) 10%

3.2. Weed Control Efficacy in Spring Oats and Winter Wheat in Hirrlingen and Eningen

A reduction of the weed density was observed for all chemical and non-chemical treatments at every trial location (see Figure 3a–c). The herbicide treatment achieved a WCE between 98 and 100% over all experiments. A similar result (WCE 98%) was obtained when harrowing was performed with a CSC threshold of 20% in spring oats in Eningen (Figure 3a). The treatment with the lowest CSC threshold (CSC of 5%) also had the lowest reduction of weed density at all locations. Nonetheless, WCE of the 5% CSC treatment ranged from 30% in oats in Hirrlingen (Figure 3b) to 63% in oats in Eningen (Figure 3a).

The WCE did not differ in the treatments with a CSC threshold of 15, 25, 45, and 70% (Figure 3a) in Eningen. It varied between 87% at CSC of 25% and 95% at the CSC threshold of 20%. The variants with a CSC threshold of 45% and 70% were between these extremes.

There was a continuous increase in the WCE in oats in Hirrlingen from the 5% CSC treatment (30% WCE) to 86% WCE in the 25% CSC treatment. With a threshold of 45% CSC, WCE decreased slightly to 80% but did not differ from the aforementioned mechanical treatments. The highest value of WCE was achieved with the threshold of 70% CSC (WCE 90%). The CSC threshold of 70% resulted in WCE equal to that of the herbicide application.

In winter wheat in Hirrlingen, the highest WCE of 100% was achieved with the herbicide application. The highest WCE with harrowing was measured for the CSC threshold of 70% (91% WCE). The threshold for CSC of 5% and 15% controlled 47% of the weeds. In the range of 20 to 25% CSC threshold, WCE was 78–86%.

Table 4 shows the weed densities before and after harrowing in all treatments of the experiments. Based on the weed densities, WCE was calculated for each treatment.

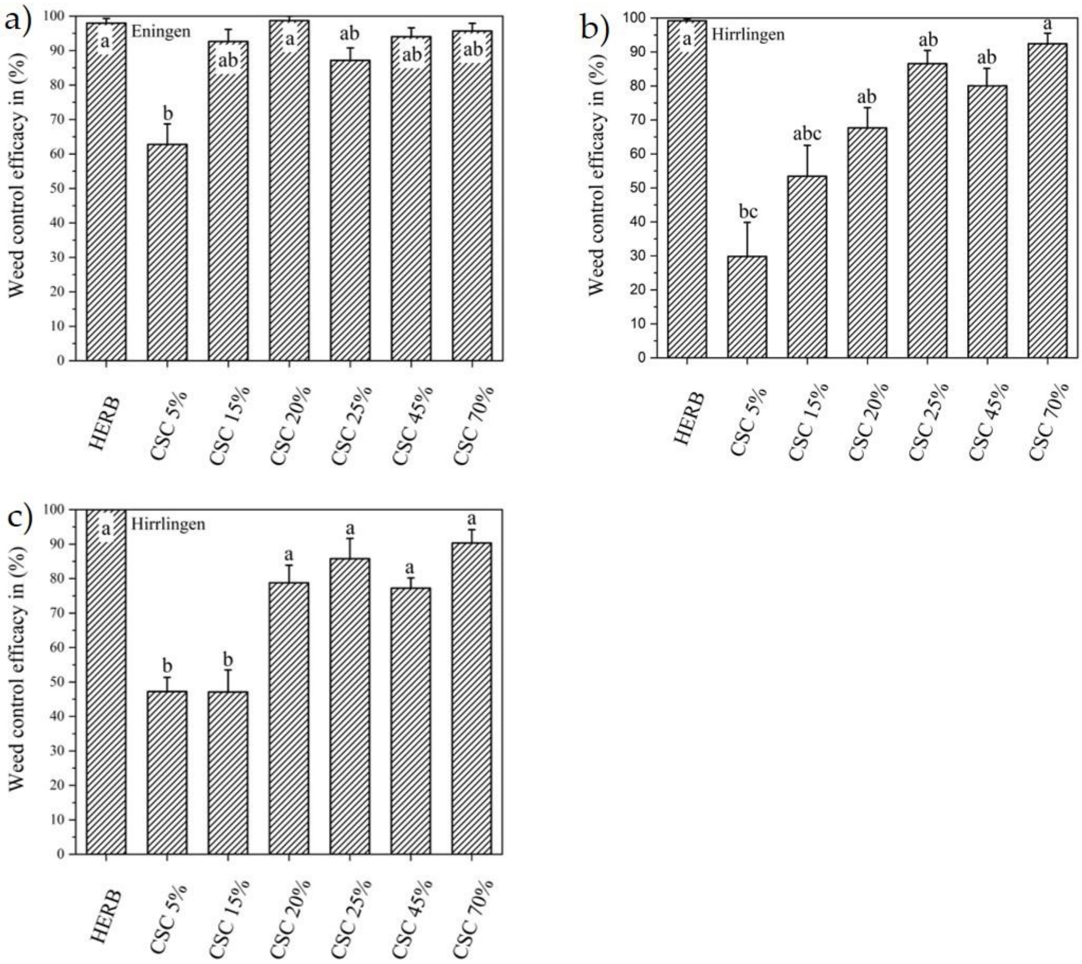

Figure 3. Weed control efficacy (WCE%) recorded in oats in Eningen (**a**), in oats in Hirrlingen (**b**), and in winter wheat in Hirrlingen (**c**). WCE for harrowing was measured directly after treatment. Herbicide efficacy was assessed 14 days after application. Means with the same letter are not significantly different according to an HSD-test at $\alpha \leq 0.05$. HERB = herbicide application, crop soil cover (CSC) 5, 15, 20, 25, 45, and 70% = crop burial by 5, 15, 20, 25, 45, and 70% soil respectively.

Table 4. Weed densities before and after treatment and weed control efficacy (WCE%) in spring oats in Eningen and Hirrlingen and in winter wheat in Hirrlingen. Means with the same letter are not significantly different according to an HSD-test at $\alpha \leq 0.05$.

Location	Crop	Treatment	Before Harrowing (Weeds m^{-2})	After Harrowing (Weeds m^{-2})	Weed Control Efficiency (%)	Significance $p < 0.05$
Eningen	Spring oats	Control	140	135	-	-
		Herbicide *	122	2	98	a
		CSC_5%	57	21	63	b
		CSC_15%	116	6	95	ab
		CSC_20%	106	2	98	a
		CSC_25%	111	14	87	ab
		CSC_45%	86	6	93	ab
		CSC_70%	71	3	96	ab
Hirrlingen	Spring oats	Control	82	82	-	-
		Herbicide *	70	1	99	a
		CSC_5%	68	48	30	bc
		CSC_15%	80	37	53	abc

Table 4. *Cont.*

Location	Crop	Treatment	Before Harrowing (Weeds m^{-2})	After Harrowing (Weeds m^{-2})	Weed Control Efficiency (%)	Significance $p < 0.05$
		CSC_20%	92	30	68	ab
		CSC_25%	60	8	86	ab
		CSC_45%	148	30	80	ab
		CSC_70%	81	6	92	a
Hirrlingen	Winter wheat	Control	46	45	-	-
		Herbicide *	57	0	100	a
		CSC_5%	60	32	47	b
		CSC_15%	56	30	47	b
		CSC_20%	52	11	79	a
		CSC_25%	29	4	86	a
		CSC_45%	30	7	77	a
		CSC_70%	50	5	90	a

* Herbicide weed control efficacy was measured 14 days after application.

3.3. Crop dry Biomass in Spring Oats and Winter Wheat in Hirrlingen and Eningen

Crop dry mass was lowest in the untreated control and the harrowing variant with 70% CSC threshold (Figure 4a–c). The highest amount of dry matter at all locations was achieved at a CSC threshold of 15% with values ranging from approx. 400 to 490 g·m^{-2}. In the lowest intensity of 5% CSC threshold, 210–245 g·m^{-2} dry crop mass was observed.

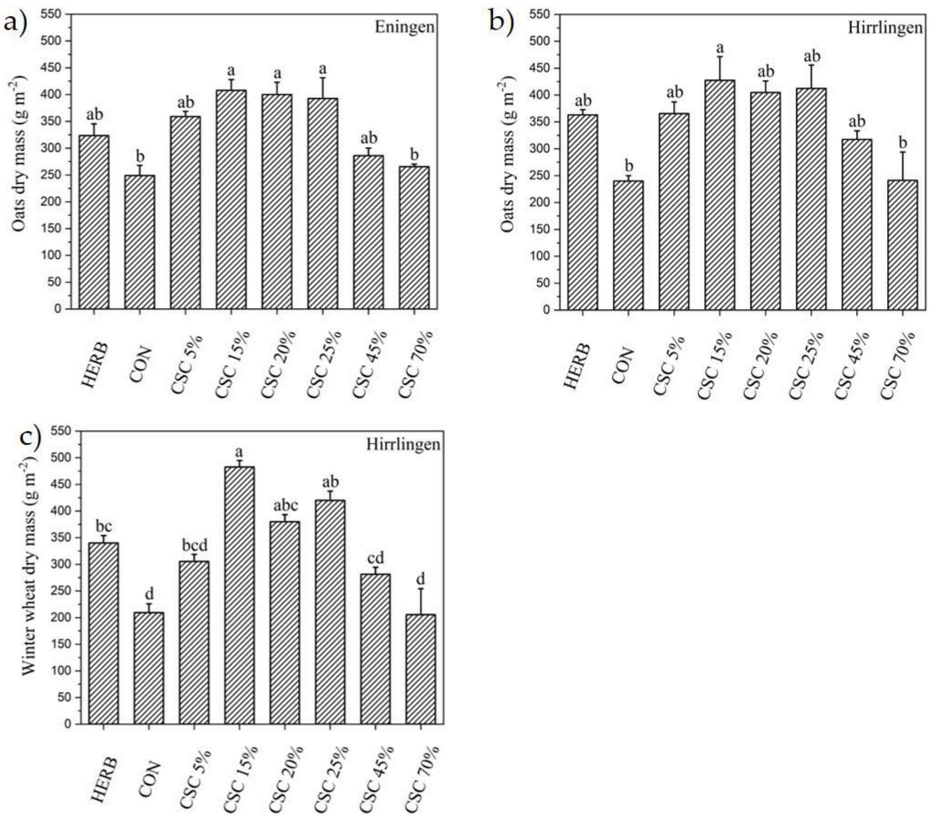

Figure 4. Dry crop mass (g·m^{-2}) recorded in oats in Eningen (**a**), in oats in Hirrlingen (**b**), and in winter wheat in Hirrlingen (**c**). The measurements were made at BBCH 49 in spring oats and BBCH 59 in winter wheat. Means with the same letter are not significantly different according to an HSD-test at $\alpha \leq 0.05$. CON = untreated control, HERB = herbicide application, crop soil cover (CSC) 5, 15, 20, 25, 45, and 70% = crop burial by 5, 15, 20, 25, 45, and 70% soil respectively.

In Eningen (Figure 4a), the highest oats dry mass was observed for the CSC threshold of 15%, with a total amount of 408 g·m^{-2}. Similarly, high dry biomass was achieved for the CSC threshold of 20% and 25% (400 and 393 g·m^{-2}). A reduction of crop dry mass was observed for the herbicide application. It had only 323 g·m^{-2} dry crop mass. The highest intensity of harrowing (CSC threshold of 70%) and the untreated control had the lowest crop dry biomass of 265 and 249 g·m^{-2}.

In spring oats in Hirrlingen the dry matter did not differ significantly between the treatments with a CSC threshold of 5, 20, 25, and 45%. The untreated control achieved the lowest crop dry biomass of 240 g·m^{-2}, followed by a CSC threshold of 45% with 317 g·m^{-2}. The CSC threshold of 25% resulted in the highest crop dry biomass of 412 g·m^{-2}.

At the winter wheat trial in Hirrlingen the highest crop dry mass (Figure 4c) was achieved at CSC threshold of 15% (482 g·m^{-2}). Similar to the other experiments, the CSC threshold of 70% and the untreated control had the lowest crop dry mass with 205 g·m^{-2} for CSC threshold of 70% and 209 g·m^{-2} for the untreated control. The highest crop dry biomass was observed with 15% CSC threshold.

3.4. Grain Yield in Oat and Winter Wheat in Hirrlingen and Eningen

The highest grain yields (7.3 t·ha^{-1}) in oats in Eningen were recorded in the herbicide treatment and the harrowing treatment with CSC of 25% (Figure 5a). Only in these two treatments were yields significantly higher than in the untreated control with 5.9 t·ha^{-1}.

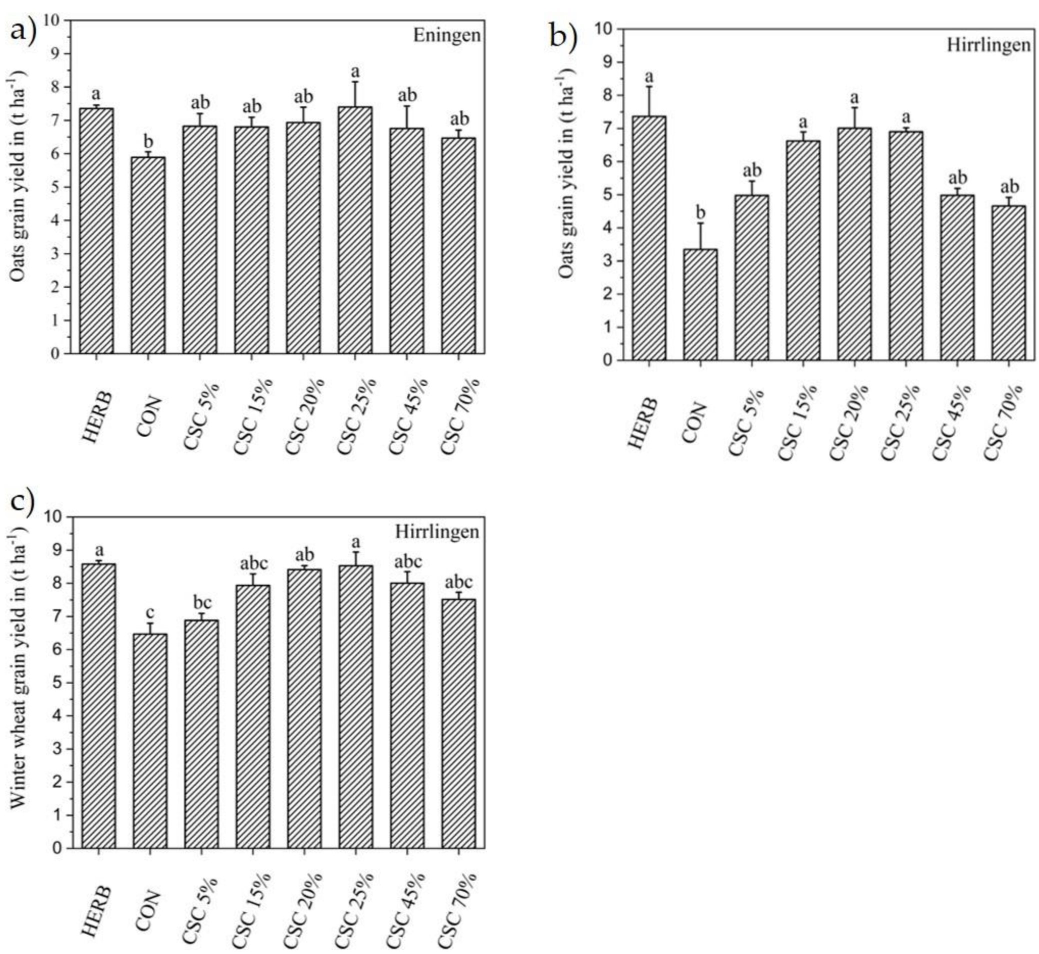

Figure 5. Grain yield (t·ha^{-1}) recorded in oats in Eningen (**a**), in oats in Hirrlingen (**b**), and in winter wheat in Hirrlingen (**c**). Means with the same letter are not significantly different according to an HSD-test at $\alpha \le 0.05$. CON = untreated control, HERB = herbicide application, crop soil cover (CSC) 5, 15, 20, 25, 45, and 70% = crop burial by 5, 15, 20, 25, 45, and 70% soil respectively.

In oats in Hirrlingen, the herbicide treatment and the harrowing intensities at 15%, 20%, and 25% CSC had significantly higher yields with 6.6–7.0 $t \cdot ha^{-1}$ than the untreated control with only 3.4 $t \cdot ha^{-1}$. In the other treatments (CSC threshold of 5%, 45%, and 70%), the yields ranged from 4.6 to 5.0 $t \cdot ha^{-1}$.

Similar results were measured in winter wheat in Hirrlingen. The herbicide treatment and the CSC threshold of 20% and 25% achieved the highest grain yields with approximately 8.5 $t \cdot ha^{-1}$. The untreated control plot had the lowest grain yield of 6.5 $t \cdot ha^{-1}$, followed by the CSC threshold of 5% with 6.8 $t \cdot ha^{-1}$. The grain yield of other mechanical treatments varied from 7.5 (CSC threshold of 70%) to 8.4 $t \cdot ha^{-1}$ (CSC threshold of 15%).

4. Discussion

This study presents a new approach to mechanical weeding with a sensor-based harrow for post-emergence weed control in cereals. Different harrowing intensities were applied to determine weed control efficacy and crop response. Tine angle was adjusted to heterogeneous, site-specific field conditions to achieve a constant CSC. This work is an improvement of previous studies on weed harrowing [3,7,15–18]. It uses a simple image analysis algorithm to continuously adjust harrowing intensity taking the actual CSC as a parameter for deciding if intensity needs to be decreased or increased [21]. CSC has been identified as a suitable measure for selectivity of weed harrowing [3,5,9]. Similar to [3,5], we set a threshold for % CSC that should not be increased during harrowing to avoid yield loss due to crop damage. With the two RGB-cameras continuously measuring crop coverage before and after harrowing, we could realize a constant CSC close to the threshold set even under heterogeneous field conditions. Other systems, such as [20], used a bi-spectral-camera to detect and separate weeds and crop in the field to adjust the intensity of the harrow. However, that algorithm was based on images prior to harrowing and could not react to variable field conditions. In a different approach, three parameters (soil density, weed density, and CSC) were measured to increase the selectivity of harrowing [16–18]. However, these algorithms were too complex for making online decisions about harrowing intensity. The simplicity of the presented system is a significant advantage for the practical application and commercial use in cereal production. The presented system is independent of the crop growth stage, driving speed, tine pressure, and soil texture [21]. It depends only on CSC. The results of this study show that it is meaningful to increase the CSC threshold in high density weed patches and locations with difficult-to-control weed species, such as *G. aparine* and *C. arvense*, and to tolerate a higher crop burial in these patches. However, with the current system a steady CSC threshold was applied.

Soil burial is the main effect of post-emergence harrowing [7]. Efficacy of mechanical weed control strongly depends on weather conditions and the weed species composition and weed growth stages [7,8]. Up to 97% of *Lepidium sativum* L. and *Chenopodium quinoa* Willd. were covered by harrowing [7]. With the presented new sensor-based harrow, 98% WCE against *Thlaspi arvense* and *Veronica persica* was achieved in oats at Eningen with a CSC threshold of 20%. At Hirrlingen, a CSC threshold of 70% was needed in oats to achieve 90% WCE. This was probably due to the more problematic weed species, such as *Cirsium arvense* and *Polygonum aviculare*, which were more tolerant to weed harrowing. In winter wheat, a threshold of 70% CSC was also necessary to control 90% of the major weed species *Galium aparine*. Although a threshold of 25% CSC was found to result in the highest grain yield, it might be advantageous in aggregated high-density patches of problematic weed species to increase harrowing intensity for higher WCE. Controversially, areas with few or no weeds could be treated with a CSC threshold lower than 25% to avoid crop damage.

In this study, the mechanical weeding at Eningen and Hirrlingen achieved results in WCE and grain yield equal to those of the herbicide treatment. Several studies reported that under optimum conditions mechanical weeding was as effective as herbicides [4,23,24]. In our case, better or similar yield results were also achieved with a crop-adapted burial intensity of maximum 25% CSC. This facilitation of control that automatically adjusts to the heterogeneous field conditions provides both organic and conventional farmers the opportunity to avoid crop damage and reduce weed density. Furthermore, it is independent of the manufacturer of the harrow implement and can be adapted to every hydraulically adjustable harrow.

Innovations in automated mechanical weed control have increased WCE and selectivity. However, mechanical weeding still needs to be combined with preventive weed control methods, such as rotating autumn sown crops with spring crops, ploughing, and false seed-bed preparation to achieve results equal to those of WCE as herbicide treatments. Machleb et al. [25] provides an overview of commercial sensor-based mechanical weed control systems in agriculture. Sensor-based inter-row hoeing systems with an automatic side-shift control are state of the art and commercially available. Studies such as [26] showed that an average reduction of weed density by 85% in maize could be achieved with a camera-steered hoe. However, it was difficult to control the weeds in the intra-row space without damaging the crop. Therefore, the herbicide application achieved a higher WCE. For sufficient WCE between and in the crop rows, the authors suggested a combination of inter-row hoeing and band herbicide spraying in the intra-row space. In a different approach [27], automatic hoe guidance achieved WCE of up to 89% in soybeans and 87% in sugar beet. For cereals, this study demonstrates that sensor-based harrowing provides a new approach to whole field cultivation, achieving up to 98% WCE without harming the crops. Sensor-based mechanical weed control systems aim to achieve a sustainable alternative for integrated crop protection, with results similar to those of herbicide applications. In previous studies, [21] achieved a WCE of up to 96% at 20% CSC, [5] reported a WCE of at least 80% using CSC of approx. 20%, and [28] achieved a weed control efficacy of 84% by combining pre- and post-emergence harrowing using a manually controlled harrow. In our experiment, in a field of 1.5 ha, the system performed well during the entire experiment. Furthermore, due to adjusting the harrow intensity to heterogeneous, site-specific field conditions using a CSC threshold between 15% and 25%, the damage due to crop burial was reduced compared to harrowing with a constant intensity. Crop biomass and grain yield was highest at a CSC threshold of 15–25% at both locations. Harrowing might even promote crop growth as was found for winter wheat by [18] and for winter wheat and barley by [16].

The outdoor agricultural environment presents complexities that make automation challenging. The systems utilized must be able to operate in an unstructured agricultural environment, but still be able to perform uniformly and robustly throughout the treatment [29]. These complexities include but are not limited to variable light conditions, both regarding the light intensity and its direction in comparison to the implement. Machine vision systems for field use need to be designed to be robust to sunlight variations [30]. In our sensor-based harrow the cameras did not have an automatic shutter regulation, therefore the exposure settings had to be adjusted manually. In cases of high exposure, the captured images were overexposed and therefore misleading, and when the implement was shadowed, the images were underexposed making it hard for the algorithm to detect the coverage of the plants. To regulate the lighting effects, powerful external illumination that would eliminate the shadow effects and regulate the light conditions or a closed canopy could be installed [31]. Improvements should be made in the generation of field images due to these varying conditions [32,33]. Plant identification can also be considered to increase the harrowing intensity on difficult-to-control weed species.

5. Conclusions

Automatic adjustment of harrowing with a maximum crop soil cover of 25% resulted in grain yields equal to those of herbicide application and average weed control efficacy of 80%. This automatic harrow provides an opportunity for integrated weed control and reduction of herbicide use. Furthermore, it might be a solution to decrease the risk of herbicide resistance and an effective tool to control problematic weeds such as *G. aparine*. More investigations are needed to better understand the effects of harrowing on cereal development in addition to direct weed control. Study is needed to determine how weeds and crops recover from harrowing, if crop growth can be stimulated by harrowing mainly during tillering, and if new weeds are induced to germinate after harrowing.

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References

1. Lotz, L.A.P.; Van der Weide, R.Y.; Horeman, G.H.; Joosten, L.T.A. Weed management and policies: From prevention and precision technology to certifying individual farms. In Proceedings of the 12th EWRS (European Weed Research Society) Symposium, Wageningen, The Netherlands, 24–27 June 2002; pp. 2–3.
2. Melander, B.; Rasmussen, I.A.; Barberi, P. Integrating physical and cultural methods of weed control examples from European research. *Weed Sci.* **2005**, *53*, 369–381. [CrossRef]
3. Rasmussen, J.; Bibby, B.M.; Schou, A.P. Investigating the selectivity of weed harrowing with new methods. *Weed Res.* **2008**, *48*, 523–532. [CrossRef]
4. Van der Weide, R.Y.; Bleeker, P.O.; Achten, V.T.J.M.; Lotz, L.A.P.; Fogelberg, F.; Melander, B. Innovation in mechanical weed control in crop rows. *Weed Res.* **2008**, *48*, 215–224. [CrossRef]
5. Rasmussen, J.; Nielsen, H.H.; Gundersen, H. Tolerance and Selectivity of Cereal Species and Cultivars to Postemergence Weed Harrowing. *Weed Sci.* **2009**, *57*, 338–345. [CrossRef]
6. Machleb, J.; Kollenda, B.; Peteinatos, G.G.; Gerhards, R. Adjustment of Weed Hoeing to Narrowly Spaced Cereals. *Agriculture* **2018**, *8*, 54. [CrossRef]
7. Home, M.C.W.; Tillett, N.D.; Hague, T.; Godwin, R.J. An experimental study of lateral positional accuracy achieved during inter-row cultivation. In Proceedings of the 5th EWRS Workshop on Physical and Cultural Weed Control, Pisa, Italy, 11–13 March 2002; pp. 101–110.
8. Kurstjens, D.A.G.; Kropff, M.J. The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Res.* **2001**, *41*, 211–228. [CrossRef]
9. Rydberg, T. Weed Harrowing—The Influence of Driving Speed and Driving Direction on Degree of Soil Covering and the Growth of Weed and Crop Plants. *Biol. Agric. Hortic.* **1994**, *10*, 197–205. [CrossRef]
10. Rasmussen, J.; Svenningsen, T. Selective Weed Harrowing in Cereals. *Biol. Agric. Hortic.* **1995**, *12*, 29–46. [CrossRef]
11. Rasmussen, J.; Mathiasen, H.; Bibby, B.M. Timing of post-emergence weed harrowing. *Weed Res.* **2010**, *50*, 436–446. [CrossRef]
12. Findlay, S.; Carreiro, M.; Krischik, V.; Jones, C.G. Effects of damage to living plants on leaf litter quality. *Ecol. Appl.* **1996**, *6*, 269–275. [CrossRef]
13. Steinmann, H.-H. Impact of harrowing on the nitrogen dynamics of plants and soil. *Soil Tillage Res.* **2002**, *65*, 53–59. [CrossRef]
14. Jensen, R.K.; Rasmussen, J.; Melander, B. Selectivity of weed harrowing in lupin. *Weed Res.* **2004**, *44*, 245–253. [CrossRef]
15. Søgaard, H.T. Automatic control of a finger weeder with respect to the harrowing intensity at varying soil structures. *J. Agric. Eng. Res.* **1998**, *70*, 157–163. [CrossRef]
16. Rueda-Ayala, V.; Weis, M.; Keller, M.; Andújar, D.; Gerhards, R. Development and testing of a decision-making based method to adjust automatically the harrowing intensity. *Sensors* **2013**, *13*, 6254–6271. [CrossRef]
17. Rueda-Ayala, V.; Peteinatos, G.; Gerhards, R.; Andújar, D. A Non-Chemical System for Online Weed Control. *Sensors* **2015**, *15*, 7691–7707. [CrossRef]
18. Engelke, B. Entwicklung eines Steuersystems in der Ganzflächig Mechanischen Unkrautbekämpfung. Development of a Self-Adjusting System for Broadcast Mechanical Weed Control. Ph.D. Thesis, Christian-Albrechts-Universität zu Kiel, Göttingen, Germany, 2000.
19. Müter, M.; Damerow, L.; Schulze, L.P. Kameragesteuerte mechanische Unkrautbekämpfung in Pflanzenreihen. *Landtechnik* **2014**, *69*, 120–124. [CrossRef]

20. Peteinatos, G.; Gierer, F.; Gerhards, R. Precision harrowing using a bispectral camera and a flexible tine harrow. *Julius-Kühn-Arch.* **2018**, *458*, 385–389. [CrossRef]
21. Gerhards, R.; Spaeth, M.; Sökefeld, M.; Peteinatos, G.G.; Nabout, A.; Ayala, V.R. Automatic adjustment of harrowing intensity in cereals using digital image analysis. *Weed Res.* **2020**, in press. [CrossRef]
22. Rasmussen, J. A Model for Prediction of Yield Response in Weed Harrowing. *Weed Res.* **1991**, *31*, 401–408. [CrossRef]
23. Wiltshire, J.J.J.; Tillett, N.D.; Hague, T. Agronomic evaluation of precise mechanical hoeing and chemical weed control in sugar beet. *Weed Res.* **2003**, *43*, 236–244. [CrossRef]
24. Riemens, M.M.; Van der Weide, R.Y.; Bleeker, P.O.; Lotz, L.A.P. Effect of stale seedbed preparations and subsequent weed control in lettuce (cv. Iceboll) on weed densities. *Weed Res.* **2007**, *47*, 149–156. [CrossRef]
25. Machleb, J.; Peteinatos, G.G.; Kollenda, B.L.; Andújar, D.; Gerhards, R. Sensor-based mechanical weed control: Present state and prospects. *Comput. Electron. Agric.* **2020**, *176*, 105638. [CrossRef]
26. Kunz, C.; Weber, J.F.; Peteinatos, G.G.; Sökefeld, M.; Gerhards, R. Camera steered mechanical weed control in sugar beet, maize and soybean. *Precis. Agric.* **2017**, *19*, 708–720. [CrossRef]
27. Kunz, C.; Weber, J.; Gerhards, R. Benefits of precision farming technologies for mechanical weed control in soybean and sugar beet—Comparison of precision hoeing with conventional mechanical weed control. *Agronomy* **2015**, *5*, 130–142. [CrossRef]
28. Brandsaeter, L.O.; Mangerud, K.; Rasmussen, J. Interactions between pre- and post-emergence weed harrowing in spring cereals. *Weed Res.* **2011**, *52*, 338–347. [CrossRef]
29. Bechar, A.; Vigneault, C. Agricultural robots for field operations: Concepts and components. *Biosyst. Eng.* **2016**, *149*, 94–111. [CrossRef]
30. McCarthy, C.L.; Hancock, N.H.; Raine, S.R. Applied machine vision of plants: A review with implications for field deployment in automated farming operations. *Intell. Serv. Robot.* **2010**, *3*, 209–217. [CrossRef]
31. Elstone, L.; How, K.Y.; Brodie, S.; Ghazali, M.Z.; Heath, W.P.; Grieve, B. High Speed Crop and Weed Identification in Lettuce Fields for Precision Weeding. *Sensors* **2020**, *20*, 455. [CrossRef]
32. Arroyo, J.; Guijarro, M.; Pajares, G. An instance-based learning approach for thresholding in crop images under different outdoor conditions. *Comput. Electron. Agric.* **2016**, *127*, 669–679. [CrossRef]
33. Riehle, D.; Reiser, D.; Griepentrog, H.W. Robust index-based semantic plant/background segmentation for RGB-images. *Comput. Electron. Agric.* **2020**, *169*, 105201. [CrossRef]