147. Comparing a camera-AI-controlled inter- and intrarow weeding system with a camera-guided inter-row hoe

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Abstract

A camera-AI-controlled inter and intrarow weeder (AI-weeder) and a camera-guided inter-row hoe (guided hoe) were compared on two field experiments, during the growing seasons 2022 and 2023. Both systems demonstrated acceptable weed control at the inter-row area (55-85%). The guided hoe consistently outperformed the AI-weeder in the intra-row zone, achieving > 75% control efficacy, resulting comparable to the efficacy of the herbicide reference. The AI-weeder achieved nearly 90% intra-row control with 25% crop damage, on average. The guided hoe ranged between 15 and 90% intra-row weeding efficacy, with maximum 6% crop damage. After two seasons, the guided hoe offers a viable step towards herbicide reduction in sugarbeet farming. The AI-weeder requires further refinement to unlock its full potential.

Keywords: herbicide reduction, machine learning, plant recognition, robotic weeder, sugar production, weed competition

Introduction

Weed control in sugarbeet production confronts many challenges if herbicide use should be reduced. Sugarbeet plants show a very low competitive capability against weeds, particularly during initial growth stages, such as the emergence and formation of the first true leaves. Without proper weed control, sugar yield could be reduced up to 90% (Jursík *et al.*, 2008). Numerous herbicidal active ingredients are persistent in the soil and water soluble, thus posing a contamination high risk to groundwater. In Switzerland an action plan to strongly reduce chemicals in agricultural production is in place since 2017. The visible consequence has been an increase of the cultivated area (ca. 60%) with resistant to ALS-inhibitors' sugarbeet varieties, while 39% is based on other herbicides and only 1% is under organic farming. The extra costs of applying alternative weed control methods (e.g., mechanical) may not be covered from the savings of herbicide reduction. In Switzerland, herbicide reduction is encouraged through direct payments to farmers.
Mechanical weed control in sugarbeet has been marginally utilized. It is mostly effective in the inter-row region, while the intra-row region remains almost uncontrolled. The most favourable weather conditions allowing success in mechanical weeding are sunny and dry days before and shortly after weeding operations. Mechanical weeding performs better in light textured types, such as sandy and sandy-loamy soils. Weeding robots (>40) have been commercially available since 2015 and vary in their degree of automation, crop/weed detection, guidance and cultivating tools (Gerhards *et al.*, 2024). These technologies offer greater efficiency and increased crop quality, mainly by means of accurate crop/weed identification through artificial intelligence (AI) and automated actuator control through robotics (Zhang *et al.*, 2022). Many intra- and interrow cultivators have a pair of knife blades controlled by machine vision guidance systems, opening (i.e., when the crop plants are recognized) and closing (between crop plants) the knives to cultivate the intrarow region for weed control or plant thinning in vegetable production (Lati *et al.*, 2016) An earlier version of the AI-weeder used in this study, the *Robovator* (Poulsen Engineering, Hvalsø, Denmark), showed positive results in only one experiment in broccoli, removing 39% more weeds than a standard cultivator and reducing hand-weeding by 6 times (Lati *et al.*, 2016).

This study had three main objectives, (i) to test and improve alternative weed management methods for sugarbeet production in Swiss conditions, covering the inter- and intra-row regions; (ii) to employ an AI-powered tool for crop recognition and inter/intra-row weeder; and (iii) to compare the weeding efficacy with a camera guided hoeing system. It was hypothesized that the intra-row weeder prevented crop damage while effectively controlling most weeds than the inter-row hoe; weed control in the interrow region was assumed to be similar for both systems.

Materials and methods

Weeding technologies

The first technology tested (i.e., guided hoe) was the ECONET hoeing system (CARRÉ Agricultural machine manufacturer, Noyers, France) which includes the PRECICAM guidance system from the same manufacturer. The guidance system is fully-autonomous based on a multispectral camera for crop row recognition and coupled between the tractor and the hoe. It works on a 6-row width, 50 cm distance between rows, with 7 hoeing elements mounted on flexible tines with a rigid assembly for depth adjustment. Finger weeders (⌀ 360 mm) are mounted behind the hoe unit, with an S support. Total weight of the guided hoe is 1160 kg and the cost for a 2018 system in Switzerland was €52 533. The other technology evaluated was an AI-based crop recognition system with intra-row weeding actuators and implements (i.e., AI-weeder). The system includes fixed interrow hoes and mobile knives. It is commercialized as the Robovator, version 2024. The AI-weeder requires 400 rpm power take-off (PTO) and 7–8 KW, weights 800 kg for a 6-row machine (50 cm between rows) and uses hydraulic operated tools. The AI software version used was 2022, which works at a maximum of 1.8 km/h driving speed. There are 6 models available to analyse continuous (long) images acquired and saved on the go (Figure 1a). The model showing a red rounded shape indicates success in recognizing a beet plant. An Android-based GUI is available for parameter adjustment, through self-generated Wi-Fi and smartphone App. The system offers two modes for opening and closing the knives in the proximity of a recognized plant, before and after, and automatic (Figure 1b). The big green circles represent well developed and recognized beets, while a smaller green circle could be a younger beet that might not be recognized. In this case, if the before & after mode is on, the knives could be kept open to avoid damage, while the automatic mode could destroy unrecognized crops, as well as weeds (red circles). The commercial cost of this system and set-up for the 2022 AI-version was €76 000.

Experimental site and field trials

Three weed control trials were implemented in sugarbeet during the growing seasons 2022 (experiment 1) and 2023 (experiments 2 and 3) at the experimental farm AGROSCOPE Changins, near Nyon, Switzerland. The site is of clay soil type for experiment one and loamy for the others. Soil preparation consisted of ploughing during autumn and false seedbed in early spring. The preceding crop was autumn wheat followed by green manure. The beets were sown on 4 April 2022, 10 April 2023 and 27 July 2023, for experiments 1, 2 and 3, respectively. The sugarbeet varieties used were Agueda KWS in 2022 and Escadia KWS in 2023, sown in early April (experiments 1 and 2) and early June (experiment 3). The seeding density was 110 000 seeds/ha for the herbicide treatment and 90 000, 120 000 and 200 000 seeds/ha for the treatments with mechanical weeding, which resulted in a distance between plants of 10 to 22.2 cm. In experiments 1 and 2, irrigation campaigns were applied from June through August with a total of 220 and 160 mm, respectively. The weeding systems guided hoe and AI-weeder were evaluated, including an additional herbicide reference. Experiment 1 tested two treatments arranged in a completely randomized design with 2 repetitions; the guided hoe was particularly evaluated. Experiment 2 tested five treatments arranged in a randomized complete block design with 3 repetitions; both technologies guided hoe and AI-weeder were evaluated. Experiment 2 tested the AI-weeder using the automatic open/close of knives settings. Experiment 3 was designed to test two AI-weeder ‘ settings (subplot) applied on two crop densities (main plot) arranged in a split-plot with 3 repetitions. The AI-weeder’ settings before & after were applied only for the first weeding operation. The second pass with the AI-weeder was done with the automatic mode, which resulted in 6 repetitions. Further details are given in Table 1.

Data collection and analysis
Weed density before and after weeding was counted in three georeferenced 50 cm×50 cm frames (0.25 m^2), randomly distributed across each treated plot. Weed densities were counted inside the crop row (R) and on the inter-row (IR) regions. Weed density reduction (i.e., difference between weed density before and after weeding) was used to evaluate weeding efficacy (%). Crop density before and after weeding was assessed by 3 random samples, 10m along the row each (total 30 m). Crop density reduction (i.e., difference between crop density before and after weeding) allowed for evaluating crop damage (%). Beet yield and white sugar percent were estimated per plot and extrapolated to t/ha. Analysis of variance (ANOVA) and comparisons of means via Tukey HSD tests were applied to weed density reduction and crop damage data, when statistically significant at an error level of 0.05.

Results and discussion

Average weed control efficacy and crop damage effects per experiment and passes are presented in Table 1. Further details are shown in Figures 2, 3 and 4. Weed control in the inter-row region was similar (between 75 and 90%) for both systems, the guided hoe and the AI-weeder (Figure 2a). Both mechanical weeders showed a higher weed control than the herbicide reference. After a second pass, the guided hoe performed significantly better than the AI-weeder in the interrow region. In the intrarow region, weed control was higher with the AI-weeder, particularly after the second pass. However, weed pressure was relatively low, particularly in Experiment 2. There was no difference on weed control levels between the different modes of action automatic or before & after in the AI-weeder (Figure 3), although a slight indication was observed that the automatic mode controlled better weeds when crop plants were well developed and cases with high crop density (i.e., 200 000 plants/ha). Kunz *et al.* (2018) obtained ~78% weed control efficacy in the intrarow zone with a

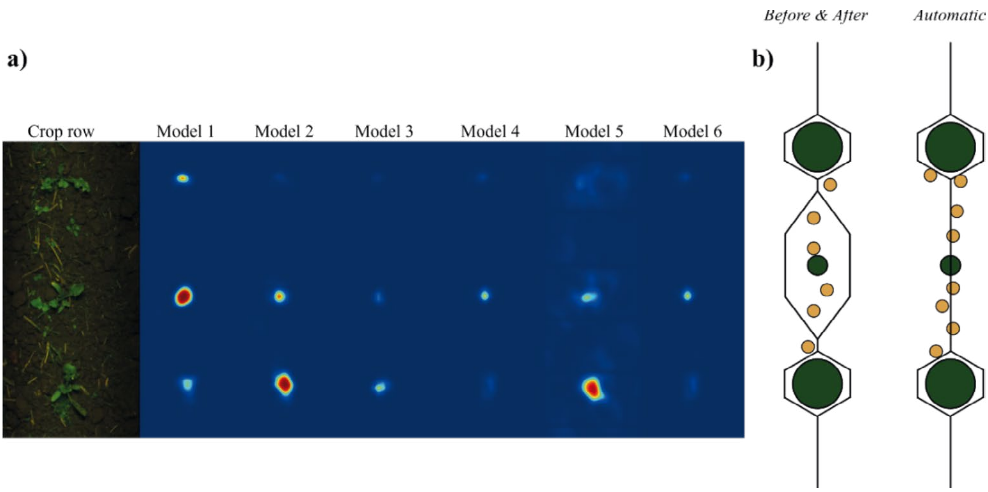

Figure 1. Images and AI-models to discriminate sugarbeets available in the AI-weeder (a), and weeding knives settings available (b).

Table 1. Specifications of the weed control experiments in sugarbeet

Experiment (year)	Treatment	Plot size (m×m)	Passes	CD (%)	WC (%)	BY (t/ha)
1 (2022)	herbicide*	6×60	3	2	23	87.1
	guided hoe	6×60	2	8	64	88.5
2 (2023)	herbicide*	6×35	3	4	38	66.5
	guided hoe	6×35	3	7	45	59.5
	AI-weeder$_{90}$	6×35	3	25	62	51.4
	AI-weeder$_{120}$	6×35	3	27	58	58.3
	AI-weeder$_{200}$	6×35	3	50	53	51.0
3 (2023)	B&A$_{120}$	3×60	2	18	62	21.8
	B&A$_{200}$	3×60	2	3	64	21.0
	auto$_{120}$	3×60	2	28	77	24.8
	auto$_{200}$	3×60	2	19	80	24.0

CD, crop damage; WC, weed control; BY, beet yield, all averaged by treated plot. Crop densities (plants/ha) used: 90=90 000; 120=120 000 and 200=200 000. AI-weeder's settings for opening and closing of knives: B&A, before and after; auto, automatic. Herbicides used: Sugaro Gold, Sugaro Duo, Fusilade Max & Lontrel 100, all at the recommended doses.

camera steered hoe and about 65%, using manual steering in sugarbeet, maize and soybean. They found in both cases an average of 79% weed control efficacy in the inter-row region. Gerhards *et al*. (2023) demonstrated a weed control efficacy of 87% averaged from results of 7 robotic weeding systems, although some combined herbicide application on the crop row. Therefore, those studies and the present ones confirm that weed control using intelligent machines is achievable. In this study, it has been found that band herbicide application might be avoided in most cases, without affecting beet and sugar yield (see below).

Crop density was reduced between 23 and 50% with the AI-weeder (Figures 2b and 4) even if a sowing density of 200 000 plants/ha was initially used. Crop damage was much lower with the guided hoe (between 1 and 12%), being comparable and not statistically different than the damage caused by herbicides (1-3%). An earlier version of the AI-weeder did not damage broccoli and lettuce densities, except on one experiment where the damage reached 12% (Lati et al. 2016). Findings in the current version tested suggest no improvement, contrary to the claims of the AI-weeder developer (<3%). Gerhards *et al.* (2023) reported a maximum 3% crop damage, except for two robotic weeders, which reduced crop density by 21% and nearly 40%, respectively to the other 5 tested robots.

Beet and sugar yields for guided hoe treatments in experiments 1 and 2 were correspondingly similar to those of the herbicide references (>90 t/ha; Tables 1 and 2), and much higher than the AI-weeder's (<70 t/ha). However, weather conditions were particularly dry during both summer seasons (2022 and 2023), and in general beet yield was lower for all treatments. Sugar yield was statistically higher for the guided hoe, even compared with the herbicide reference (Table 2). The best result achieved with the robotic weeder was obtained for treatment AI-weeder$_{120}$ with before and after knives' settings, with 8.5 t/ha sugar yield. As expected, beet- and sugar yields were lower in experiment 3, due to its late sowing date and the experiment's intention, *i.e.*, calibrating the AI-weeder optimal operation settings. The current settings seem inadequate for preventing crop damage or improving weed control and yield due to problems of the system to identify crop plants at very early growth stages accurately. This latter problem caused some large row distances to be wrongly cut by the knives, although the actuators have the capability to react fast enough. Furthermore,

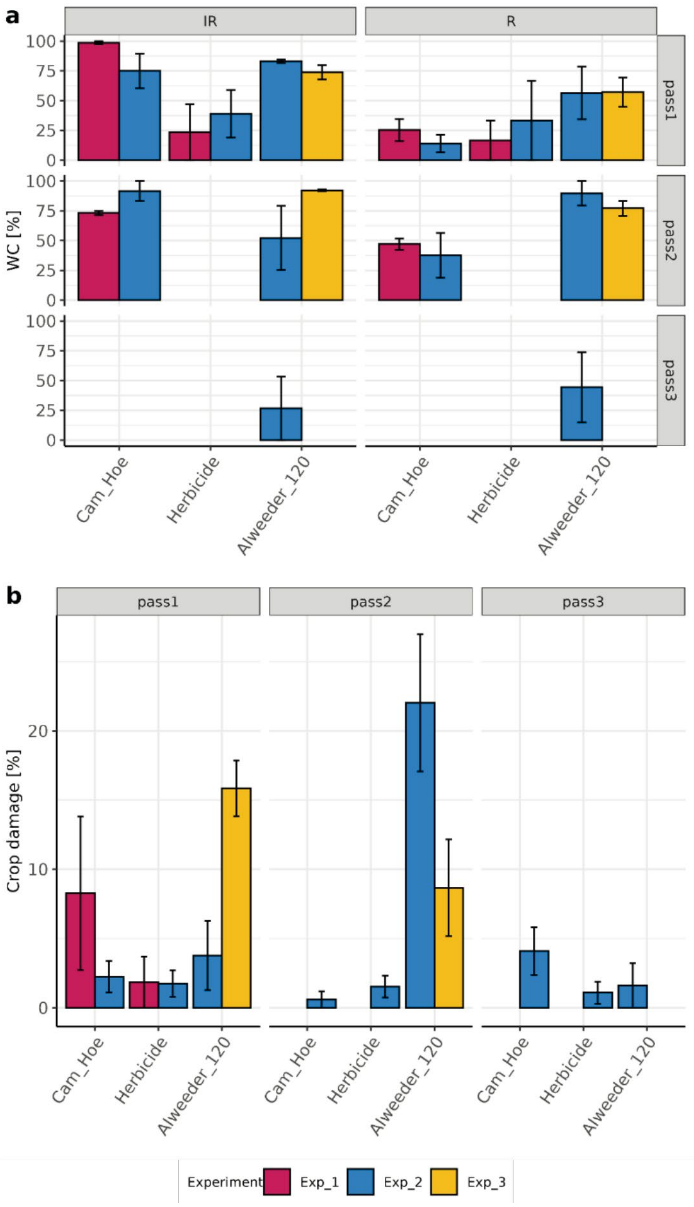

Figure 2. Weed control (WC%, a) and crop damage (CD%, b) in the field trials 1, 2 and 3. Standard errors are depicted and if not overlapping, statistical differences were found.

due to the irregularities of the field (such as the presence of stones) the whole implement failed to maintain the correct camera hight or detect the forward movement of the distance-sensing wheel. Such failures could be easily corrected, for example by means of implementing distance sensors (e.g., ultrasonic or laser sensors) and automatic adjustment of the camera height.

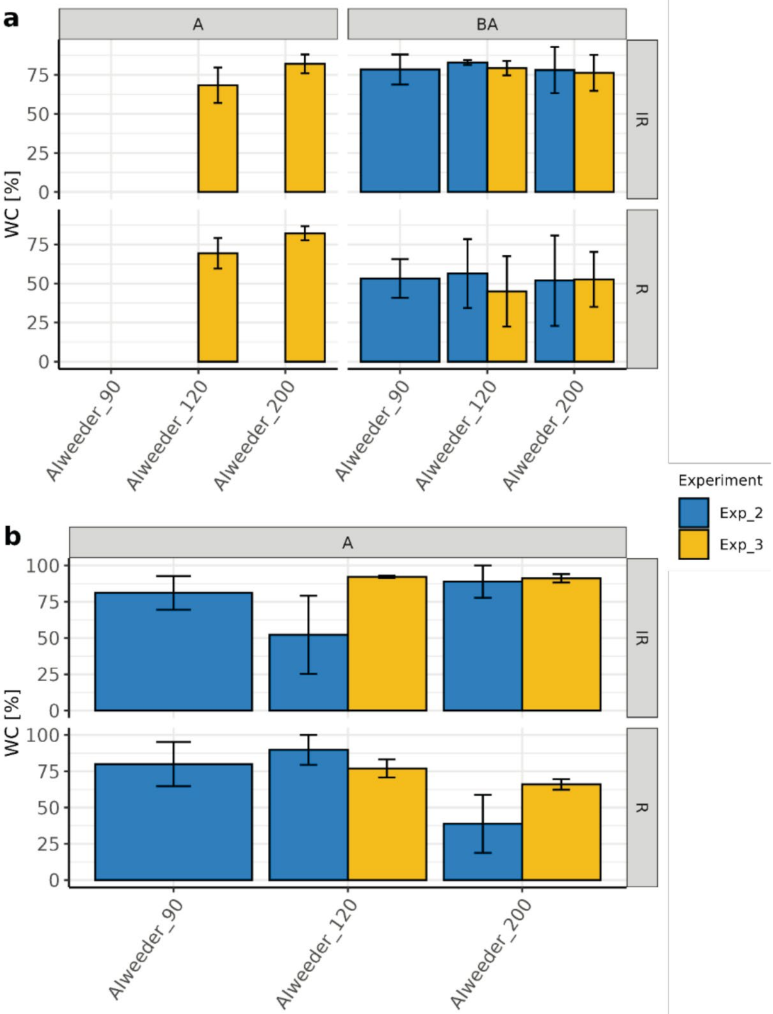

Figure 3. Weed control (WC%) for the first (a) and the second pass (b) in the field trials 2 and 3. Standard errors are depicted and if not overlapping, statistical differences were found.

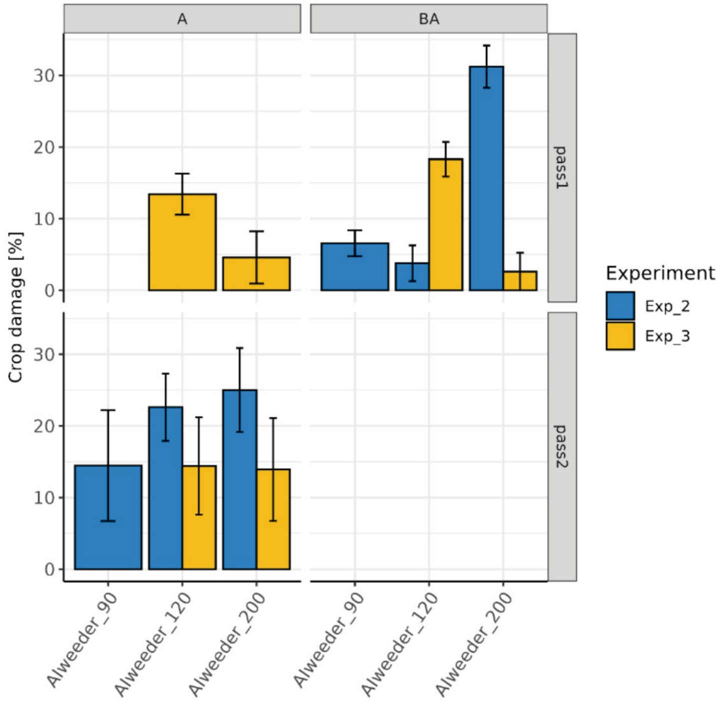

Figure 4. Crop damage (CD%) based on the tool mode used (A, automatic; BA, before and after) in the field trials 2 and 3. Standard errors are depicted and if not overlapping, statistical differences were found.

Table 2. Sugar yield averaged by treated plots. Crop densities (plants/ha) used: $_{90}$ = 90,000; $_{120}$ = 120,000 and $_{200}$ = 200,000. *AI-weeder*'s settings for opening and closing of knives: *before & after* and *automatic*.

Experiment	Treatment	Tool mode	Sugar±SE (t/ha)
1	herbicide		10.5 ± 0.3
1	guided hoe		11.8 ± 0.4
2	herbicide		9.8 ± 0.5
2	guided hoe		8.7 ± 0.2
2	AI-weeder$_{90}$		7.6 ± 1.0
2	AI-weeder$_{120}$		8.5 ± 0.3
2	AI-weeder$_{200}$		6.7 ± 1.0
3	AI-weeder$_{120}$	automatic	3.0 ± 0.2
3	AI-weeder$_{120}$	before and after	2.7 ± 0.4
3	AI-weeder$_{200}$	automatic	3.0 ± 0.1
3	AI-weeder$_{200}$	before and after	2.6 ± 0.3

Conclusions

Considering the technologies tested and conditions applied, using a highly specialized robotic weeder does not improve the intra-row weed control efficacy achieved with a normal hoeing tool that is capable of being guided via crop row recognition. This study suggests that advanced robotic and AI-based weeding systems do not necessarily improve weed control, diminish crop damage or stabilize crop yields in sugarbeet production. Further assessments to examine the economic performance could offer a more accurate evaluation of these types of technologies.

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