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Evaluation of weed control efficacy and yield response of inter-row and intra-row hoeing technologies in maize, sugar beet and soybean

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Maize, soybean and sugar beet are very sensitive to weed competition in early growing stages. Therefore, effective weed control is important between and within crop rows. The focus of this study was to investigate the benefits of intra-row finger weeding, torsion weeding, rotary harrowing and ridging in combination with camera-guided inter-row hoeing. Field experiments were conducted in maize 2015, soybean 2015 and sugar beet 2015 and 2016 at the University of Hohenheim Research Station. Two (maize and soybean) and three passes (sugar beet) of inter-row hoeing alone and combinations of inter-row and intra-row hoeing were compared to an untreated control, a broadcast herbicide control (maize and sugar beet), a standard inter-row hoe and a combination of inter-row hoeing and herbicide band spraying (only sugar beet 2015). Weed density was counted after all treatments separately for the inter-row area and within crop rows. Relative crop losses and crop yield were recorded for all four experiments. Inter-row weed control efficacy was equal to the herbicide control and ranged between 90 and 95%. However, intra-row hoeing reduced weed densities on average by 67% only. In maize, 30 weeds m^{-2} survived in the intra-row area in the best mechanical treatment, in soybean 4 weeds m^{-2} and in sugar beet 13 weeds m^{-2} on average. Only in one out of four experiments, intra-row mechanical weeding controlled more weeds than camera-guided inter-row hoeing alone. This study shows that improvements in intra-row weeding are necessary to avoid yield losses and reduce costs for hand weeding.

Keywords
Mechanical weed control, Precision Farming, Automatic steering systems, Sensor technologies, Integrated weed management

Effective weed control is very important in maize, sugar beet and soybean production. Even low weed infestations of less than five plants m^{-2} of common weed species such as Chenopdium album may cause yield losses of 15-30% in maize, 15-40% in soybean and 77% in sugar beet (Kropff and Spitters 1991; Gummert 2012; Carballido et al. 2013; Keller et al. 2014; hock et al. 2006). Additional costs arise from harvest problems and seed contamination. Weed competition is extremely problematic during the critical period of crop establishment, which is estimated to occur between 20 and 60 days after sowing (DAS) in maize, sugar beet and soybean (Keller et al. 2014; May and Wilson 2006; Van Acker et al. 1995; Knezevic et al. 2002). During this period, crops do not tolerate co-existence of weeds without losing yield.

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Weeds are often controlled by combinations of pre-emergence and post-emergence herbicides until closure of crop canopy. However, due to restrictions in herbicide use and the spread of herbicide resistant weed populations, alternative methods of weed control are becoming more important. Camera-guided hoeing technologies with automatic side-shift control have significantly improved mechanical weed control efficacy (Tillett et al. 2002; Griepentrog et al. 2007, Kunz et al. 2015, 2018). Kunz et al. (2015) tested a Kult-Robocrop® hoe and an OEM Claas stereo camera® in combination with an Einböck Row-Guard® hoe with duck-foot blades between the rows in sugar beet and soybean. This hoe increased weed control efficacy by 12 % compared to machine hoeing with manual guidance. They explained higher weed control efficacy by guiding ducks-foot blades closer along crop rows and stronger burial of weeds with soil due to higher driving speed.

Still, the problem of weed competition in the 10-15 cm wide band within crop rows remains. Bowman (1997) and Van der Weide et al. (2008) observed great variations of weed control efficacy of intra-row harrows, finger weeders and torsion weeders depending on weed species, size and growth stages of weeds and crops. Those tools can uproot small weeds without harming the crop. They concluded however that additional weed control methods such as false seedbed cultivation and pre-emergence harrowing were necessary to increase selectivity of intra-row hoeing. Selectivity describe the ratio of weed control efficacy to crop damage. These methods ensure that weeds are smaller at the time of the first post-emergence hoeing.

Combinations of inter-row hoeing with band spraying were more effective in maize and sugar beet than only mechanical weed control treatments and reduced herbicide input by 50-70 % (Mehrtens et al. 2005; Wiltshire et al. 2003).

Several manufactures provide mechanical hoes with intra-row weeding tools (Kunz et al. 2015). However, the benefits of intra-row mechanical weeding with finger weeder, torsion weeder, rotary harrow has not yet been proved (Pannacci and Tei 2014, Van der Weide et al. 2008). Weeds can be buried by soil movement into the crop rows. With intra-row weeding, soil on some of these weeds might be removed again.

Therefore, the objective of this study was to evaluate inter-row and intra-row weed control efficacies of mechanical weed control strategies in maize, sugar beet and soybean. Inter-row hoes and combinations of inter-row and intra-row elements were tested at low and high speed. It was hypothesized that intra-row hoeing does not provide additional weed control compared to inter-row hoeing alone with weed burial within crop rows due to soil movement. We further hypothesized that higher speed of inter-row and intra-row hoeing increases weed control efficacy and crop damage. The third hypothesis was that camera guided hoeing resulted in equal yields as the broadcast herbicide application in maize and sugar beet.

Material and Methods

Study area and cropping practices

Field studies were conducted in maize 2015, soybean 2015 and sugar beet 2015 and 2016 at the Research Station of the University of Hohenheim. Soil texture was a heavy loamy clay. The long-term mean temperature at the site is 9.5 °C with an average rainfall of 804 mm. Average temperatures during both vegetation periods were 0.8 - 1.0 °C warmer than the long-term mean from 1980 until 2009.

In 2015, 60% less precipitation was received from March until September. In the vegetation period 2016, precipitation was 15% above average.

Maize, cv. Frederico, was sown after two passes with a rotary disc on April 27, 2015 with 94,000 seeds ha^{-1} at a depth of 5 cm. Soybean, cv. Sultana, was sown after ploughing on May 8, 2015 at a density of 64,000 seeds ha^{-1}. Seeds were inoculated with HiStick® (Bradyrhizobium japonicum) directly before sowing. Sowing depth was 4 cm. Sugar beets were sown into the residues of the previous cover crop Sinapis alba on April 10, 2015 and April 11, 2016 with 107,000 seeds ha^{-1} at a depth of 2.5 cm after one pass with a rotary disc.

Experimental setup

Experiments were set up as randomized complete block design with four repetitions. Plot size was 3 m x 10 m. Row distance for all crops was 50 cm. Hoeing was conducted at 3 and 6 km h^{-1} with a 3 m wide Einböck Row-Guard® hoe (Einböck, Dorf an der Pram, Austria) with a hydraulic side-shift control using OEM Claas stereo vision® for crop row detection. For inter-row weeding, ducks-foot blades were used at a depth of 3-4 cm. Each blade was mounted on a separate parallelogram to adjust for variations of soil elavation. The camera was set to guide the ducks-foot blades with a distance of 6 cm along the crop rows. For the intra-row weeding, finger weeders, torsion weeders and rotary harrows were moved along the crop rows at a depth of 1 cm. Ridging blades were steered with a distance of 6 cm aside the crop rows at a depth of 3 cm. They moved soil into the crop rows. Manual steering of the hoe was done with an extra person on the rear to steer the hoe. In sugar beet 2015, band spraying (Agrotop 80E; 1.7-2 bar spray pressure; 80° spraying angle) over the crop rows was combined with inter-row camera-steered hoeing. A band of 15 cm width was sprayed three times with the same herbicides as in the overall herbicide treatment (Table 1, Figure 1). In maize and soybean, two passes of hoeing were conducted at 25 and 45 DAS, when maize had developed 2-6 leaves and soybean 2-4 trifolia. Weeds had developed 2-4 true leaves at times of hoeing. In sugar beet, hoeing was done three times at 19, 31 and 42 DAS, when sugar beet had developed 2, 4 and 6 true leaves. Most of the weeds were in the cotyledon stage at the times of hoeing. Some weeds had developed 2-4 leaves. Only inter-row hoeing was applied at the first date, because sugar beets were not tolerant to intra-row hoeing, when they had developed only 2 leaves.

Each block included an untreated plot. Standard chemical controls were established in maize and sugarbeet. In maize, 1.25 l ha^{-1} MaisTer (30.0 g l^{-1} foramsulfuron + 1.0 g l^{-1} iodosulfuron-methyl-natrium + 30.0 g l^{-1} isoxadifen-ethyl) and 0.3 l ha^{-1} Sabel (225 g l^{-1} bromoxynil) were sprayed 25 DAS at 4-leaf stage of maize followed by a second application of 1.5 l ha^{-1} Callisto® (100 g l^{-1} mesotrione) 45 DAS at 6-leaf stage of maize. In sugar beet, three applications of 1 l ha^{-1} Betanal maxxPro (47 g l^{-1} desmedipham + 60 g l^{-1} phenmedipham + 75 g l^{-1} ethofumesat + 27 g l^{-1} lenacil) and 1 l ha^{-1} Goltix Titan (525 g l^{-1} metamitron + 40 g l^{-1} quinmerac) were performed 14, 30 and 42 DAS. It was not possible to include a herbicide control treatment in soybean because the field was managed according to the guidelines of organic farming.

Table 1 Treatments of intra-row and inter-row mechanical weeding and control plots in field studies with maize, soybean and sugar beet

No.	Crop	Treatment	Speed (km h^{-1})
1	Maize, soybean, sugar beet	Untreated control	-
2	Maize, sugar beet	Herbicide	3.6
3	Maize, soybean, sugar beet	Manually steered hoe	3.0
4	Maize, soybean, sugar beet	Camera-guided hoe	6.0
5	Maize, soybean	Camera-guided hoe	3.0
6	Maize, soybean, sugar beet	Camera-guided hoe + finger weeder	6.0
7	Maize, soybean	Camera-guided hoe + finger weeder	3.0
8	Maize, soybean, sugar beet	Camera-guided hoe + torsion weeder	6.0
9	Maize, soybean	Camera-guided hoe + torsion weeder	3.0
10	Maize, soybean, sugar beet	Camera-guided hoe + rotary harrow	6.0
11	Maize, soybean	Camera-guided hoe + rotary harrow	3.0
12	Maize, soybean, sugar beet	Camera-guided hoe + ridging element	6.0
13	Maize, soybean	Camera-guided hoe + ridging element	3.0
14	Sugar beet (2016 only)	Camera-guided hoe + band spraying	6.0

Figure 1: Intra-row weeding elements; A: Finger weeder in combination with camera-guided inter-row hoeing in sugar beet, B: Torsion weeder in maize, C: Rotary harrow in sugar beet, D: Ridging in sugar beet

Sampling method

Weeds and crops were counted before and four days after each treatment. However, only the data of the last assessment are shown in the results. Weeds were assessed separately between the rows and within the row in a 10 cm wide strip using a frame of 0.5 m^2 (Figure 2). The frame was placed at three randomly selected spots in each plot. Weed density was averaged over the three counts. Crop density was determined using a 1 m scale placed along crop rows. The mean of six counts was recorded for each plot. Relative crop losses were calculated relating crop density in the treated plots to the crop density in the untreated plots before the first post-emergence hoeing.

Figure 2: Counting frame with a size of 0.5 m^2 to measure weed density in the inter-row and intra-row sections

Maize was harvested 134 DAS with a 3-row field chopper (Kemper, Stadtlohn, Germany) in an area of 15 m^2 at a height of 15 cm. Fresh plant biomass was dried for 48 h at 80 °C and weighed. Soybean was harvested with a 1.5 m plot harvester (Zürn 150, Obergurig, Germany) in an area of 15 m^2 157 DAS. Sugar beets were harvested with a plot harvester (Edenhall 623, Vallakra, Sweden) 157 DAS. Beets were washed and sugar content was determined polarimetrically according to Icumsa (1994). White sugar yield (WSY) was calculated according to the German standard procedure (Glattkowski and Märländer 1993).

Data analysis

Date were analyzed using R-Studio version 1.2.5033., applying the linear model (equation 1):

$$y_{ij} = \mu + \alpha_i + \beta_j + e_{ij} \qquad \text{(Eq. 1)}$$

with y_{ij} representing the variable $_i$ in block $_j$, α_i is the treatment effect, β_j the block effect and eij is the error. Prior to ANOVA, observed data were log-transformed, if necessary. Means were compared using the Tukey HSD test at a significance level of $\alpha \leq 5$ %.

Results

Weed infestations

Weed species were common for spring field crops in Southwest Germany. In maize, Veronica persica Poir. was the most frequent species with 50.9 %, followed by Matricaria chamomilla L. with a frequency of 15.7 % and Capsella bursa-pastoris (L.) Med. with 12.7 %. Other relevant weed species were Stellaria media (L.) Vill., Galium aparine L., Chenopodium album L. and Lamium purpureum L.. In soybean, C. album was the most frequent species (33.6 %), followed by S. media (15 %), Sonchus asper L. (9.8 %), M. chamomilla (8.6 %), Thlaspi arvense L. (7.8 %), C. bursa-pastoris (6.2 %), Polygonum aviculare L. (5.6 %), G. aparine (4.1 %) and Polygonum convolvulus L. (2.2 %). In sugar beet, P. convolvulus (35 %), C. album (18 %), S. media (13 %) and T. arvense (11 %) were the predominant weed species during both experimental seasons. Mean weed densities in the untreated control varied from a low infestation rate in sugar beet 2015 of 13 weeds m^{-2} to a high infestation rate in maize 2015 and sugar beet 2016 of 101 - 153 weeds m^{-2}.

Maize experiment

Weed infestation in maize was high. Inter-row weed density in the untreated plot amounted 76 plants m^{-2} and intra-row weed density 116 weeds m^{-2}. Weed competition caused yield losses of almost 70 %. Up to 6 % of maize plant were damage or removed by the treatments (Figure 3). Herbicide application controlled almost all weeds between and within maize rows without causing any plant losses. Inter-row weed control efficacy of all camera-steered hoeing treatments was equal to the herbicide plots. Intra-row weed control efficacy of hoeing was much lower. A minimum of 30 intra-row weeds m^{-2} survived in all hoeing treatments. Lowest weed density after mechanical weeding was observed in the combination of camera-hoeing and finger weeding at 6 km h^{-1}. Camera-guided hoeing was more effective against weeds than manually steered hoeing and weed control efficacy at 6 km h^{-1} was higher than at 3 km h^{-1}. Combinations of inter-row and intra-row hoeing did not provide any benefits compared to camera-guided inter-row hoeing alone. Highest maize dry biomass yield was measured in the herbicide treatment with 49 t ha^{-1}. Yields of the hoeing treatment ranged from 27 - 43 t ha^{-1}. Lowest yield of 13 t ha^{-1} was recorded for the untreated control. Crop losses were low in all treatments except for manual steered hoeing (Figure 3).

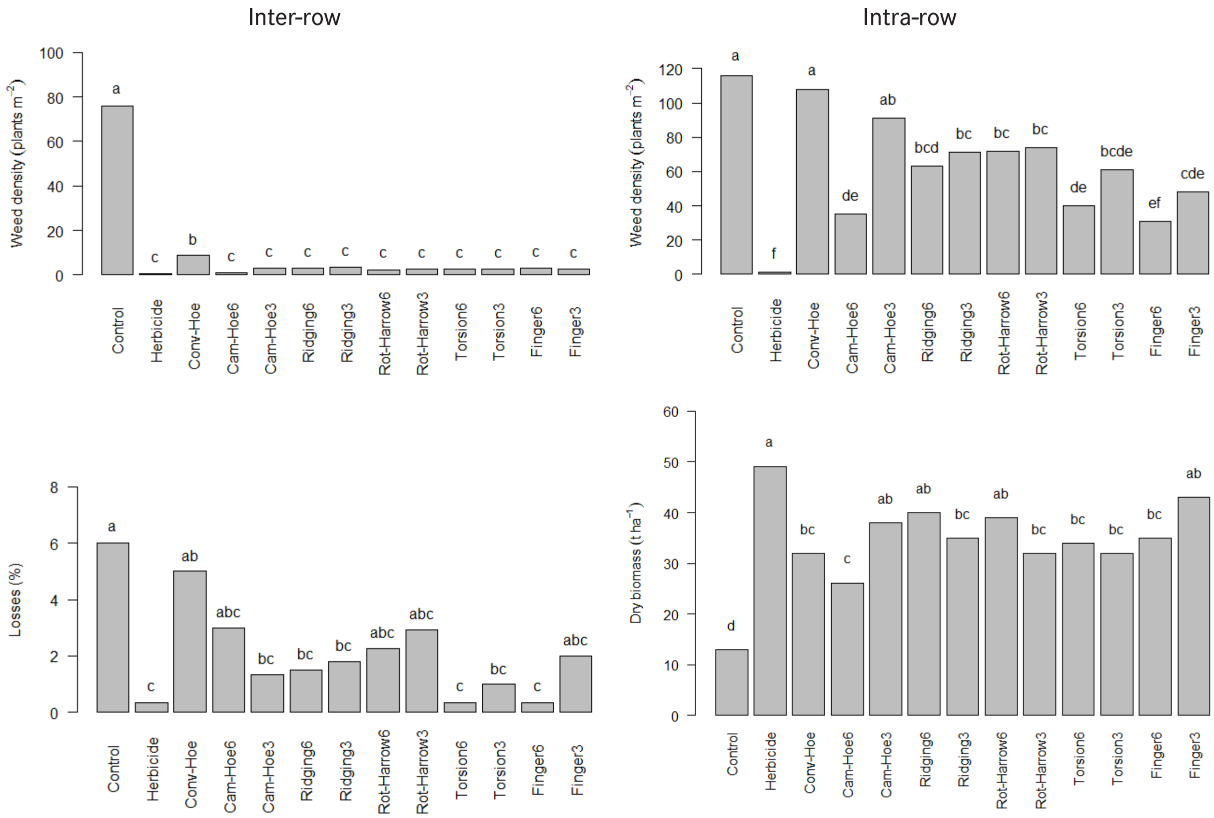

Figure 3: Effect of two passes of weed hoeing on inter-row and intra-row weed control efficacy, plant losses and dry biomass yield in maize 2015; Control = untreated control, Herbicide = chemical weed control, Conv-Hoe = manually steered hoeing at 3 km h^{-1}, Cam-Hoe6 = camera-guided hoeing at 6 km h^{-1}, Cam-Hoe3 = camera-guided hoeing at 3 km h^{-1}, Ridging6 = camera-guided hoeing + ridging element at 6 km h^{-1}, Ridging3 = camera-guided hoeing + ridging element at 3 km h^{-1}, Rot-Harrow6 = camera-guided hoeing + rotary harrow at 6 km h^{-1}, Rot-Harrow = camera-guided hoeing + rotary harrow at 3 km h^{-1}, Torsion6 = camera-guided hoeing + torsion weeder at 6 km h^{-1}, Torsion3= camera-guided hoeing + torsion weeder at 3 km h^{-1}, Finger6 = camera-guided hoeing + finger weeder at 6 km h^{-1}, Finger3 = camera-guided hoeing + finger weeder at 3 km h^{-1}. Means with identical letters within a graph do not differ significantly based on the Tukey HSD test ($p \leq 0.05$)

Soybean experiment

In soybean, weed density in the untreated control was high causing approximately 50 % yield loss compared to all mechanical treatments (Figure 4). Inter-row weeding was very effective reducing weed density from 54 plants m^{-2} in the untreated control to 1-4 plants m^{-2}. Intra-row weed densities after hoeing were slightly higher than inter-row weed densities. Average intra-row weed densities ranged from 2-7 plants m^{-2} in the treated plots. Inter-row hoeing alone was as effective as combinations of inter-row hoeing with intra-row weeding elements. Ridging and torsion weeding at 3 km h^{-1} caused slightly higher plant losses than all other treatments tested (Figure 4). Except for finger weeding, all mechanical operations at 6 km h^{-1} significantly reduced yields compared to hoeing at 3 km h^{-1}.

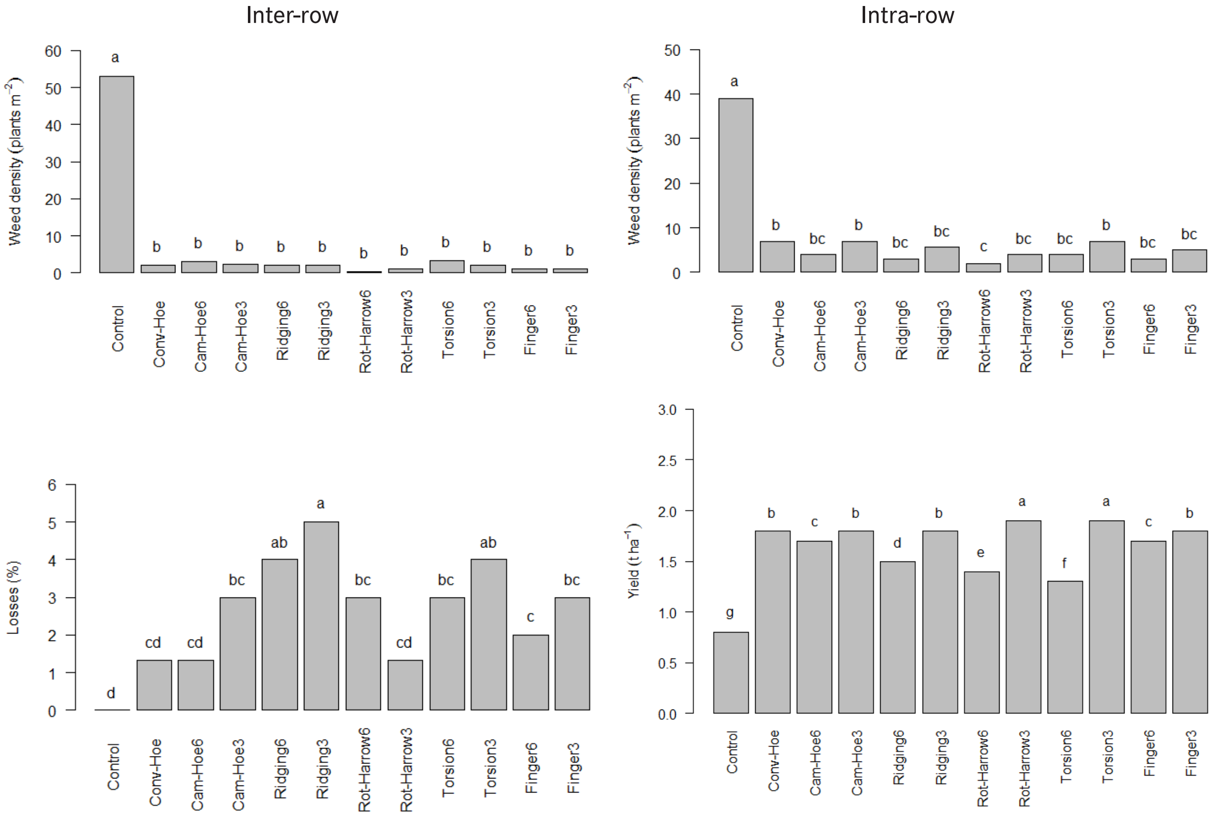

Figure 4: Effect of two passes of weed hoeing on inter-row and intra-row weed control efficacy, plant losses and yield in soybean 2015; C = untreated control, Conv-Hoe = manually steered hoeing at 3 km h^{-1}, Cam-Hoe6 = camera-guided hoeing at 6 km h^{-1}, Cam-Hoe3 = camera-guided hoeing at 3 km h^{-1}, Ridging6 = camera-guided hoeing + ridging element at 6 km h^{-1}, Ridging3 = camera-guided hoeing + ridging element at 3 km h^{-1}, Rot-Harrow6 = camera-guided hoeing + rotary harrow at 6 km h^{-1}, Rot-Harrow = camera-guided hoeing + rotary harrow at 3 km h^{-1}, Torsion6 = camera-guided hoeing + torsion weeder at 6 km h^{-1}, Torsion3= camera-guided hoeing + torsion weeder at 3 km h^{-1}, Finger6 = camera-guided hoeing + finger weeder at 6 km h^{-1}, Finger3 = camera-guided hoeing + finger weeder at 3 km h^{-1}. Means with identical letters within a graph do not differ significantly based on the Tukey HSD test ($p \leq 0.05$)

Sugar beet experiments

In sugar beet, weed infestations were low in 2015 and high in 2016. The overall herbicide treatment resulted in highest weed control efficacies in both years. In 2015, the combinations of camera-guided inter-row hoeing with the finger weeder, torsion weeder, rotary harrow and ridging element in the row did not increase weed control efficacy compared to camera-guided hoeing alone. Plant losses were relatively low for all treatments with a maximum of 4 % for the combination of camera-guided hoeing and rotary harrow. White sugar yields were equal for all treatments and approximately 55 % higher than in the untreated control plots indicating that even low weed infestations of 16 plants m^{-2} caused high yield losses (Figure 5).

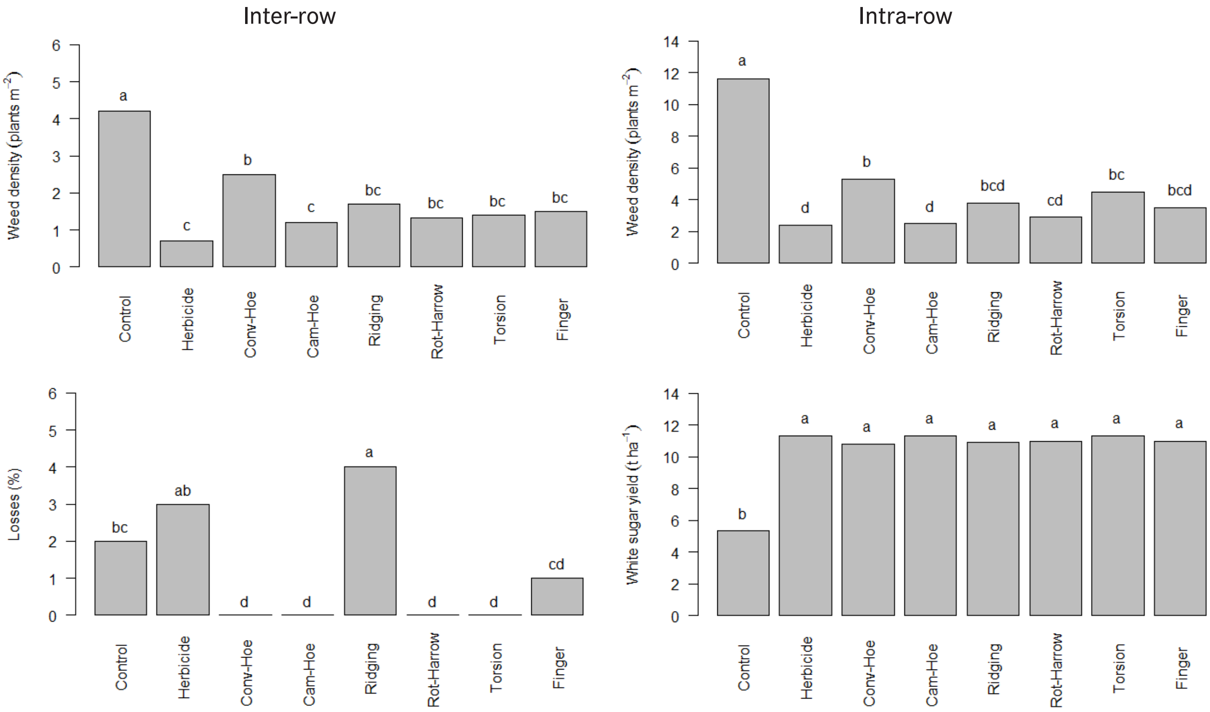

Figure 5: Effect of three passes of weed hoeing on inter-row and intra-row weed control efficacy, plant losses and white sugar yield in 2015; Control = untreated control, Herbicide = overall herbicide spraying, Conv-Hoe = manually steered hoeing 3 km h^{-1}, Cam-Hoe = camera-guided hoeing 6 km h^{-1}, Finger = camera-guided hoeing 6 km h^{-1} + finger weeder, Torsion = camera-guided hoeing 6 km h^{-1} + torsion weeder, Rot-Harrow = camera-guided hoeing 6 km h^{-1} + rotary hoe, Ridging = camera-guided hoeing 6 km h^{-1} + ridging element. Camera guided hoeing + intra-row band spraying was not included in 2015. Means with identical letters within a graph do not differ significantly based on the Tukey HSD test ($p \leq 0.05$)

In 2016, all mechanical treatments resulted in approximately 80 % inter-row weed control efficacy. The combination of intra-row band spraying and inter-row hoeing achieved better weed control than most mechanical treatments. However, it was less effective than the overall herbicide treatment. Ridging resulted in highest intra-row weed control efficacy of all mechanical treatment. However, after three passes of hoeing, 22-140 weeds m^{-2} remained in the intra-row area.

Plant losses were again relatively low except for the combinations of camera-steered inter-row hoeing and intra-row torsion weeder, rotary harrow and ridging causing 4-5 % plant losses. White sugar yields were significantly higher in all treatments compared to the untreated control. Significantly highest white sugar beet yields were recorded in the hoeing-band spraying treatment with 12.1 t ha^{-1}, followed by the hoeing-rotary harrow treatment with 11.9 t ha^{-1}, the broadcast herbicide treatment with 11.6 t ha^{-1} and the hoeing-ridging plots with 11.5 t ha^{-1} (Figure 6).

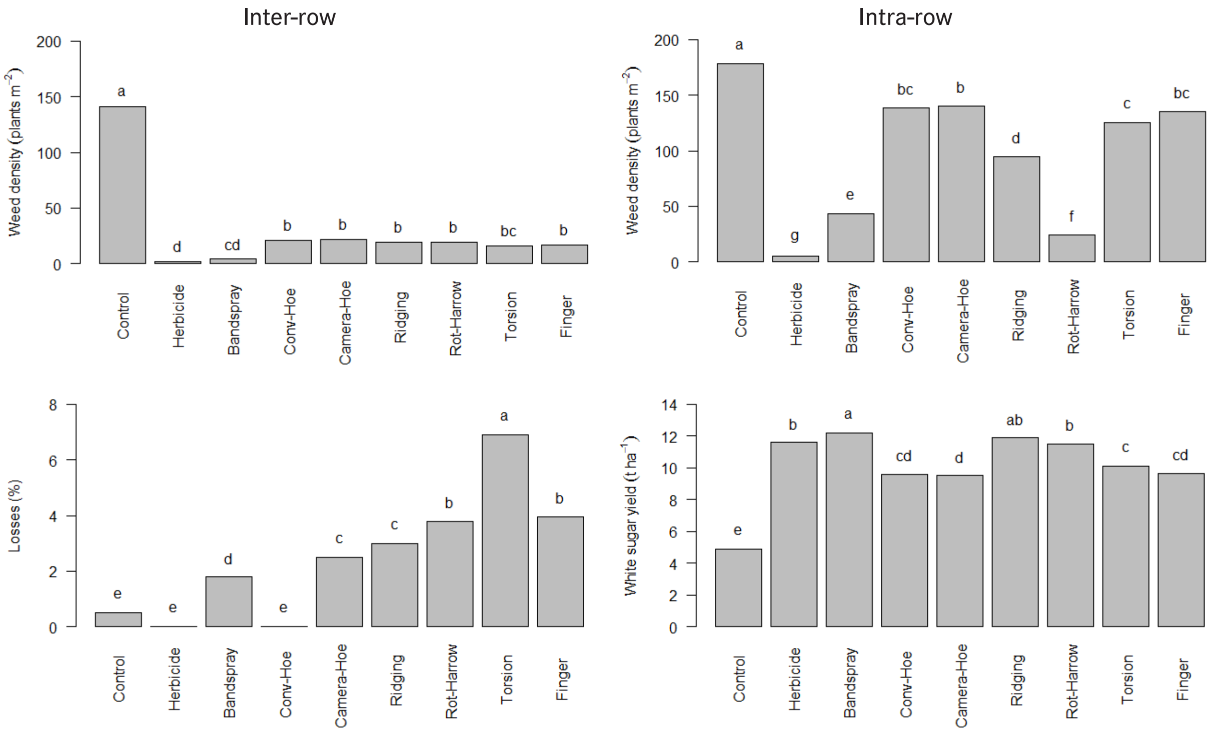

Figure 6: Effect of three passes of weed hoeing on inter-row and intra-row weed control efficacy, plant losses and white sugar beet yield in 2016; Control = untreated control, Herbicide = overall herbicide spraying, Conv-Hoe = manually steered hoeing 3 km h^{-1}, Cam-Hoe = camera-guided hoeing 6 km h^{-1}, Bandspray = camera-guided hoeing 6 km h^{-1} + band spraying, Finger = camera-guided hoeing 6 km h^{-1} + finger weeder, Torsion = camera-guided hoeing 6 km h^{-1} + torsion weeder, Rot-Harrow = camera-guided hoeing 6 km h^{-1} + rotary harrow, Ridging = camera-guided hoeing 6 km h^{-1} + ridging element. Means with identical letters within a graph do not differ significantly based on the Tukey HSD-test ($p \leq 0.05$)

In conclusion, intra-row weeding elements did not increase weed control efficacy compared to camera-guided weed hoeing alone (hypothesis 1). Speed had no clear impact on weed control and plant losses (hypothesis 2). Camera-guided hoeing achieved equal sugar yields as the broadcast herbicide application (hypothesis 3).

Discussion

Intra-row weeding is seen as one of the greatest challenges for organic crop production (Kurstjens and Kropff 2001; Cirujeda et al. 2003; Ascard 2007). The key question and first hypothesis of the present study was if intra-row mechanical weeding increases intra-row weed control efficacy. Only in one out of four experiments, intra-row mechanical weeding controlled more weeds than camera-guided inter-row hoeing alone. In sugar beet 2016, combinations of camera-guided inter-row hoeing with intra-row torsion weeder, ridging and rotary harrowing controlled significantly more weeds than inter-row hoeing alone or the combination of inter-row hoeing with finger weeding. In the other three experiments, combinations of inter-row hoeing with intra-row weeding elements were equal to camera-guided hoeing between crop rows alone. Intra-row weeding elements, except for ridging might uproot some small weed seedlings within the crop rows but they might also remove soil from other weeds that have been buried immediately before by inter-row weeding. Therefore, the overall benefit might be low. It might be more suitable to place intra-row weeding tools before the inter-row goosefoot blades. Mechanical intra-row weed control effect was never higher than 90 % and in average only

67 %. Similar results were reported by Pannacci and Tei (2014) in maize and sunflower. They measured a maximum intra-row weed biomass reduction in maize after finger weeding of 68 %.

Ridging resulted in 95 % intra-row weed control, indicating that soil burial plays a major role in mechanical weed control (Kunz et al., 2018). With inter-row hoeing, soil is moved into the intra-row area and small weeds are buried. Burial of intra-row weeds is greater with camera-steered hoeing compared to manual steered hoeing, because inter-row blades can be guided closer to the crop rows and they can be applied at higher speed of up to 7-14 km h^{-1} (Wiltshire et al. 2003; Kunz et al. 2018). Intra-row weed control in maize and soybean was higher at 6 km h^{-1} than at 3 km h^{-1} driving speed. Also plant losses were lower at 6 km h^{-1} than at 3 km h^{-1} driving speed. Therefore, overall weed control efficacy using camera-guided hoeing technologies was 12 % higher in soybean and sugar beet compared to manual steered hoeing (Kunz et al. 2015). Kunz et al. (2015) reported that manual-guided maschine hoeing at 7-14 km h^{-1} was not feasible without significant crop damage. We noticed in maize that camera-guided side shift control of the hoe worked better at higher speed.

Intra-row weeding elements and ridging may cause crop damage (Van der Weide et al. 2008). Intensity of all intra-row weeding elements needs to be adjusted to achieve best selectivity. Proper adjustment is extremely important when a torsion weeder is used (Braun 2011). It can cause severe crop damage if tine resistance is too aggressive. However, on compacted soils, torsion weeders provide only poor intra-row weed control efficacy (Cirurjeda et al. 2013). In our study, crop losses were relatively low with a maximum of 5 % and similar to Kunz et al. (2015), probably because all intra-row weeding tools were applied in combination with camera-guidance. Growers can easily compensate for crop losses with slightly higher seed rates.

In the present study, it was not possible to show a preference for a specific intra-row weeding element. In other studies, none of the tested intra-row weed elements could be identified to result in higher weed control efficacies and selectivity than others as well (Pannacci and Tei 2014; Melander et al 2005). In the present maize experiment, finger weeding at high speed was slightly more effective than the other intra-row weeders. Finger weeding was also more effective in weed control in onions and other sown vegetables than other intra-row tools tested (Melander et al. 2015; Van der Weide et al. 2008). In soybean, finger weeding and rotary harrowing at high speed controlled more weeds and in sugar beet, ridging resulted in highest weed control efficacy.

It was not possible in this study to prove that higher speed of hoeing increased weed control efficacy and crop damage. For weed control efficacy, a tendency towards higher weed control at high speed was observed. However, speed had no clear effect on plant losses. The third hypothesis that camera guided hoeing resulted in equal yields as the herbicide treatments was proofed for sugar beet.

Van der Weide et al. (2008) showed a significant reduction of labor hours for hand weeding of remaining intra-row weeds in vegetables after inter-row hoeing combined with finger weeding, torsion weeding, harrowing and pneumatic weeding (weed blowing). However, 8-9 hours ha^{-1} of hand weeding were still necessary in transplanted vegetable crops and 38-99 hours ha^{-1} in sown vegetables to remove surviving weeds in crop rows. This demonstrates the need for more efficient strategies for intra-row weed management. Three strategies are currently discussed. The first strategy includes pre-emergence harrowing or false seedbed cultivation controlling the first flash of germinated weeds and weed seedlings. Therefore, crops potentially emerge several days earlier than the second flush of weed seeds and at the time of post-emergent hoeing, crops are bigger than weeds. Thus, selectivity of hoeing is higher (Rasmussen 1990, Kunz et al. 2015). Besides a temporal advance for crop seedlings, pre-emergence harrowing and false seedbed cultivations reduce weed densities.

The second strategy is a combination of inter-row hoeing and herbicide band spraying. This was practiced in the present study in sugar beet 2015 and reduced the area sprayed (Kunz et al. 2018). It provided less intra-row weed control than the overall herbicide spraying but higher weed control efficacy than most of the mechanical intra-row weeders. White sugar yield was equal to the herbicide treatment. Pannacci and Tei (2014) observed equal weed control with a combination of inter-row hoeing and band-spraying. Wiltshire et al. (2003) found that weed control was even better with band spraying compared to overall spraying.

The third strategy is a combination of camera-guided inter-row hoeing with sensor-based selective intra-row weed control (robotics) (Rasmussen et al. 2012). Ruckelshausen et al. (2006) developed and applied a weeding robot for maize. A sensor system identified maize plants based on plant height and shape parameters. If a maize plant was detected, the intra-row hoeing blade was moved out of the crop row. Gobor et al. (2013) designed a rotary hoe, which was positioned over the crop row. However, this system has not been combined with a sensor to differentiate between weeds and crop. Several studies were conducted to record the position of crop seeds during seeding using RTK-GNSS. Pre- and post-emergent hoeing was later directed around the crop plants (Nørremark et al. 2012; Sun et al. 2010; Perez-Ruiz et al. 2012, 2014) using a RTK-GNSS-controlled guidance system. Two commercial sensor-based intra-row hoeing robots have been introduced by Garford (2019) (Garford Robocrop In-Row Weeder), Stekete (2019) and Poulsen (2019) for transplanted vegetables. The systems work precisely if weeds are relatively small compared to the crop. They controlled approximately 70 % of the intra-row weeds. However, working speed is low with a maximum of 1.8 km h^{-1} (Tillett et al. 2002, 2008). Latest improvements in machine learning using neural networks can improve those robots. Neural networks have been be applied to differentiate between weed species and crop in real-time and with an accuracy of more than 90 % (Lee et al. 2015; Kamilaris and Prenafeta-Boldu 2018; Dyrmann et al. 2016; Redmon and Farhadi 2017).

Conclusions

Those autonomous systems have a great potential for increasing weed control efficacy and selectivity of intra-row weeding operations. However, computer vision technologies need to be integrated in intra-row hoeing and their efficiency and robustness in practical farming need to be investigated.

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