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Potentials of post-emergent mechanical weed control in sugar beet to reduce herbicide inputs

Christoph Kunz, Carolin Schröllkamp, Heinz-Josef Koch, Clemens Eßer, Peter Schulze Lammers, Roland Gerhards

Weed control in sugar beet (*Beta vulgaris*) is usually performed with herbicides applied across the whole field at several timings in the early growth stage of sugar beet. It was tested if herbicide input could be reduced with a combination of preventive, mechanical and chemical weed control strategies. In field experiments conducted at 6 locations mechanical weeding in the inter-row area was combined with band application of herbicides in the intra-row area. At one location, precision farming technologies including camera steering and GNSS-RTK steering were used. Weed densities of up to 91 plants m^{-2} were detected in the untreated control plots. Band spraying in combination with inter-row hoeing reduced herbicide input by 50 to 75% compared to uniform herbicide applications. Weed control efficacy was 72% in the conventional herbicide treatments, 87% for the combination of weed hoeing and band spraying, 78% for precision hoeing with camera steering and 84% for precision hoeing with GNSS-RTK steering system. Weed control treatments increased white sugar yield (WSY) by 30% compared to the untreated control. The combination of mechanical weed control, band application of herbicides and precision hoeing have shown promising concepts for integrated weed management resulting in significantly reduced herbicide input and high weed control efficacy.

Keywords
Mechanical weed control, camera guidance, RTK-GNSS, band spraying, sugar beet (*Beta vulgaris*)

Weed competition in sugar beet production is very strong due to low crop density and slow early leaf growth (Petersen 2008). Therefore, effective weed control methods are needed to avoid significant yield losses. In Europe, weed control in sugar beet is mostly performed with repeated applications of herbicides in early growth stages of sugar beet (Petersen 2008, Wellmann 1999). Due to the high environmental risks and negative side-effects of herbicides, there is a need for alternative weed control strategies with reduced herbicide inputs (Gummert 2012). Gummert (2012) elaborated integrated weed management strategies for sugar beet production. Better formulations of herbicides and improved recommendations for weed control in sugar beet regarding timing of applications have created a potential for herbicide savings (Gummert 2012). Integrated weed management strategies also include preventive and mechanical methods of weed control (Diercks 1990). Bezuidenhout (2012) and Brust (2014) have found that cover crops strongly suppressed weeds and volunteer crops. Another option for reducing herbicide input in sugar beet production is the band application of herbicides in the

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intra-row area in combination with hoeing between the rows resulting in 68% herbicide savings (Kouwenhoven 1991).

Hoeing with blades working in the upper soil surface, between the crop rows, is a common practice often resulting in high weed control efficacy (Jones 1996). However, hoeing may also induce new emergence of weed species and requires dry soil conditions and small weed plants (Fogelberg 1998). A major disadvantage of hoeing is the relative low driving speed and working width of implements both causing low labor efficiency. A second constraint of weed hoeing is the limited efficacy of weed control in the intra-row area (Bowman 1997). New technologies have been developed to automatically steer hoes close to crop rows using imaging and GNSS technologies. These technologies have been applied in maize, sugar beet, soybean and several vegetable crops (Melander 2001, Tillett 2002, Søgaard 2003). Digital image analysis has been applied to discriminate weeds from crop based on shape features (Gerhards 2003). This technology can be used to identify and control weed species selectively in the intra-row area (Fischer 2012).

The objectives of this study were to analyze: (i) if combinations of band spraying with mechanical hoeing reduce herbicide input in sugar beet; (ii) if they result in equal weed control efficacy as conventional herbicide applications across the entire field; (iii) if mechanical weed hoeing can be combined with cover cropping and mulch tillage practices; if (iv) weed control efficacy and labor efficiency can be increased when RTK-GNSS or cameras are used to guide mechanical hoes close to the crop row. We (v) further studied, if alternative weed control methods can increase sugar beet yields compared to standard chemical weed control strategies.

2 Material and Methods

2.1 Experimental sites and design

Nine Sugar beet experiments at six sites were carried out at Gützingen (GÜ) [49.62° N, 9.88° E., 290 m altitude], Unterickelsheim (UI) [49.6 °N 10.16° E, 298 m altitude], Ihinger Hof (IHO) [48.74° N, 8.92° E, 478 m altitude], Kupferzell (KU) [49.22° N, 9.6° E, 340 m altitude], Grouven (GR) [50.93°N, 6.6° E, 77 m altitude] and Widdendorf (WD) [50.92°N, 6.61° E, 69 m altitude] in 2014. At IHO and UI the soil was a deep loam on subsoil clay. At GÜ, KU, GR, and WD, the soils were characterized as silty loam. The average annual rainfall varied between 713 mm at GR/WD and 790 mm at IHO and temperatures ranged from 9.2 °C at IHO to 10.3 °C at GR/WD. All experiments were designed as a randomized complete block design with four replicates, except for UI. At UI, only two replicates were performed. The plot size varied from 20 to 30 m^{-2} at GÜ, IHO, KU and from 200 to 300 m^{-2} at UI, GR, WD, depending on the machinery used for sowing. Row distances was 0.45 or 0.5 m.

2.2 Experimental setup

Sugar beet 'Lisanna' (GÜ), 'Artus' (UI), 'Hannibal' (IHO), 'Sandra' (KU), BTS 440 (GR) and 'Hella' (WD) were sown in the end of March, 2014. Winter cereals were grown in the previous year. After harvest of winter cereals, white mustard (*Sinapis alba* L.) was grown as a cover crop at all experimental sites. At GÜ and IHO, half of the field was ploughed 20 cm deep in fall and cultivated twice before sowing. Mulch tillage was performed on the other half of the field, leaving cover crop residues on the soil surface. Sugar beets were sown 3 cm deep at around 100.000 seeds ha^{-1}. Plots were at least 10 m long to allow weed hoeing at constant speed in the center of the plots. Around 3 weeks before sowing of sugar beet, 4 L ha^{-1} Taifun® Forte (360 g a. i. L^{-1} glyphosate were sprayed at IHO, GÜ, UI. Approximately 120–150 kg ha^{-1} N were applied at all locations. Experiments included 6 treatments (Table 1). An untreated control was included in all sugar beet experiments. Treatment 2 was the conventional herbicide application across the entire field with Agrotop Albuz® CVI-TWIN nozzles at a spray pressure of 2.4 bar. Treatment 3 was a combination of: (i) a first conventional herbicide application, (ii) two times a common band sprayer (Agrotop 80E; spray pressure 1.7–2 bar; spraying angle 80°) and the usage of a hoe with goose-foot blades. In treatment 4 the implementation per measure was done at their optimum time, while in treatment 5 both applications were done simultaneously (Table 1). In all hoeing treatments the configuration was: (i) a driving speed of 7 km h^{-1} and (ii) a hoeing depth of 3–4 cm. In GÜ, UI, KU, GR and WD a Schmotzer and at IHO a Kress goose foot hoe was used. Both hoes had parallelogram guidance.

Table 1: Description of experimental treatments investigated in sugar beet in 2014

	BBCH-stage sugar beet		
Treatment	**12**	**14**	**16**
1		untreated control	
2	conventional spraying	conventional spraying	conventional spraying
3	conventional spraying	band sprayer + hoe	band sprayer + hoe
4	band sprayer + hoe	band sprayer + hoe	band sprayer + hoe
5	band sprayer + hoe[1)]	band sprayer + hoe[1)]	band sprayer + hoe[1)]
6	conventional spraying	conventional spraying	"Dropleg"

[1)] Band sprayer and hoe were performed simultaneously.

In treatment 4 the most suitable application date for each operation was chosen. Conventional herbicide spraying was applied with 200–250 L water ha^{-1} and band spraying with 80 L water ha^{-1}. Band spraying was conducted by adjustment of the common spray boom 15 cm above ground level. In this position the spraying width per nozzle was limited to around 12–13 cm, with flat fan nozzles being spaced at 0.45 or 0.5 m. In treatment 6 (only at KU and IHO (mulch)) "Droplegs" (Lechler sluice nozzle, FT-1.5 408; spray pressure 1.6 bar; spraying angle 140°) were used at the 3rd application date. The spraying boom for the broadcast spraying with the "Droplegs" was 16 cm above ground level (Figure 1).

Figure 1: Dropleg for herbicide application at the third date

At IHO, a second precision farming experiment with a sensor-guided hoe was set up (IHOP) (Table 2). Intra-row was partly combined with finger-weeding in the intra-row area (Van Der Weide 2008). A Robocrop guided hoe (Garford Farm Machinery (Deeping St James, UK)) was used for the camera treatment (Figure 2 and 3). Camera images were captured at a rate of 30 frames per second. The placement of the hoe, within the row was managed based on the cameras feedback, with a hydraulic side shift. The hoe was equipped with duck-foot blades at a row distance of 50 cm and a working width of 3 m. The camera guided hoe and image analysis system was adjusted to row spacing in 45° (horizontal) to crop rows. Treatment I was the untreated control and treatment II the conventional spraying across the entire field. Treatment IV (hand-steering) was executed by manual guidance. For treatment III (RTK hoeing) and V (RTK hoeing plus finger weeders) a DGPS receiver with RTK correction signal was used. During sowing process an AB-Line which was oriented parallel to seed rows was created. The first weed control was performed with herbicides across the whole field. The times of treatment at IHOP were the same as in experiment IHO (mulch).

Table 2: Description of the precision farming treatments investigated in sugar beet at Ihinger Hof (IHOP) in 2014

	BBCH-stage sugar beet		
Treatment	**12**	**14**	**16**
I		untreated control	
II	conventional spraying	conventional spraying	conventional spraying
III	conventional spraying	RTK-hoeing	RTK-hoeing
IV	conventional spraying	manual steering	manual steering
V	conventional spraying	RTK + finger weeder	RTK + finger weeder
VI	conventional spraying	camera-hoeing	camera-hoeing

Figure 2: Camera guided hoe and image analysis system to recognize the crop rows

Figure 3: Camera steering system (treatment 3, without finger weeders) to automatically guide the hoe close to sugar beet rows

A mixture of 3 L ha^{-1} Goltix Titan® (525 g a.i. L^{-1} metamitron and 40 g a.i. L^{-1} quinmerac) and 4.5 L ha^{-1} Betanal Expert® (151 g a.i. L^{-1} ethofumesate, 75 g a.i. L^{-1} phenmedipham, 25 g a.i. L^{-1} desmedipham) was splitted into three applications with equal rates at GÜ, UI, IHO and KU. At GR and WD a mixture of Betanal® maxxPro® 2.2 L ha $^{-1}$ (75 g a.i. L^{-1} ethofumesate, 60 g a.i. L^{-1} phenmedipham, 47 g a.i. L^{-1} desmedipham, 27 g a.i. L^{-1} lenacil 5.5 L ha $^{-1}$ (525 g a.i. L^{-1} metamitron, 40 g a.i. L^{-1} quinmerac) 0.8 L ha $^{-1}$ Plantan PMP 160 SC (160 g a.i. L^{-1} phenmedipham), 0.9 L ha $^{-1}$ Ethosat® 500 (500 g a.i. L^{-1} ethofumesate), 49 g ha^{-1} Debut® (50 g a.i. kg $^{-1}$) and 0.5 L ha^{-1} Spectrum® (325 g a.i. L^{-1} chloridazon, 720 g a.i. L^{-1} dimethenamid-P and 100 g a.i. L^{-1} quinmerac) was used. Treatment dates are listed in Table 3.

Table 3: Timings for weed control methods (DAS = Days after sowing) in sugar beet experiments at Gützingen (GÜ), Unterickelsheim (UI), Ihinger Hof (IHO), Grouven (GR) and Widdendorf (WD) in 2014. Arabic numbers belong to the treatments as explained in table 1, while the Latin numbers belong to the IHOP experiment, as explained to table 2

	Treatment				
Location	**2 (II), 3 ,4, 5, 6**	**3 (III)**	**4 (IV)**	**5 (V)**	**VI**
	Sprayer/Band (DAS)	**Hoe (DAS)**	**Hoe (DAS)**	**Hoe (DAS)**	**Hoe (DAS)**
GÜ (mulch/plough)	36, 48, 61	57, 63	47, 57, 63	36, 48, 61	X
UI	16, 30, 49	39, 53	18, 39, 53	16, 30, 49	X
IHO (mulch)	28, 43, 56	49, 68	34, 49, 68	28, 43, 56	X
IHO (plough)	39, 54, 71	56, 76	41, 56, 76	39, 54, 71	X
KU	20, 28, 49	33, 54	33, 54	28, 49	X
GR	21, 39, 48	53, 58	29, 53, 58	21, 39, 48	X
WD	28, 51, 66	54, 69	30, 54, 69	28, 51, 66	X
IHOP	**28**	**49, 68**	**49, 68**	**49, 68**	**49, 68**

2.3 Data Collection

Weed density was counted directly after each treatment using a frame (0.5 m^{-2}) at three locations in each plot in GÜ, IHO, KU, GR, and WD. In UI the complete plot was sampled. Soil coverage was visually estimated at three random positions within each plot with a frame (2 x 50 + 2 x 100) by two experienced observers directly after planting and after the last application date. Sugar beets were harvested in September/October with a plot harvester (Edenhall 623, Vallåkra, Sweden). Sugar beets were washed and afterwards yield was measured. Sugar content (White sugar yield = WSY) was analysed according to the standard German procedure (Hoffmann 2006).

2.4 Statistical Analysis

All data were subjected to analysis of variance (ANOVA), which was appropriate for a randomized complete block design. Homogeneity of variances was tested and data were transformed if necessary. Main effects and interactions were tested for significance. Weed density data were transformed using the square root or LOG^{10} to normalize the data distribution. Results were back transformed. The analysis included every weed count in all treatments and replicates; therefore, the variability between treatments but also between replication could be analyzed. Statistical significance was evaluated at p-value ≤ 0.05 with appropriate pooled standard errors of the difference (s. e. d.) of treatment means. Afterwards, multiple comparison tests were performed using the Tukey test at a significance level of $\alpha \leq 0.05$. Data was analyzed with the statistical software language R version 3.0.2, “agricolae” and “lsmeans” package (Mendiburu 2014, Bates 2014).

3 Results

3.1 Soil coverage of cover crop residues

Soil coverage by cover crop residues decreased from sowing until all weed control treatments were completed. Decrease was significantly higher in the treatments 3, 4, and 5, where mechanical weed control was performed. Still, approximately 5% cover crop residue coverage was measured after two or three passes of hoeing (Figure 4).

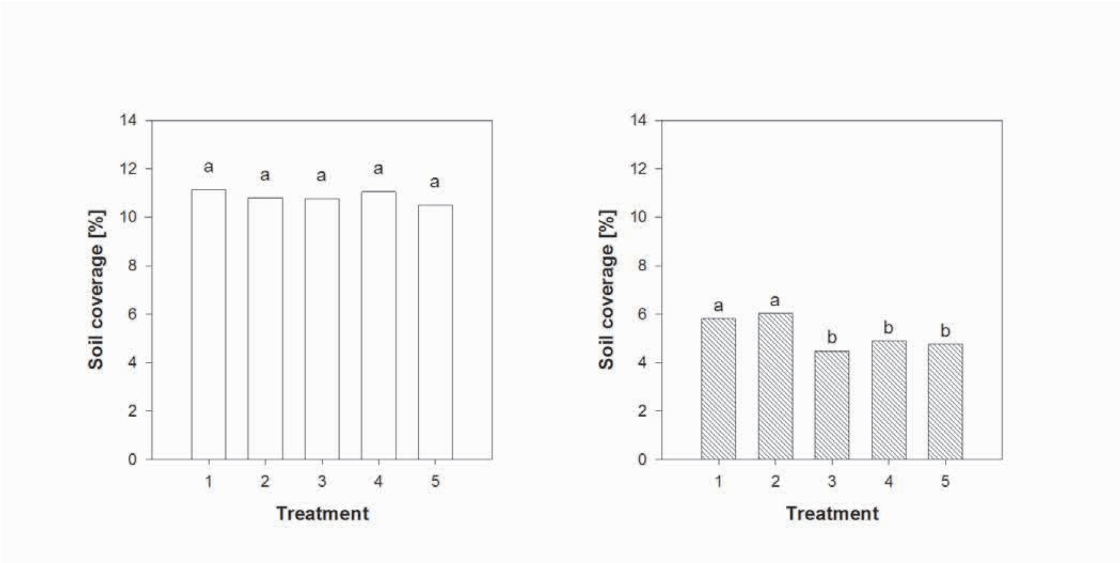

Figure 4: Soil coverage by cover crop residues three days after sowing (left) and three days after weed control was completed (right). Data were gathered from two locations (Gützingen (GÜ) and Ihinger Hof (IHO)) in 2014. Bars represent the accumulative mean values. Means with identical letters per graph do not significantly differ (Tukey HSD-test p = 0.05).

3.2 Weed density

A total of 20 different weed species were recorded. The most abundant weed species identified observed were common lambsquarter (*Chenopodium album* L.), wild buckwheat (*Polygonum conolvulus* L.) and prostrate knotweed (*Polygonum aviculare* L.) (Table 4). The highest weed density was observed at IHO with 91 plants m^{-2} (Figure 5, Table 5). Untreated control significantly reduced weed densities at all locations. However, significant interactions between treatment and time (date of evaluation) was found for all species.

In each of the 9 experiments, weed density was highest in the untreated control (Figure 5). At GÜ (plough), UI and IHO (mulch) weed control efficacy was highest in the conventional herbicide treatment. At GÜ (mulch), IHO (plough), GR and WD, band spraying in combination with inter-row hoeing resulted in highest weed control efficacy (Figure 5). Results of weed density at GÜ and UI are not shown due to the low densites of weeds. At KU, best weed control efficacy with 90% was achieved with “Droplegs” treatment. At IHO (mulch), the same treatment resulted in 86% efficacy. The lowest weed density at IHO (mulch) was observed in conventional treatment spraying across the entire surface (treatment 2) with 93%. The treatments 2, 3, 4, and 6 were more effective after mulch tillage compared to inversion tillage except for treatment 5. The combination of band spraying and hoeing (treatment 3) reduced weed density by 87%. The conventional herbicide application showed only 72%

efficacy. The lowest weed control efficacy was found in the treatment 5, where band spraying and hoeing were done at the same day, reaching only 54% of weed control efficacy (Figure 5).

Automatic RTK-GNSS steering technology for weed hoeing in sugar beets reduced weed density by 84% and the camera steered hoe by 78% (Table 5). Highest densities were measured in treatment I with 91 weed plants m^{-2}.

Table 4: List of weed species observed at 6 locations (GÜ = Gützingen, IHO = Ihinger Hof, UI = Unterickelsheim, KU = Kupferzell, GR = Grouven, WD = Widdendorf)

Species	Location					
	GÜ	IHO	UI	KU	GR	WD
Aethusa cynapium L.	X					X
Brassica napus L.			X			X
Capsella bursa-pastoris L.		X	X			X
Convolvulus arvensis L.	X					
Chenopodium album L.	X	X	X	X	X	X
Cirsium arvense L.		X			X	
Fumaria officinalis L.		X	X			
Galinsoga parviflora Cav.			X			X
Galium aparine L.		X				
Geranium dissectum (L.) Jusl.			X			
Lamium purpureum L.				X		
Matricaria sp.				X		
Mercurialis annua L.					X	X
Polygonum aviculare L.		X	X	X		
Polygonum convolvulus L.	X	X		X		
Sinapis arvensis L.		X	X			
Solanum tuberosum L.					X	
Sonchus arvensis L.		X	X			
Stellaria media (L.) Vill.	X		X			X
Veronica persica Poiret		X	X			

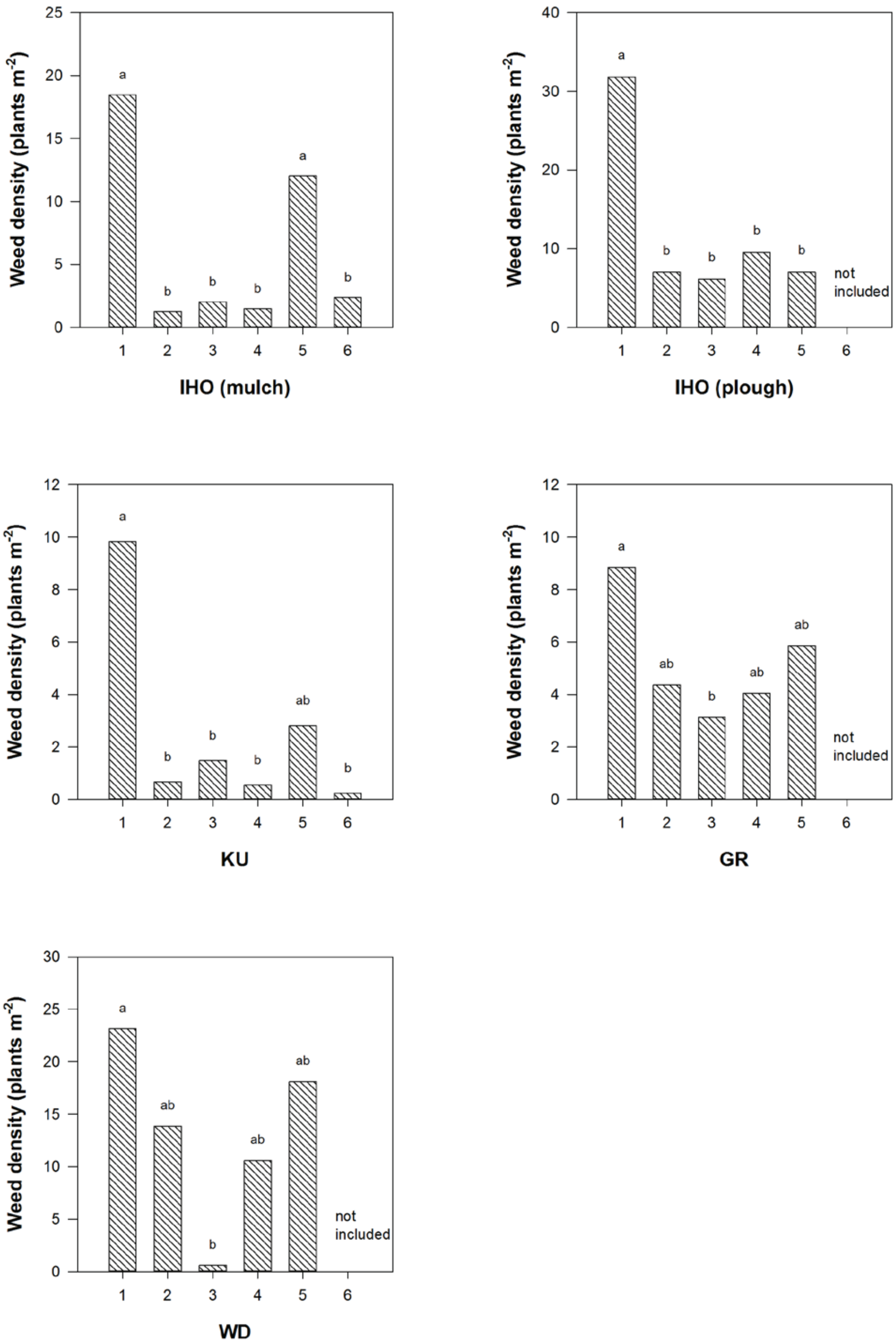

Figure 5: Weed density in sugar beet counted after the last treatment at 6 locations (Gützingen (plough + mulch) (GÜ), Unterickelsheim (UI), Ihinger Hof (IHO), Kupferzell (KU), Grouven (GR), Widdendorf (WD). Means with identical letters within on graph do not differ significantly based on the Tukey HSD-test (p = 0.05).

Table 5: Means (MV) of weed density [plants m^{-2}] and standard deviations (STD) in the Precision Farming experiment at Ihinger Hof (IHOP) after weed hoeing. Means with identical letters within on graph do not differ significantly based on the Tukey HSD-test (p = 0.05).

	Weed control treatment	**MV**	**STD**	
		Plants m^{-2}		
I	untreated control	90.9	102.9	a
II	conventional spraying	16.2	16.1	b
III	RTK-hoeing	14.4	16.6	b
IV	Hand-Steering	15.7	13.3	b
V	RTK Hoeing (+ finger weeder)	19.2	19.4	b
VI	Camera Hoeing	19.9	25.2	b

3.3 Crop Yield

Weed control treatments increased white sugar yield (WSY) in average by 30% compared to the untreated control. WSY was equal in all weed control treatments except for the untreated control plots (Figure 6, Table 6). Sugar beet quality was not influenced by treatment in none of the experiments. The mean white sugar content over all locations was 16.4% (data not shown).

Table 6: Means (MV) and standard deviations (STD) of White Sugar Yield in [t ha^{-1}] (WSY) and White sugar content [%] (WS) at the Precision Farming experiment at Ihinger Hof (IHOP). Means with identical letters within on graph do not differ significantly based on the Tukey test (p = 0.05).

	Weed control treatment	**MV**	**STD**		**MV**	**STD**	
		WSY [t ha^{-1}]			**WS [%]**		
I	untreated control	10.39	2.80	a	16.86	0.39	a
II	conventional spraying	14.70	1.95	b	17.58	0.29	a
III	RTK Hoeing	14.98	0.66	b	17.30	0.11	a
IV	Hand-Steering	13.54	0.32	ab	17.16	0.01	a
V	RTK Hoeing (+Finger weeder)	14.15	0.15	ab	17.24	0.16	a
VI	Camera Hoeing	14.31	1.10	ab	17.26	0.10	a

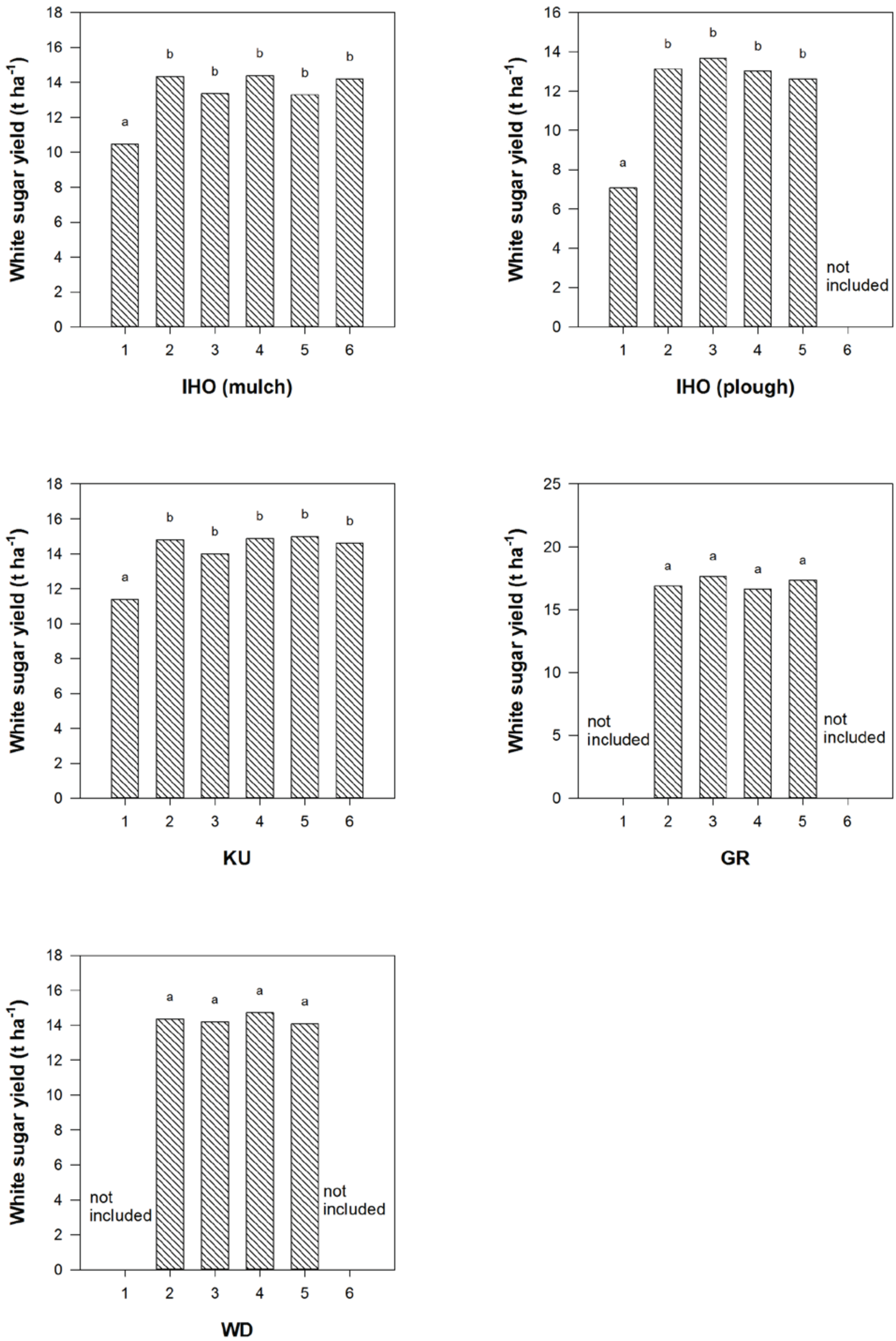

Figure 6: Means of white sugar yield in [t ha^{-1}] at 6 locations (Gützingen (plough + mulch) (GÜ), Unterickelsheim (UI), Ihinger Hof (IHO), Kupferzell). Means with identical letters within on graph do not differ significantly based on the Tukey HSD-test (p = 0.05)

Discussion

We observed a 50 to 75% reduction of herbicide use, when band-spraying was combined with intra-row hoeing at all experimental locations. Kouwenhoven (1991) achieved similar reductions of herbicide use with 60–67% of the total area not treated with herbicides. With the reduction in herbicide use, environmental impact of herbicides on ground and surface water, non-target organisms and human health is lower as well (Lotz 2002, Wiltshire 2003).

In practice, suitable soil conditions for mechanical weed control are not always given and labor demand for hoeing is higher than for chemical weed control. In the given study dry conditions before and during plant protection period were preexisting, which was beneficial for hoeing treatments at all locations.

Automatic guidance systems as applied in this study achieved similar results than conventional spraying, but allowed hoeing even at a speed of 10 km h^{-1}, and therefore significantly increased labor efficiency. The automatic steering systems guided the hoe closer to the crop row than manual steering systems. The safety distance for the IHOP trial was 3–5 cm compared to the other IHO trials (plough/mulch), which was 5–7 cm. That reduced the intra row area by ~ 0–50%. By reducing the intra row space the possibility of weed existence was decreased. As a result the intra row area can be reduced by using precision implements. Furthermore, it allows the operation with finger weeders for intra row hoeing. Unfortunately, in the specific location, there was a low weed density. Therefore, the intra row treatment was only different with the control and did not show any statistically significant difference from the other applications.

Alternative weed control methods, applied in this study, resulted in equal weed control efficacy, compared to conventional herbicide applications. It has been shown, that hoeing combined with band spraying and precision hoeing at some locations even had higher efficacies than conventional chemical weed control methods, when soil and weather conditions were suitable for mechanical weed control. These results are similar to Kurstjens (2001), who pointed out that weather conditions may influence the effectiveness of mechanical weed control. Due to extremely dry conditions at KU at the first application date, hoeing was not possible. Only two instead of three passings could be done by the hoe. However, no lower efficiency was observed.

Mechanical weed control was successfully combined with mulch tillage and cover cropping. At location UI weed hoeing with high degrees of mulch resulted in difficulties during the hoeing process compared to locations IHO, KU, GR and WD. Clogging of the hoe, manual cleaning and low labor efficacy were the consequences, but no detrimental effects on weed control efficacy could be observed. Mulch residue did not significantly affect weed control efficacy. Mulch tillage and conventional tillage resulted in similar yields at IHO. Therefore there is a high possibility of using mechanical and chemical weed control in combination in both tillage strategies. However, part of the cover crop residues were incorporated into the soil by hoeing and thus, we assume that risk of soil erosion is increased. Bilalis (2003) discovered, that mulch tillage and mulch cover affects weed abundance and weed species composition. Weed density was also found to be lower in the mulch treatments in our studies.

Moreover, Cioni (2010) expected that hoeing strategies can excite weeds to emerge at early development stages. In this study such a negative impact of hoeing was not identified. Kurstjens (2004) quantified selective uprooting by mechanical weeders of weeds and crops. Different results were observed in the given study, because no negative impact of selective sugar beet uprooting was observed over all locations. In different development stages the sensitivity regarding crop damage in sugar beets is different. The distance from the crop area to the hoeing tool should be more than 6 cm in radius at the beginning of development (Nørremark 2004).

A conventional boom sprayer can apply herbicides in bands easily, with a simple conversion. This can be done by using narrow angle nozzles and lowering boom height for band spraying in the row (May 2008).

There is a high importance of high precision of application qualities as well. In the given study a high success in KU was achieved by using “Droplegs”. The weed density was lowest compared to the other treatments. Before using “Droplegs” there are some prerequisites that have to be met. The leaf coverage should be lower than 60% to enable an application accuracy of 80% and to prevent spray shadows. Spray shadows only occur when sugar beet leaves are directly located above the soil (Roeb 2013).

Sugar beet yield was equally increased by all weed control methods tested over all locations. Higher yields at IHO (plough), KU, GR and WD demonstrate the suitability of alternative systems compared to conventional spraying. These results correspond to observations by McClean (1986) who also compared different weed control strategies in sugar beet.

Conclusion

Weed control treatments tested significantly increased white sugar yield (WSY) compared to the untreated control. The combination of mechanical weed control and band application of herbicides and precision hoeing have shown to be promising concepts for integrated weed management in sugar beet resulting in significantly reduced herbicide input and high weed control efficacy. Additional research is needed to exploit the potential of weed suppression by cover crops and cover crop residues. Furthermore, it has to be mentioned that the investigated and proved locations cannot be considered as problematic sites and locations with high weed density should be proved in additional experiments.

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Authors

M. Sc. Christoph Kunz is a PhD student and a scientific employee and **Prof. Dr. Roland Gerhards** is a professor for Weed Science at the Institute for Phytomedicine, Otto-Sander-Str. 5, 70599 Stuttgart Hohenheim, e-mail: christoph.kunz@uni-hohenheim.de.

M. Sc. Carolin Schröllkamp, studied agricultural science and **Prof. Dr.-Ing. Peter Schulze Lammers** is a professor for Mission Systems Engineering in Plant Production, Nußallee 5, 53115 Bonn

Clemens Eßer is working for the LIZ as a consulting manager, Dürener Str. 67, 50189 Elsdorf

Dr. Heinz-Josef Koch is the leader of the Agronomy department at the Institute of Sugar Beet Research, Holtenser Landstr. 77, 37079 Göttingen

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