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Integrated weed control in sugar beet (*Beta vulgaris*), using precision farming technologies and cover cropping

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Für meine Vorbilder
Reinhold, Hubert und Erhard…

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1. General Introduction

Economic, ecological and social factors characterize a modern and sustainable sugar beet production (Christen 1999). Field cropping strategies should consider environmental aims, while ensuring fair profits for farmers and the associated agricultural industry. Nevertheless, after elaboration of management factors such as pesticides, high-yielding and pest-tolerant cultivars, irrigation systems and different synthetic fertilizers, the food quality must also be guaranteed. The interaction of all these components is mandatory for prospective and sustainable food production (Geldermann and Kogel 2002).

In 2015, the worldwide production of 177 million tons of raw sugar illustrates the importance of sugar beet in the agricultural market. In Germany 2.942.281 tons of White Sugar (WS) were produced in an arable area of 254.483 ha in 2015/2016 (WVZ/VdZ 2016).

Due to widely spaced rows and slow crop development in the early growing stages of sugar beet, yield losses of up to 95% are possible, if weed control is omitted (Petersen 2004). Therefore, an effective weed management is crucial. Chemical weed control has currently evolved into an unavoidable component of weed management in sugar beet production. The most important herbicide mixtures contain the following active ingredients: *metamitron, phenmedipham, desmedipham* and *ethofumesate* (Vasel et al. 2012). For sugar beet, the common weed control practice is the implementation of 3 (or up to 5) post herbicide applications in the cotyledoneous stage of the weeds. Nevertheless, high environmental risks and crop damage may be the consequences of the herbicide application (Gummert et al. 2012). Wilson et al. (2002) reported on crop injuries and yield losses of up to 15% in different sugar beet cultivars. Herbicide application under unfavorable environmental conditions can increase the crop damage by causing discolorations and changes in plant development during the growth period (Osborne et al. 1995, EPPO Bulletin 2014).

EU directives encourage farmers to meet with stricter standards concerning pest management. That leads to restrictions on herbicide applications, and promotes the reduction of the total amounts of herbicides applied. The European Commission (EC) favors a reduced input of pesticides in the agricultural supply chain (Hillocks 2012). On the one hand, the use of pesticides should ensure the economic success of farmers – on the other hand, it should not have detrimental effects on human health and the environment. Integrated Weed Management (IWM) in general has been developed to relieve the pressure on the environment caused by constant agricultural production (Diercks and Heitefuss 1990). IWM is the minimization of pesticide amounts in the environment through the complementary use of different weed control approaches (Diercks and Heitefuss 1990, Buhler 2002, Hillocks 2012, Lamichhane 2015). Global, European, National and Regional programs need to be included and coordinated to ensure the effective implementation of IWM (Lamichhane et al. 2015).

Gummert et al. (2012) proposed the concept of using IWM for sugar beet production. These strategies include all reasonable possibilities of phytomedicine (Diercks and Heitefuss 1990). Cover crops, to exemplify, provide several ecological advantages. They reduce water and wind erosion (De Baets et al. 2011), increase biological activity in the soil (Mendes et al. 1999) and prevent nitrate leaching (Freibauer 2004). Therefore, cover crops play an important role in conservation agricultural (CA) systems (Triplett and Dick 2007). CA contains a long-lasting soil cover with organic material, like stubbles or different cover crop mulches (Kassam et al. 2009). The use of several cover crop mulch systems in sugar beet production has increased in importance during the recent past in Europe. Due to different European restrictions, the cultivation of cover crop mixtures will be financially encouraged. This policy was devised to increase biodiversity in agricultural fields. Cover crops contribute to biodiversity but also suppress weeds and volunteer crops. Prior to sugar beet sowing, they reduce weeds by up to 90% (Brust et al. 2014). Due to the competition for light, water, space and nutrients with the cover crop, weeds can be reduced significantly (Kunz et al. 2016b). Additionally, the release of biochemical substances from cover crops and crop residues can suppress weed emergence (Farooq et al. 2011). Rice (1984) described this interaction between plants as “Allelopathy”. Allelopathic compounds, mostly secondary metabolites or degradation products of the plant, were released into the environment during plant growth or by decomposition of biomass as mulch (Nichols et al. 2015, Kunz et al. 2016b, Sturm et al. 2016). After sugar beets are sown, cover crop residues on the soil surface can still inhibit weed germination and growth (Teasdale and Mohler 1993, Sturm et al. 2016). The plant mulch residues on the soil surface change the physical and chemical environment of the weed seeds (Nichols et al. 2015). Further, biological weed control can be performed by the use of living mulch. Living mulches are cover crops, sown between crops in order to cover the soil during the crop vegetation period (Hartwig and Ammon 2002).

A further system for reducing herbicides is mechanical weed control (Van Der Weide et al. 2008, Bowman 1997). An implementation of mechanical weed control tools in sugar beet production can substitute herbicide treatments and therefore reduce the amount of different herbicides in the environment (Van Der Weide et al. 2008). Due to the slow driving speeds and limited working width of the implements, the labor efficiency is relatively low compared to chemical weed control. Even more, hoeing in the intra-row area and operating as closely as possible to the crop area are the requirements for a successful mechanical weed control management strategy (Melander and Rasmussen 2001).

The use of precision agriculture (PA) is an expedient way of steering the hoe close to the crop area. The management of crops on a spatial scale, smaller than that of the whole field, is called PA or Site-Specific Management (SSM). The use of PA in agriculture is gaining more and more importance, due to the commercialization of new developments like the global positioning system (GPS). The operation with PA can reduce labor costs and is able to increase the speed of the applications (Plant 2001). The use of Global Navigation Satellite System (GNSS) technologies or digital image progression is needed for accurate guidance (Gerhards and Christensen 2003). Guidance systems within the field identify the position of the crop rows and a hydraulic side shift system steers the hoe close to the crop area and provides higher driving speeds by reducing the farmers work (Tillett et al. 2002, Slaughter et al. 2008, Nørremark et al. 2012).

1.1 Objectives

The overall aim of this research was to develop a new approach for IWM strategies. This approach focused on the sugar beet production systems in Germany. It would be capable of reducing herbicide applications, while ensuring equal or better weed control efficacies. In this research, the following specific objectives were examined:

- Evaluation of the suitability of CC and CC mixtures for weed suppression prior to sugar beet sowing
- Assessment of differences in sugar beet emergence, weed control and biomass under different CC mulches
- Application of living mulches and measurement of their weed control efficacy during the sugar beet growth period
- Evaluation of mechanical weed control along with chemical band spraying compared to an overall herbicide application
- Determination of the weed control efficacy of mechanical weeding by using visual sensors and GNSS-RTK
- Investigation of the feasibility of intra-row mechanical weed control, its prerequisites and limitations
- Detection of responses to herbicides by using chlorophyll fluorescence imaging technology

1.2 Structure of the dissertation

The current thesis consists of 3 chapters proposing several approaches for integrated weed management in sugar beet. It starts with a general introduction (chapter 1) presenting the structure of the complete thesis and emphasizing the objectives sustained in this work. The next chapter 2 includes eight research articles, composing this work. The first three subchapters 2.1, 2.2 and 2.3 deal with different alternatives for reducing the amount of weeds with cover crops and mulch before sugar beet sowing and at the early beginning of the crop development. These papers describe the results of cover crops, followed by a mulch layer. They present the advantages and drawbacks in regard to weed suppression. The next subchapter 2.4 focused on using living mulches for reducing weeds during the cropping season, with a simultaneous reduction on the herbicide use. The target was to observe if living mulches are also able to play a role in IWM for the sugar beet cultivation. The following subchapters 2.5, 2.6 and 2.7 focus on precision agriculture and especially the utilization of automated steering technologies for mechanical weed control. The potential advantages and limitations along with the results derived from different field trials are described in the above listed chapters. In subchapter 2.8, the use of sensor technologies is presented as an aid to quantify herbicide stress after herbicide applications. In the general discussion (chapter 3), a critical overview of the different articles is presented and discussed. Apart from the peer-reviewed journal articles, included in the thesis, during the course of this thesis six more contributions to national and international scientific conferences and symposiums were presented, either as a poster or as an oral presentation. This work was supplementary to the included articles, and therefore not included in the current thesis.

- Kunz, C., Weber, J. F., & Gerhards, R. (2016). Comparison of different mechanical weed control strategies in sugar beets. In: *Proceedings of the 27th German Conference on Weed Biology and Weed Control* 452, 446-451.

- Weber, J. F., Kunz, C., & Gerhards, R. (2016). Chemical and mechanical weed control in soybean (*Glycine max*). In: *Proceedings of the 27th German Conference on Weed Biology and Weed Control* 452, 171-176.

- Kunz, C., Risser, P., Maier, J., & Gerhards, R. (2016). Effect of different cover crop cultivation systems on weed suppression in sugar beets. In: *Proceedings of the 75th IIRB Congress.*

- Kunz, C., Risser, P., Maier, J., & Gerhards, R. (2016). Different mechanical weed control strategies in sugar beet. In: *Proceedings of the 75th IIRB Congress.*

- Kunz, C., Sturm, D. J., & Gerhards, R. (2016). Effect of Strip Tillage Systems on weed suppression in sugar beets by utilizing different cover crops. In: *Proceedings of the 7th International Weed Science Congress*.

- Sturm, D. J., Kunz, C., & Gerhards, R. (2016). Comparison of different cultivations of *R. sativus* var. *oleiformis* as cover crop on weed suppression. In: *Proceedings of the 7th International Weed Science Congress*.

2. Publications

2.1 Allelopathic effects and weed suppressive ability

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doi: 10.17221/612/2015-PSE

Summary

Field and laboratory experiments were performed to investigate the weed suppressing effects of cover crops in single and mixed cultivation. Weed densities in the field experiments ranged from 0 to 267 plants m^{-2} with *Chenopodium album* L., *Matricaria chamomilla* L., *Stellaria media* (L.) Vill. as predominant weeds. It was found that mustard (*Sinapis alba* L.), fodder radish (*Raphanus sativus* var. *niger* J. Kern) and spring vetch (*Vicia sativa* L.) supressed weeds by 60% and cover crop mixtures controlled weeds by 66% during the fallow period at three experimental locations in 2013, 2014 and 2015. The biochemical effect of the same cover crops/mixtures on weed growth was analyzed in laboratory experiments. Aqueous cover crop extracts were applied on weeds and analyzed using LC/MS/MS. Mean germination time, germination rate and root length of weeds were determined. Extracts prolonged the germination time by 54% compared to the control with only water. In all cases, inhibitory effects on germination rate and root length were measured. Weed density in the field was found to be correlated with the root length in the germination tests. Our work reveals that biochemical effects play a major role in weed suppression of cover crops.

Keywords: Allelopathy, erosion, root growth, competition, inter cropping

2.2 Weed suppression and early sugar beet development under different cover crop mulches

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Published in: *Plant Protection Science* (2016), **53**, 187-193

The original publication is available at: *http://www.agriculturejournals.cz/web/pps/*

doi: 10.17221/109/2016-PPS

Summary

Field experiments were performed at two locations in 2014-2015 and 2015-2016 to investigate the weed suppressive ability of cover crop mulches in sugar beets. Three cover crops and two cover crop mixtures were tested in all four experiments. Weed densities ranged from 2 up to 210 plants m^{-2} with *Chenopodium album* L. and *Stellaria media* (L.) Vill. as predominant species. *Sinapis alba* grew significantly faster than *Vicia sativa*, *Raphanus sativus* var. *niger* and both cover crop mixtures. *Sinapis alba*, *Vicia sativa*, *Raphanus sativus* var. *niger* reduced weed density by 57%, 22% and 15% across all locations. A mixture of seven different cover crops observed a reduced weed emergence of 64% compared to the control plot without cover crop mulch. Early sugar beet growth was enhanced by all mulch treatments in 2015 and decelerated in 2016.

Keywords: *Beta vulgaris*, *Chenopodium album*, conservation tillage, cover crop mixture, integrated weed management, intercropping, *Stellaria media*

2.3 Inhibitory effects of cover crop mulch on germination and growth of *Stellaria media* (L.) Vill., *Chenopodium album* L. and *Matricaria chamomilla* L.

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https://www.journals.elsevier.com/crop-protection,

doi: doi.org/10.1016/j.cropro.2016.08.032

Summary

Cover crops may suppress weeds due to their competitive effects and the release of inhibitory compounds. We observed the inhibitory influence of 11 cover crop mulches on the germination and growth of weed species (*Stellaria media* (L.) Vill., *Chenopodium album* L. and *Matricaria chamomilla* L.) in laboratory, greenhouse and field experiments. In the laboratory, cover crop extracts were tested in germination bioassays at six concentrations (0 to 500 mg ml^{-1}). The germination rate and root length (i) were measured 10 days after treatment (DAT). Pot experiments were carried out in the greenhouse to investigate the effects of cover crop mulch (ii) incorporated into the soil on weed germination and weed dry mass. Field trials measured the suppressive effects of cover crops and cover crop mixtures on weeds (iii). Correlations were determined between the experiments to quantify the competition and the biochemical effects of cover crops separately. Cover crop extracts at a concentration of 125 mg ml^{-1} (i) significantly reduced the weed germination rate by 47% and the root length by 32% on average. *M. chamomilla* showed a lower susceptibility to the extracts of *S. alba*, *R. sativus* var. *niger* and *H. annuus* compared to *C. album* and *S. media*. The mulch-soil mixtures (ii) significantly reduced the germination rate by 50% and the dry mass by

47% on average across all three weed species, while *M. chamomilla* showed the highest tolerance to the mulches of *V. sativa* and *A. strigosa*. The correlation analysis revealed a strong positive correlation between extract toxicity and field weed suppression and, thus, indicated a high impact of the biochemical effects of the tested cover crops on weed suppression, especially for *S. media* and *M. chamomilla*.

Keywords: Allelopathy, germination test, phytotoxicity, plant extracts, root length, sugar beet

2.4 Weed Suppression of Living Mulch in Sugar Beets

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doi:10.1007/s10343-016-0370-8

Summary

Weed suppression in sugar beets (*Beta vulgaris.*) is commonly achieved with two to three post-emergent herbicide applications across the entire field. Field studies were conducted, in order to investigate the weed suppressing ability of *Medicago lupulina*, *Trifolium subterraneum* and a mixture of *Lolium perenne* and *Festuca pratensis* as living mulches in sugar beet at four locations in South Germany during 2014 and 2015. Living mulches were sown 2 and 30 days after sowing (DAS) of sugar beet. Weed densities ranged from 0 to 143 plants m^{-2} with *Chenopodium album*, *Polygonum convolvulus* and *Polygonum aviculare* being the most abundant weed species. It has been found that living mulches could reduce herbicide input up to 65%. Weed suppression of living mulch was highest with *Trifolium subterraneum* (71%). The early sown living mulches (2 DAS) revealed a 28 g m^{-2} higher biomass compared to late sowing (30 DAS). However, no any linear correlation was found between living mulch biomass and weed suppression. White sugar yield (WSY) was highest in the herbicide treatments (12.6 t ha^{-1}). *Trifolium subterraneum* yielded the highest WSY of the living mulches with 11.1 t ha^{-1} across all locations. Our work reveals that living mulch can play a major role in integrated plant protection by reducing herbicides in sugar beet production.

Keywords: Biomass, *Beta vulgaris*, cover crop, *Festuca*, *Lolium*, *Trifolium*, intercropping, sugar content, sugar yield, weed density

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

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https://www.landtechnik-online.eu/, doi: dx.doi.org/10.15150/lt.2015.2661

Summary

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 monitored 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*)

2.6 Benefits of Precision Farming Technologies for Mechanical Weed Control in Soybean and Sugar Beet - Comparison of Precision Hoeing with Conventional Mechanical Weed Control

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http://www.mdpi.com/journal/agronomy, doi: 10.3390/agronomy5020130

Summary

Weed infestations and associated yield losses require effective weed control measures in soybean and sugar beet. Besides chemical weed control, mechanical weeding plays an important role in integrated weed management systems. Field experiments were performed at three locations for soybean in 2013 and 2014 and at four locations for sugar beet in 2014 to investigate if automatic steering technologies for inter-row weed hoeing using a camera or RTK-GNSS increase weed control efficacy, efficiency and crop yield. Treatments using precision farming technologies were compared with conventional weed control strategies. Weed densities in the experiments ranged from 15 to 154 plants m^{-2} with *Chenopodium album*, *Polygonum convolvulus*, *Polygonum aviculare*, *Matricaria chamomilla* and *Lamium purpureum* being the most abundant species. Weed hoeing using automatic steering technologies reduced weed densities in soybean by 89% and in sugar beet by 87% compared to 85% weed control efficacy in soybean and sugar beet with conventional weeding systems. Speed of weed hoeing could be increased from 4 km h^{-1} with conventional hoes to 7 and 10 km h^{-1}, when automatic steering systems were used. Precision hoeing technologies increased soybean yield by 23% and sugar beet yield by 37%. After conventional hoeing and harrowing, soybean yields were increased by 28% and sugar beet yield by 26%.

Keywords: Mechanical weed control, automatic steering systems, sensor technologies, integrated weed management

2.7 Camera steered mechanical weed control in row crops – A novel approach for integrated weed management?

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2.7.1 Summary

Weed control in sugar beet, maize and soybean is usually performed with herbicide application across the whole field. Beside chemical weed control, mechanical weeding can play a major role for integrated weed management (IWM). In 2015 and 2016, field experiments were conducted to proof the ability of (a) a camera steered hoe in combination with different intra-row mechanical weeding tools in sugar beets, maize and soybean and the use of (b) herbicide banding combined with mechanical weed control in sugar beets. Weed densities in the experiments ranged from 0 to 153 plants m^{-2} with *Chenopodium album*, *Polygonum convolvulus*, *Thlapsi arvense* being the most abundant weed species. Camera steered hoeing showed a 78% weed control efficacy compared to manual guidance (65%). Different intra-row elements revealed a weed control efficacy of up to 79%. Disparities in the number of uprooted crops were insignificant among all treatments in sugar beets and soybean. In maize, the rotary harrow significantly reduced weed density in 2016 but not in 2015. Best weed control was found after herbicide application and the combination of band spraying plus mechanical weed control. Mechanical weed control treatments increased white sugar yield by 39%, maize biomass yield by 43% and soybean grain yield by 58% compared to the untreated control in both experimental years. Yet, they were outperformed by the herbicide treatment. Based on the results of this study, there is a possibility of a more intense use of mechanical weeding technologies in combination with precision farming technologies for sugar beet, maize and soybean cultivation.

Keywords: *Chenopodium album*, goose food hoe, herbicide saving, intra-row weeding, *Polygonum convolvulus*, visual guidance

2.7.2 Introduction

Effective weed control is mandatory for sugar beets (Petersen 2004), soybean (Hock et al. 2006), and maize (Mehrtens et al. 2005) mainly during the period of crop establishment until canopy closure. Negative consequences of neglected weed control includes: yield losses, reduced crop quality, increased weed seedbank which will increase the coming years weed population, and complications during harvest (Bastiaans and Kropff 2003). Besides chemical weed control, mechanical weeding can play an important role in integrated weed management systems. This is related to an ongoing prosperity linked with the demand of high food quality in Europe. Due to European, national, and local restrictions, farmers are forced to reduce their herbicide input (Hillocks 2012). Furthermore, repeated herbicide applications promote herbicide resistant weed populations (Powles and Yu 2010). Therefore, mechanical weed control has gained increased importance during the last decades (Kunz et al. 2015a, b).

The use of mechanical weed control strategies can reduce the amount of herbicide residues in the environment (Van der Weide et al. 2008). Wiltshire et al. (2003) described a higher weed control efficacy of band spraying in combination with a mechanical hoe compared to an overall herbicide application. With this strategy the authors could achieve herbicide reductions of up to 70%. However, labor efficiency of band application in combination with hoeing is much lower than broadcast herbicide applications. Mehrtens et al. (2005) concluded, the use of a mechanical treatment in maize can halve the herbicide input with no reduction in weed control efficacy and crop yield. Furthermore, there is a higher dependency on optimum weather conditions compared to chemical weed control. Therefore, a chemical ‘rescue treatment’ can be substantial (Bowman 1997). An additional challenge for mechanical weed control is the occurrence of intra-row weeds, i.e., weeds growing close to the crop space. Moreover, the success of mechanical weed control strongly correlates with pre-existing soil conditions, weed species, and growth stages of weeds and the crop. The most powerful mechanical weed suppression is reached, if crops are taller than weeds during the mechanical operation time (Bowman 1997, Van der Weide et al. 2008).

Different mechanical approaches e.g. the use of finger weeders, harrowing, torsions weeders, and weeding with compressed air (Pneumat) can be used for the weeds close to crop proximity (Van der Weide et al. 2008). Mentioned mechanical intra-row tools can reduce working time compared to hand weeding with up to 110 hours ha^{-1} (Van der Weide et al. 2008).

Moreover, the introduction of the Global Navigation Satellite System (GNSS) and optical sensors in farming leads to an improved capability for recording the variability of different structures in plant production (Gerhards and Christensen 2003). Guidance systems for tractors identify the crop row position and a hydraulic side shift system is able to steer the hoe close to the crop area and provide higher driving speeds and thus reduced farm labor (Tillett et al. 2002, Nørremark et al. 2012). Yet, there is a lack of information concerning the performance of finger weeder, torsion weeder, rotary harrow and heap element in combination with visual guidance in sugar beet, maize and soybean. Until now there have not been enough information about the increase of the weed control efficacy, the reduced crop damage, or the possible yield potential that these methods provide compared to the traditional mechanical weed control. Moreover, the optimum time frame for their application is still undefined.

The objectives of this study were to analyze:

- Weed control efficiency of a camera steered hoe compared to a manually steered hoe.
- Assessment of the quality of different intra-row implements in regard to weed control efficacy.
- The number of uprooted plants due to the applied techniques.
- Efficacy of mechanical weed control in combination with band spraying compared to a broadcast herbicide application.
- Differences in yield depending on the applied weed control techniques.

2.7.3 Material and Methods

Three mechanical intra-row weed control field trials (a) in sugar beets, soybeans and maize were conducted at Renningen (RE) (48.74° N, 8.92° E, 478 m altitude) in 2015 and 2016 (Table 1).

Table 1: Treatments in the field experiments (a) in sugar beet, maize and soybean.

	BBCH stage of the crop		
Treatment	**12***	**14**	**16**
UC	untreated control		
HB	herbicides broadcast	herbicides broadcast	herbicides broadcast
MS	herbicide banding+ hoe	manual steering	manual steering
CS	herbicide banding+ hoe	camera steering	camera steering
CFW	herbicide banding+ hoe	CS + Finger weeder	CS + Finger weeder
CTW	herbicide banding+ hoe	CS + torsion weeder	CS + torsion weeder
CRH	herbicide banding+ hoe	CS + rotary harrow	CS + rotary harrow
CHE	herbicide banding+ hoe	CS + heap element	CS + heap element

*1st application was only performed in the sugar beet experiment at BBCH 12

Two additional field trials in sugar beets (b) were performed for herbicide to mechanical crossing, combining mechanical applications with chemical band spraying in Gaukönigshofen (GK) in 2015 (49.63° N, 9.9° E, 270 m altitude) and in RE in 2015 and 2016 (Table 2). At RE, the soil type was loam in the sugar beet and the maize plots and sandy loam in soybean plots. At GK the soil type was a silty clay. The average temperature was 8°C at GK and 9.5°C at RE. Annual rainfall on the long term was 790 mm at RE and 600 mm at GK.

Table 2: Treatments in the field experiment (b) (chemical and mechanical weed control) in sugar beet.

		BBCH-stage of sugar beet	
Treatment	**12**	**14**	**16**
I		untreated control	
II	herbicides broadcast	herbicides broadcast	herbicides broadcast
III	herbicides broadcast	herbicide banding+ hoe	herbicide banding+ hoe
IV	herbicide banding+ hoe	herbicide banding+ hoe	herbicide banding+ hoe
V	herbicide banding + hoe*	herbicide banding + hoe*	herbicide banding + hoe*

*Band sprayer and hoe were performed simultaneously

For mechanical weed control a parallelogram hoe (3 m working width) equipped with goose feet (Einböck, Dorf an der Pram, Austria) was used. At a cultivation depth of 30 - 50 mm and a driving speed of 7 km h^{-1}, a 120 mm wide strip in the crop row was left untreated. The placement of the hoe within the row was steered with the guidance of a camera system (Claas, Harsewinkel, Germany) feedback, with a hydraulic side shift. For the intra-row mechanical application (a) a finger weeder, torsion weeder, rotary harrow and a heap element were used at a cultivation depth of 10-30 mm. For the second experiment in sugar beets (b) an additional band sprayer (Agrotop 80E; 1.7-2 bar spray pressure; 80° spraying angle) instead of intra-row elements was used. Application rates of the herbicide treatments are listed in Table 3.

Table 3: Herbicide dosages and active ingredient composition of the used herbicides at Renningen (RE) and at Gaukönigshofen (GK).

Herbicide rate (L ha^{-1})		**Herbicide information**			
RE	**GK**	**Trade name**	**Formulation**[a]	**Herbicide concentration (g a.i. kg^{-1} or L^{-1})**	**a.i.**
3.75[b]	3.9	Betanal maxxPro	OD	47	desmedipham
				60	+ phenmedipham
				75	+ ethofumesate
				27	+ lenacil
3.75		Goltix Titan	SC	525	metamitron
				40	+ quinmerac
	5	Metafol SC	SC	696	metamitron

[a] Abbreviations: OD = oily dispersion; SC = soluble concentrate.

[b] 60% reduced herbicide and water amount with band spraying.

Experimental design was a randomized complete block design including four replicates with a row distance of 50 cm for all cultivars. At all locations, plot size was 3 x 12 m (6 crop rows for all three crops). Alleys were 10 m wide to allow the tractor with the different implements to reach the desired speed of 7 km h^{-1} for efficient hoeing. An untreated control was included in each block.

2.7.3.1 Experimental setup

2.7.3.1.1 Sugar beet

After the preceding crop (spring barley at RE in 2015, winter wheat at GK in 2015 and triticale at RE in 2016) white mustard (*Sinapis alba* L.) was established as a cover crop, which remained until the sugar beets were sown. At location RE, sugar beets cv. Hannibal, were sown at the 10th and 11th of April in 2015 and 2016. At location GK, sugar beets cv. Artus, were sown at the 17th of March in 2015. 107 000 sugar beet seeds ha^{-1} were sown in 3 cm depth at both locations. Prior to crop emergence 120 kg N ha^{-1}, 62 kg S ha^{-1} and 0.8 kg B ha^{-1} were applied as ammonium-sulphate-nitrate with boron (ass®bor®).

2.7.3.1.2 Maize

After winter wheat harvest, two soil preparations (5 and 15 cm) were performed in 2015 and 2016. Before maize was sown, soil was cultivated with a rotary harrow (8 cm). Maize, cv. Frederico (2015) (FAO class 240) and Liberator (2016) (FAO class 240), was sown at the 27th of April 2015 and the 18th of May 2016, at a seeding rate of 94 000 seeds ha^{-1} in a depth of 4 cm. Prior to emergence, 160 kg N ha^{-1} were applied as calcium ammonium nitrate in both years.

2.7.3.1.3 Soybean

In 2015 and 2016 after winter wheat and barley harvest, fields were ploughed (20 cm) on frozen soil and cultivated twice with a rotary harrow (7 cm) before soybean sowing. Soybean, cv. Sultana, was sown at the 8th of May in 2015 and at the 18th of May in 2016. 64 000 seeds ha^{-1} were sown in a depth of 4 cm. The seeds were inoculated with HiStick® (*Bradyrhizobium japonicum*) directly before sowing. No additional fertilizer was applied in both years.

2.7.3.2 Data collection

Two weeks after the treatments were performed, weed density and weed species composition were determined using a frame (0.5 x 1 m). Crop density was measured in the complete 3rd and 4th crop row. Sugar beets were harvested with a plot harvester (Edenhall 623, Vallakra, Sweden) on 24th and 21st of September in 2015 and 2016, respectively. Plants were washed and white sugar yield (WSY) was measured. Sugar content was calculated according to the standard German procedure (Glattkowski and Märländer 1993). Maize was harvested on 9^{th} of September 2015 and on the 21^{th} of September in 2016 with a 3 row field chopper (Kemper, Stadtlohn, Germany) in an area of 15 m^2. Plant material was dried and weighed. Soybean was harvested with a 1.5 m plot harvester (Zürn 150, Obergurig, Germany) in an area of 15 m^2 at the 12^{th} of October in 2015 and at the 11^{th} of October in 2016.

2.7.3.3 Data analysis

Prior to ANOVA, data on weed density, biomass yield, crop yield were log or square root transformed, if necessary. Data were fitted by a linear model [1], and a multiple comparison test was performed using the Tukey-*HSD* test at a significance level of $\alpha \leq 0.05$. Date were analyzed using R version 3.0.2. The linear model describing the applied setup is:

$$Yijkl = \mu + \alpha j + \beta i + \gamma k + \delta l + (\beta\gamma)ik + (\beta\delta)il + (\gamma\delta)kl + (\beta\gamma\delta)ikl + eijkl \quad [1]$$

where Yijkl describes the yield, crop density and weed density in treatment i, block j, location k and year l, αj is the effect of block j, βi is the effect of treatment i, γk is the effect of location k, δl is the effect of year l, (βγ)ik represents the interaction of treatment i and location k, (βδ)il represents the interaction of treatment i and year l, (γδ)kl represents the interaction of location k and year l, (βγδ)ikl represents the interaction of treatment i, location k and year l and eijkl is the residual error in treatment i, block j, location k and year l. Graphs were performed by SigmaPlot (vers. 12.5, SYSTAT, San Jose, CA).

2.7.4 Results

2.7.4.1 Intra-row mechanical weed control

In this section inter-row treatments with manual steering (MS) and camera steering (CS) were compared with combining the aforementioned treatments with intra-row elements like CS + finger weeder (CFW), CS + torsion weeder (CTW), CS + rotary harrow (CRH) and CS + heap element (CHE) and a broadcast herbicide application (HB) in sugar beet, maize and soybean. In total 15 different weed species were identified in sugar beet, maize, and soybean in 2015 and 2016. The most abundant weed species were common lambsquarter (*Chenopodium album* L.), field penny-cress (*Thlapsi arvense* L.), common chickweed (*Stellaria media* (L.) Vill.) and wild buckwheat (*Polygonum convolvulus* L.).

The highest weed density for all crops averaged over the years 2015 and 2016 was found in the untreated control (UC) with 82, 70 and 43 plants m^{-2} in sugar beet, maize, and soybean, respectively (Figure 1).

In sugar beet, treatment HB reduced weed density by 89% in 2015, compared to UC. Even, treatments HB and CHE (85% weed reduction) differed significantly compared to the other treatments. Treatment CS, CFW, and CTW significantly reduced the mean weed density by 69% compared to the UC. MS reduced weed density by 36% (not significant) compared to UC. In 2016, in treatment HB 5.5 plants m^{-2} were measured. This was significantly lower compared to the other treatments. All in all, mechanical weed control (MS, CS, CFW, CTW, CRH, and CHE) significantly reduced weed density in sugar beet by 80% compared to UC.

In maize, the significantly highest weed control efficacy of 100% was found in treatment HB in 2015. Treatment CFW (12 plants m^{-2}) reduced weed density by 85% compared to the UC and differed significantly to treatment MS (28 plants m^{-2}) and CS (21 plants m^{-2}). In 2016 the lowest weed density in mechanical treatments was observed in CHE (6 plants m^{-2}), which differed significantly to treatments MS (22 plants m^{-2}), CS (18 plants m^{-2}), CFW (18 plants m^{-2}) and CRH (21 plants m^{-2}).

In soybean, differences were insignificant in 2015 across all mechanical treatments. The lowest weed density was observed in CFW (2.4 plants m^{-2}), whereas the highest weed density, of all treated plots, of 4.1 plants m^{-2} was found in CTW. In 2016, HB showed the significantly lowest weed density (1 plant m^{-2}) among all treatments. Taken together, mechanical treatments reduced the mean weed density in soybean by 53% compared to UC.

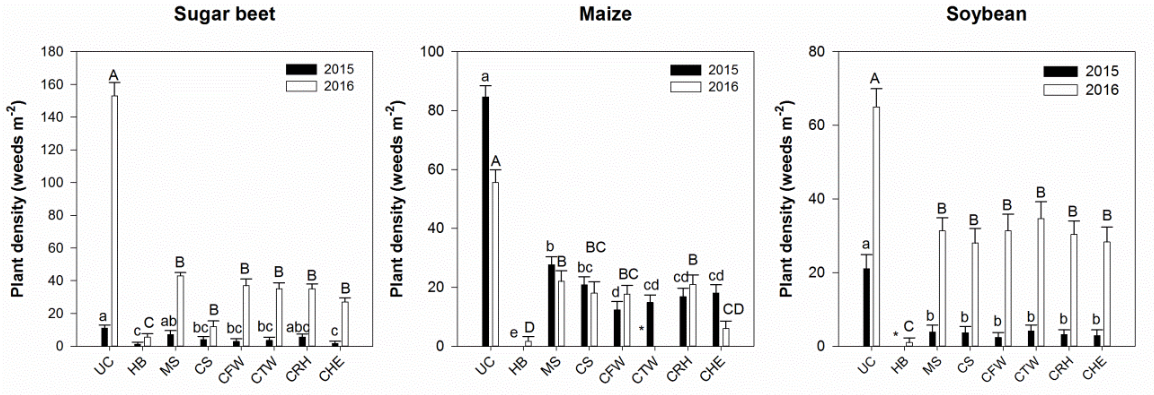

Figure 1: Weed density in sugar beet, maize and soybean counted after the last treatment at Renningen in 2015 and 2016. Means with identical letters within on graph do not differ significantly based on the Tukey HSD-test (p≤0.05). Years 2015 (small letters) and 2016 (capital letters) were separately grouped. Treatments marked with * were not performed in this year.

In 2015 among all treatments and crops no significant differences in the number of crop plants m^{-2} were found after the performance of the weed control treatments (Figure 2). The mean crop density among all treatments was 84% for sugar beet, 86% for maize, and 77% for soybean over both years. In 2016, no differences in crop density were found for sugar beets (84%) and soybean (72%). In maize, however, treatment CRH (73%) was different compared to treatment UC (84%) and HB (86%).

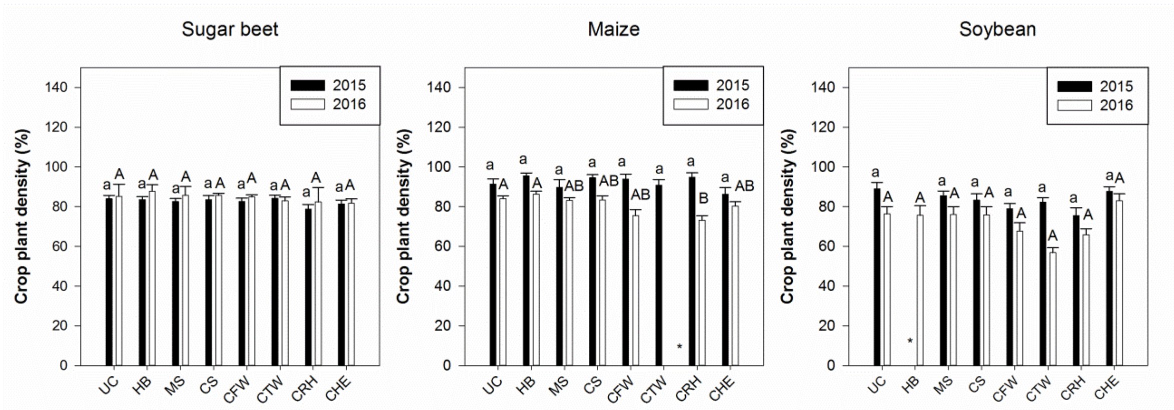

Figure 2: Percentage of mean crop density of sugar beet, maize and soybean plants counted after treatment and prior to crop row closing in Renningen in 2015 and 2016. Means with identical letters within on graph do not differ significantly based on the Tukey HSD-test (p≤0.05). Years 2015 (small letters) and 2016 (capital letters) were separately grouped. Treatments marked with * were not performed in this year.

Yields of sugar beet, maize, and soybean were significantly higher in all treatments compared to UC over both years. In 2015, white sugar yield (WSY) ranged from 6.2 t ha^{-1} in the UC up to 12.4 t ha^{-1} in treatment CFW (Figure 3). WSY was statistically equal among all weed control treatments with an average of 11.91 t ha^{-1}. In 2016, a significant highest WSY was observed in treatment HB with 11.6 t ha^{-1}. For treatments CFW, CTW, CRH and CHE a mean WSY of 9.74 t ha^{-1} was measured. In maize, the highest crop dry matter was yielded in treatment HB with 10.75 t ha^{-1} in 2015. Averaged among all mechanical weed control measurements maize resulted in a 48% lower crop yield compared to HB. No significant differences in maize yield were found in the mechanical treatments. In 2016, all weed control treatments were statistically equal, with a mean yield of 15.46 t ha^{-1}. In soybean, all mechanical treatments have shown no significant differences concerning soybean crop yield in 2015. Yields varied between 2 t ha^{-1} in CHE and 1 t ha^{-1} in UC. In 2016, treatments HB (1.4 t ha^{-1}) and CHE (1.07 t ha^{-1}) showed the highest soybean crop yield, significantly different from the rest of the treatments.

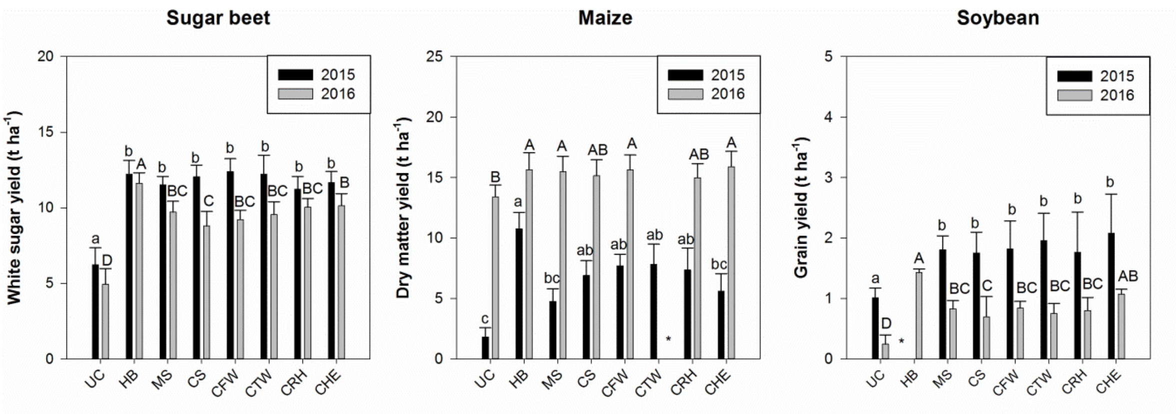

Figure 3: Means of white sugar yield, maize dry matter yield and soybean grain yield (t ha^{-1}) at Renningen in 2015 and 2016. Means with identical letters within on graph do not differ significantly based on the Tukey HSD-test ($p \leq 0.05$). Years 2015 (small letters) and 2016 (capital letters) were separately grouped. Treatments marked with a * were not performed in this year.

2.7.4.2 Combination of chemical and mechanical weed control

A total of 10 weed species at both locations and years were identified. The most abundant weed species observed were common lambsquarter (*Chenopodium album* L.), wild buckwheat (*Polygonum convolvulus* L.) and prostrate knotweed (*Polygonum aviculare* L.). In each of both experiments and years, weed density was highest in treatment 1 (Figure 4) showing noteworthy differences compared to the weed control treatments. In 2015 at location RE, lowest weed density (0.8 plants m^{-2}) was observed in treatment 5 but it was not significantly different to treatment 2 (1.5 plants m^{-2}), treatment 3 (1.3 plants m^{-2}) and treatment 4 (1.1 plants m^{-2}). In 2016, treatment 2 showed the lowest weed density (4.7 plants m^{-2}) at the same location. No significant differences compared to treatment 3 (11 plants m^{-2}), 4 (33 plants m^{-2}), and 5 (14 plants m^{-2}) were found. At location GK in 2015, highest weed control efficacy was found in treatment 3 (2.8 plants m^{-2}). Differences in WSY were insignificant among all weed control treatments and both years. The average WSY of all treatments was 12.7 t ha^{-1} at GK and 14.5 t ha^{-1} at RE. The highest yields were achieved in treatment 4 at GK with 12.9 t ha^{-1} and at RE with 14.8 t ha^{-1}.

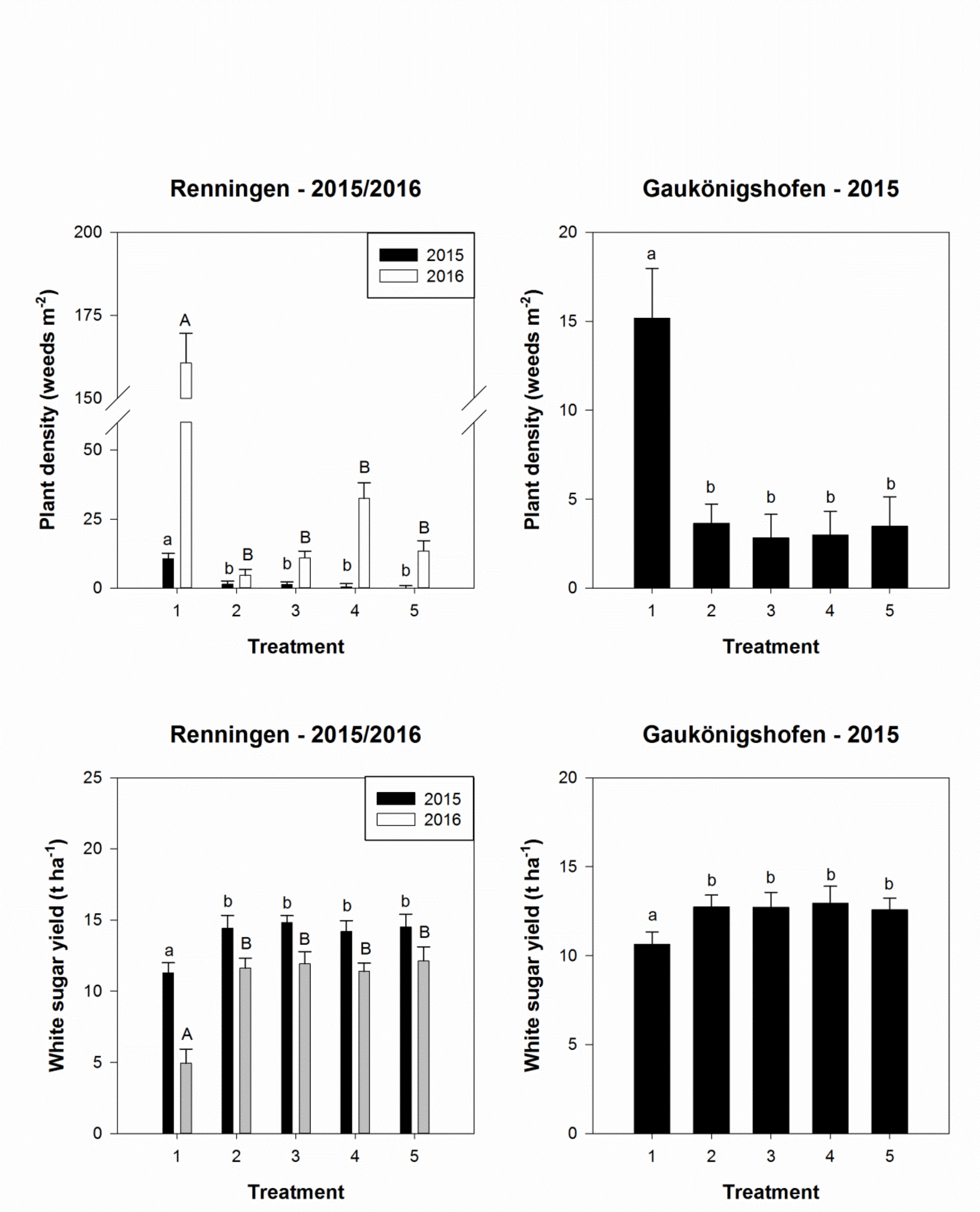

Figure 4: Weed density (weeds m^{-2}) counted after the last treatment and white sugar yield (t ha^{-1}) at Renningen (RE) in 2015 and 2016 and at Gaukönigshofen (GK) in 2015. Means with identical letters within on graph do not differ significantly based on the Tukey HSD-test (p≤0.05). Years 2015 (small letters) and 2016 (capital letters) were separately grouped.

2.7.5 Discussion

The first aim of this two-year study was to investigate the ability of a camera guided hoe for weed control in different row crops. Currently, pesticide use is still a mandatory tool for economic weed control in Germany, as the highest weed control efficacy is still achieved with the use of chemical weed control. The value of chemical weed control is reflected by the high amount of herbicides on the total pesticide use (Gummert et al. 2012). With regard to the increasing awareness of herbicide residues in the environment, intelligent mechanical weed control systems should be implemented to reduce pesticide use. For example, camera guided hoeing systems could reduce the weed density, compared to manual steered hoeing in sugar beet, maize and soybean by precise steering of the hoe in the crop row. This precision provides a reduced amount of intra-row weeds, and an increased driving speed as well as a relief of the operator. Rasmussen (2004) found that hoeing was able to control even high quantities of weeds. Furthermore, labor and machine costs per ha can be reduced up to 20 % in the current study.

In the case of high amounts of intra-row weeds an additional weed control to the goose food treatments in the inter-row area is necessary. In most cases, the used intra-row tools (CFW, CTW, CRH and CHE), showed a higher weed control efficacy compared to MS and CS in all observed crops. Especially, the finger weeder was a successful weed control element in 2015. It offers a high precise intra-row weed control efficacy, but steering becomes crucial. Therefore, using an auto steering system can reduce the burden from the driver. Several studies reported that mechanical intra-row treatments can be as effective as the common herbicide application (Mulder and Doll 1993, Wiltshire et al. 2003, Kunz et al. 2015b). Riemens et al. (2007) observed a weed control efficacy of up to 99% by using finger weeder and torsion weeder. On the other hand, Pannacci and Tei (2014) found a lower weed control efficacy in maize by using the finger weeder (77%). This value was similar to the mean of our study (a) in both years. Mechanical intra-row weeders have shown a limited weed control efficacy in the late weed growth stages (> 6 leaves) in this study. Therefore, intra-row weeding is mandatory at the early weed development stages, especially in the case of monocot weeds. Monocots were less sensitive to uprooted action after mechanical crossing (Pannacci and Tei 2014). Melander et al. (2005) described a higher weed control efficacy as well as higher cost effectiveness by using the torsion weeder compared to the finger weeder, differences in weed suppression when comparing both weeders were insignificant in this study. In the current research the heap element revealed a high weed control efficacy, while requiring a lower driving speed compared to the other hoeing treatments. A speed of 7 km h^{-1} could not be performed, due to the risk of crop burial. The use of a heap element allowed only a speed of 4 km h^{-1}. Moreover, it covered the sugar beet plants with soil. Therefore, harvesting of sugar beets was difficult by this treatment. In 2016, a lower weed control efficacy was observed compared to 2015 in all mechanical treatments. In this specific year detrimental weather conditions prevented an optimum mechanical application. In practice, dry soil conditions, during the crop protection period are a prerequisite, for mechanical weed control treatments. These conditions are not always provided. The inability to achive optimum cultivation conditions for mechanical weed control can pose as a significant drawback and reduces farmers' willingness to invest in non-chemical weed control systems for their farms.

For all experiments, the number of uprooted crop plants was insignificant among most treatments. Only in maize, the rotary harrow showed a significant reduction of plants in 2016. Pannacci and Tei (2014) found similar results for maize, sunflower and soybean plants. Tractor hoeing combined with selective harrowing induced a high weed control efficacy without reducing crop density in the study of Rasmussen and Svenningsen (1995). Kurstjens et al. (2004) proposes that plant anchorage force, which is correlated with crop height, number of leafs and biomass yield, plays an important role for mechanical weeding. The use of a herbicide band spraying in sugar beets was crucial at the first weed control crossing, due to small sugar beet plants with insufficient plant anchorage force for mechanical intra-row weeding at the cotyledon stage. In maize and soybean, no problems occurred.

In the second study (b), we observed a significant herbicide reduction, when mechanical weed control was combined with chemical band spraying compared to a broadcast herbicide application. The use of herbicide band spraying resulted in equal weed control efficacy compared to broadcast herbicide application in sugar beets (McClean and May 1986, Van Zuydam et al. 1995, Wiltshire et al. 2003). This was also found for maize and soybean (Pannacci and Tei 2014), potato (Ivany 2002) and carrot (Main et al. 2013). The implementation of band spraying decreases the use of herbicides and leads to a reduced pollution of the environment. The width of the mechanically untreated strip defines the required herbicide amount for band spraying. Wiltshire et al. (2003) suggested reducing the mechanically treated strip by technical improvements in regard to accuracy, but these improvements mean a higher capital expenditure. Vasileiadis et al. (2016) found that band spraying plus hoeing was economically sustainable at 12 on-farm experiments.

The yield in all crops was increased by all weed control treatments, compared to the untreated control. The mechanical treatments in combination with camera steering and intra-row elements have the potential to produce similar yields to the herbicide treatment, which was shown by the current research. Using intra-row elements have increased the yield, comparing to the manual and camera steering treatments, in all three crops. Yet, they have not achieved the effectives of the herbicide treatment, in both years. The combination of mechanical weed control and chemical herbicide band application have increased WSY compared to the untreated control in all experiments (Kunz et al. 2015a). Therefore, the combination of both mechanical treatments with specialized herbicide applications might be the best way to simultaneously reduce the herbicide input in the field and achieve similar yield outputs.

2.7.6 Conclusion

This work emphasizes the high potential of mechanical intra-row weed control in combination with visual guidance systems with a weed suppression of up to 80% in sugar beet, maize and soybean over a two-year period. Even more, the use of mechanical intra-row tools has shown the finger weeder and the heap element as the most effective mechanical intra-row hoeing tools for reducing weed density. The combined application, of mechanical goose foot hoe plus a chemical band spraying, eliminated weeds in sugar beet completely and reduced herbicide input by 65%. However, the interaction between soil tillage after hoeing and herbicide band spraying, the time of application and their combined weed control efficacy needs further research. The dust produced from the soil tillage possibly negative affects the herbicide application efficacy. Crop yields were significantly increased compared to the untreated control with all weed control treatments. The use of camera guided weed control has shown to be a promising concept to fulfill different national and international programs concerning Integrated Weed Management. As seen in the 2016 date weather conditions can reduce the effectiveness of mechanical weed control. Since mechanical weed control regains an important role in weed management there is a need to improve its effectiveness, even in years where the environmental data hinder its performance.

Furthermore, more work needs to be done in order to have a robust steering framework and to pinpoint the proper application window for automatic steering.

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2.8 Utilization of Chlorophyll Fluorescence Imaging Technology to Detect Plant Injury by Herbicides in Sugar beet and Soybean

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Summary

Sensor technologies are expedient instrument for precision agriculture, aiming for yield protection while reducing operating costs. A portable sensor based on chlorophyll fluorescence imaging was used in greenhouse experiments to investigate the response of sugar beet and soybean cultivars to the application of herbicides. The sensor measured the maximum quantum efficacy yield in photosystem II (PS-II) (F_v/F_m). In sugar beet, the average (F_v/F_m) of 9 different cultivars 1 d after treatment of desmedipham plus phenmedipham plus ethofumesate plus lenacil was reduced by 56% compared to the nontreated control. In soybean, the application of metribuzin plus clomazone reduced F_v/F_m by 35% 9 d after application in 7 different cultivars. Sugar beets recovered within few days from herbicide stress while maximum quantum efficacy yield in PS-II of soybean cultivars was reduced up to 28 d. At the end of the experiment, approximately 30 d after treatment, biomass was reduced up to 77% in sugar beet and 92% in soybean. Chlorophyll fluorescence imaging is a useful diagnostic tool to quantify phytotoxicity of herbicides on crop cultivars directly after herbicide application, but does not correlate with biomass reduction.

Keywords: Chlorophyll fluorescence, crop injury, F_v/F_m, imaging sensor, PS-II, stress detection

3. General Discussion

The target of this thesis was to evaluate different concepts in terms of Integrated Weed Management (IWM), and examine the benefit of different strategies on weed suppression, crop performance and yield characteristics in sugar beets. For this purpose, laboratory, greenhouse and field experiments were conducted. Buhler (2002) suggested various tools and techniques that could be used for IWM. Consequently, to achieve an implementation of these strategies robust demonstrations on the economic sustainability are needed to motivate farmers for their adaption. In this thesis, all 8 articles give an overview on how to improve plant protection in sugar beets aiming a reduced herbicide input. Every journal article can be read independently and each article has already been discussed independently. In this chapter, the main results of the articles are pinpointed and discussed as a general overview of the thesis and prospects for further research are given. The target of IWM is to utilize the provided methods and techniques in their optimum capacities, thus, providing the best feasible short-term outcome, without discounts or compromisations to the long-term productivity and quality of the fields. Based on the results the following strategies for IWM can be derived:

The implementation of i) cover crops (CC) and ii) the resulting mulch residues which can decrease the weed infestation prior to crop establishment, iii) living mulches which can suppress weeds during the crop growth period and iv) precision mechanical weed control which can reduce the herbicide input. Further, v) herbicide applications should be optimized with sensor technologies to identify and reduce herbicide stress on crops.

Prior to sugar beet sowing, successful weed and volunteer crop suppression of up to 90% can be achieved by cultivating CC in autumn (Brust et al. 2014, Kunz et al. 2016b). Kruidhof et al. (2009) described the high potential of the following CC mulch in regard to weed suppression. Different CC mulches have shown early-season weed suppression in different crops (White and Worsham 1990, Reddy 2001). This is due to unfavorable environmental conditions for weeds during the presence of the mulch layer. Additionally, the release of different allelopathic compounds by CC and mulches can reduce weed emergence and survival of the weed seedlings as well (Kruidhof et al. 2008, Bezuidenhout et al. 2012, Nichols et al. 2015). During the cropping season, the use of living mulches can be an integrated tool for weed suppression. Living mulches also reduce weeds due to shading, resource competition and allelopathic interaction

(Ilnicki and Enache 1992, Weston 1996, Hiltbrunner et al. 2007 a,b). CC, mulch management and the use of living mulch can be an expedient device for a noteworthy weed reduction in the early-season of a cultivated crop, but not for full-season weed control. CC cultivation combined with chemical and mechanical methods significantly improved the weed control efficacy in the given studies. From the current thesis, we can conclude that the combination of mechanical weed control, CC and the following CC mulches can be implemented in the agricultural practice, since it provided successful results in all cases. Unfortunately, the combination of mechanical weed control and living mulches is not possible, because mechanical treatments will incorporate the living mulch into the soil.

One interesting observation, derived from the current study is that the use of protective discs mounted on the hoe in the early stage of the crop was beneficial for i) cutting the CC mulch close to the crop proximity and simultaneously ii) not burying the sugar beet with soil. Furthermore, a high precision for an improved effectiveness of mechanical applications is needed. Yet, new developments in Precision Agriculture, can improve the effectiveness of mechanical applications, while possibly presenting them as an alternative to herbicide treatments. Furthermore, accurate steering provides precise hoeing with higher cost effectiveness, which increases labor efficiency and autonomous operations within the field. Lower labor costs may justify the investment in precise steering technologies (Wiltshire 2003, Van der Weide 2008, Peteinatos 2014).

Herbicide reductions are desirable in modern agriculture in order to reduce the chemical burden on the fields, to avoid the evolution of resistant weed populations and to improve the food quality and safety. Yet in modern agriculture herbicide usage is still a necessity. The aforementioned methods of mechanical weeding, CC usage and mulch usage can offer an alternative in some cases and reduce the overall herbicide application, but cannot be proposed as a panacea. Therefore, research on pesticide reduction is crucial, while simultaneously ensuring effectiveness. For a successful weed reduction with concurrent herbicide input reduction in the intra-row area i) herbicide band spraying ii) or an intra-row mechanical application is needed. Vasileiadis et al. (2016) described i) band spraying plus hoeing as an economically sustainable tool for farmers. The use of chemical band spraying resulted in equal weed control efficacy compared to an overall herbicide application in the given research. The weeds, nearest to the crop plants present the highest challenge for ii) mechanical treatments and they can directly influence the crop performance. The operation of intra-row mechanical weed control (Bowman 1997, Van der Weide 2008) can simultaneously be used in conjunction with inter-row mechanical crossing at a similar speed. By using this mechanical application, the crop needs to be more robust than the weeds to ensure a high weed control efficacy without damaging the crop. The tested mechanical intra-row tools resulted in a similar weed control efficacy compared to an overall herbicide application in some years. Nevertheless, the use of a chemical band spraying in sugar beets was crucial at the first weed control treatment, due to small sugar beet plants in the cotyledon stage with lacking plant anchorage force for mechanical intra-row weed control. Furthermore, mechanical weed control is very time consuming, cost intensive and less area efficient compared to an overall chemical herbicide application (Van der Weide et al. 2008). Moreover, the flexibility of the mechanical application is reduced due to the dependency on dry field conditions (Kurstjens and Kropff 2001). Vasileiadis et al. (2016) observed new emerging weeds due to the favorable weed growing conditions after hoeing. This was not found for this research. Furthermore, some of the CC mulch residues were incorporated into the soil after mechanical hoeing. The risk of soil erosion may increase after mechanical application and consequently reduce the positive effects of mulch. The mentioned limiting conditions for mechanical weed control can reduce the farmers' motivation to invest in these systems.

Up to now, the use of herbicides in sugar beet cultivation has been and is still a pre-requisite for an economical and sustainable sugar yield production. The reliance on herbicides can be demonstrated by the total herbicide use in Germany (Gummert et al. 2012). Since the herbicide use is mandatory, a method of monitoring the herbicide results, not only on the weeds but also on the crop, is necessary. Fast and precise herbicide damage evaluation is a fundamental key for the comparison of different herbicides and cultivars as well. The use of sensor technology can help to estimate the correct time for herbicide application and can evaluate the most suitable herbicide mixtures, actual weather conditions and crop cultivars. The utilized sensor in this study was considered as an initial investigation to identify herbicide stress in sugar beets by using a mobile chlorophyll imaging sensor. The results revealed that the sensor is indeed suitable for the investigation of herbicide stress in crops. Sugar beets typically show reduction in their photosystem activity directly after herbicide application (Smith and Schweizer 1983, Voss et al. 1984, Wilson 1999, Starke and Renner 1996, Abbaspoor and Streibig 2007).

The success for the implementation of IWM in sugar beets highly depends on the interaction and balance of the presented chemical, mechanical, biological and sensor guided approaches. CC and following mulches, if they are properly and well established, can help in the reduction of the weed population. This can result in less herbicide treatments, but not their complete replacement. Mechanical weed control has improved with the implementation of precision farming. The applications can be performed faster and closer to the crop with less effort and time of the operator. For weed control in the inter-row area, studies have to focus on how much precision is needed to gain a maximum of weed control efficacy. Cameras should be able to validate differences between crops and weeds to steer the hoe with a well-engineered algorithm as close as possible to the crop. Up to now, there have been different approaches available, but no machine has been able to compete with the overall herbicide application under all field conditions. Yet, the low weed tolerance of the sugar beet cultivation cannot be achieved with mechanical applications, only. Herbicide use is imperative, but the effect of the herbicides on the crop should also be monitored. For a successful implementation, an interdisciplinary use of the obtained results is crucial.

Summary

Weed control is one of the major challenges in sugar beet (*Beta vulgaris*) production worldwide. Due to the high flexibility and low costs, herbicide applications are the common agricultural practice for successful weed control. Yet, due to European and national restrictions, farmers are forced to substitute their herbicide input in order to reduce the chemical influence on the environment. Beside chemical weed control systems, integrated weed management (IWM), can be an alternative, to reduce the chemical preponderance. The five essential parts in composing a successful IWM system are: i) cover crops (CC) and ii) resulting mulch residues which can decrease the weed infestation prior to the actual crop establishment, iii) living mulches which can suppress weeds during the crop growth period and iv) precision mechanical weed control which can provide herbicide reductions. Last but not least v) herbicide applications should be optimized with sensor technologies to identify and reduce stress on crops. In the current study, all the named aspects of IWM were examined in sugar beets. In order to accomplish that, the following research objectives were investigated and answered in the course of the papers composing this thesis:

- Evaluation of the suitability of CC and CC mixtures for weed suppression prior to sugar beet sowing
- Assessment of differences in sugar beet emergence, weed control and biomass under different CC mulches
- Application of living mulches and measurement of their weed control efficacy during the sugar beet growth period
- Evaluation of mechanical weed control along with chemical band spraying compared to an overall herbicide application
- Determination of the weed control efficacy of mechanical weeding by using visual sensors and GNSS-RTK
- Investigation of the feasibility of intra-row mechanical weed control, its prerequisites and limitations
- Detection of responses to herbicides by using chlorophyll fluorescence imaging technology

1st paper: Field and laboratory experiments were conducted to investigate the competitive and biochemical weed suppressive ability of CC. Applied aqueous CC extracts in germination tests inhibited weed growth and potential allelochemicals were identified. In the field all CC either in mixture- or mono-cultivation were able to suppress weeds compared to an untreated control by 66%. **In the 2nd and 3rd paper** sugar beet plant emergence was investigated in greenhouse and field experiments, in order to evaluate the influence of various CC mulches on weed suppression. Different CC mulches reduced weed germination successfully. During one dry growing season sugar beet emergence was enhanced by increased soil moisture due to the existence of a CC mulch layer compared to uncovered soil. Our findings suggest that CC mulch layers can substantially effect crop and weed development within the field. To assess the weed suppressive ability of living mulches in sugar beets, field studies were carried out at four sites in southern Germany, presented in the **4th paper**. Results show that living mulches can reduce the total amount of different weed species in the inter-row area up to 71%. The white sugar yield was increased in average by 42% with the existence of living mulch as compared to the untreated control. **In the 5th, 6th and 7th paper** sensor technologies were used for mechanical weed control combined with chemical band application to reduce the herbicide input, with similar weed control results to the overall chemical application. Sensor based, mechanical precision steering technologies, reduced weeds more effectively than when compared to manual operator guidance. This is due to accurate fast driving speeds close to the crop area. Intra row elements (finger weeder, rotary harrow, torsion weeder, heap element) for mechanical weed control showed effective weed suppression. Nevertheless, suitable soil and weather conditions for mechanical weed control were not always given, which can result in an efficacy loss. Finally, **in the 8th paper**, a portable sensor, based on chlorophyll fluorescence imaging, was used in greenhouse experiments to investigate the response of plants after herbicide application. Various active ingredients have shown different damage concerning the photosystem II. The use of this sensor can quantify phytotoxic effects due to herbicides and can help to find the most suitable herbicide application date, active ingredients or herbicide mixture.

The overall result of this dissertation reveals the great potential of CC, living mulches, precision mechanical methods and sensor technologies as part of an IWM system in sugar beet production.

Zusammenfassung

Eine effektive Unkrautkontrolle in der Zuckerrübenproduktion (*Beta vulgaris*) bedeutet für den Landwirt eine große Herausforderung. Aufgrund der hohen Flexibilität und den geringen Kosten stellt die mehrfache Herbizid-Applikation die gängigste Methode dar, um eine erfolgreiche Unkrautkontrolle zu betreiben. Der zunehmende politische Druck auf die deutsche Landwirtschaft - in Form von europäischen und nationalen Auflagen - soll den Eintrag von Pflanzenschutzmitteln in die Umwelt reduzieren. Integrierte Pflanzenschutz-Maßnahmen (IPM) können neben der rein chemischen Unkrautkontrolle eine sinnvolle Alternative darstellen. Zu einem erfolgreichen IPM-System gehören alternative Verfahren wie i) Zwischenfruchtanbau (ZF) und ii) der daraus resultierende Mulch, welcher den Unkrautdruck reduzieren kann, bevor die Kultur etabliert wird. Des Weiteren können iii) Untersaaten die Unkräuter während der Wachstumsperiode der Kultur unterdrücken. Der Einsatz von iv) präziser, mechanischer Unkrautkontrolle kann zu einer Reduktion von Herbiziden führen. Abschließend kann v) durch den Einsatz von Sensor-Technologie die Herbizid-Applikation optimiert werden, um einen Stress an der Kultur zu reduzieren. In der vorliegenden Studie wurden die aufgelisteten Aspekte des IPM in Zuckerrüben geprüft. Folgende Zielsetzungen wurden im Rahmen verschiedener Veröffentlichungen dieser Arbeit untersucht und beantwortet:

- Evaluation von Zwischenfrüchten und Zwischenfruchtmischungen zur Unkrautunterdrückung vor der Zuckerrübenaussaat
- Bewertung von Zwischenfruchtmulch auf das Auflaufen und die Biomasse der Zuckerrüben sowie die Verunkrautung vor der ersten Herbizidapplikation
- Anwendung von Untersaaten in Zuckerrüben zur Unkrautunterdrückung
- Eignung von mechanischer und chemischer Unkrautkontrolle im Vergleich zur rein chemischen Applikation
- Bewertung von kameragesteuerter Hacke und GNSS-RTK in Bezug auf die Unkrautunterdrückung in Zuckerrüben
- Prüfung von mechanischen Hackelementen auf ihre Anforderungen und die limitierte Wirkung in der Zuckerrübenreihe
- Erkennung von Herbizidstress an Zuckerrüben mit Hilfe bildgebender Chlorophyllfluoreszenz-Messung

Erste Veröffentlichung: Es wurden Feld- und Laborversuche durchgeführt, um die kompetitive und biochemische Unkrautunterdrückung von ZF zu quantifizieren. Die applizierten ZF-Extrakte hemmten in Keimfähigkeitstests das Unkrautwachstum. Weiter wurden potentielle allelopathische Substanzen chemisch-analytisch identifiziert. In den Feldversuchen konnten alle Zwischenfrüchte sowohl in Misch- als auch in Reinkultur das Unkrautpotential um bis zu 66% im Vergleich zu einer unbehandelten Kontrolle reduzieren. In der **zweiten und dritten Veröffentlichung** wurde der Einfluss von verschiedenen ZF-Mulchen in Bezug auf die Unkrautunterdrückung und die Entwicklung von Zuckerrübenpflanzen im Gewächshaus sowie in Feldversuchen bewertet. Die verschiedenen ZF-Rückstände konnten die Unkrautkeimung erfolgreich reduzieren. Während eines trockenen Anbaujahres konnte durch die ZF-Mulchschicht ein schnellerer Zuckerrübenfeldaufgang im Vergleich zu fehlender Bodenbedeckung ermittelt werden. Die vorliegenden Ergebnisse stellen die Bedeutung von ZF-Mulch in Bezug auf die Unkrautbekämpfung und Kulturentwicklung im Feld dar. Die Unkrautunterdrückung mit Untersaaten zwischen den Zuckerrübenreihen wurde an vier Standorten in Südwestdeutschland in der **vierten Veröffentlichung** getestet. Diese Ergebnisse zeigen, dass Untersaaten die Gesamtverunkrautung zwischen den Reihen um bis zu 71% reduzieren konnten. Der bereinigte Zuckerertrag konnte im Vergleich zur unbehandelten Kontrolle durchschnittlich um 42% erhöht werden. In der **fünften, sechsten und siebten Veröffentlichung** wurde die Kombination von mechanischer Unkrautkontrolle ergänzend mit einer chemischen Bandapplikation zur Herbizid-Reduktion untersucht und ergab einen ähnlichen Unkrautbekämpfungserfolg wie eine ganzflächige, chemische Applikation. Ebenso wies die sensorgesteuerte Reihenhacke ein geringeres Unkrautaufkommen als die manuelle Traktorsteuerung auf. Dies wurde der exakteren Spurführung aufgrund der Sensorsteuerung zugeschrieben. Mechanische Hackelemente in der Reihe (Fingerhacke, Rollstriegel, Torsionsstriegel und Häufelschar) zeigten ebenso eine effektive Unkrautbekämpfung. Allerdings waren für mechanische Unkrautbekämpfungsmaßnahmen nicht immer optimale Witterungsbedingungen gegeben, was zu Wirkungsverlusten führte. In der **achten Veröffentlichung** wurde ein portabler Sensor, basierend auf bildgebender Chlorophyllfluoreszenz-Messung, eingesetzt, um unterschiedliche Herbizid-Verträglichkeiten der Zuckerrüben zu messen. Verschiedene aktive Wirkstoffe zeigten unterschiedliche Stressreaktionen im Photosystem II. Mit Hilfe dieses Sensors können zukünftig phytotoxische Effekte nach einer Herbizidapplikation quantifiziert und bewertet werden. Somit können sowohl der bestmögliche Applikationszeitpunkt als auch der optimale Wirkstoff bzw. die ideale Wirkstoffmischung ausgewählt werden.

Zusammenfassend weist diese Dissertation ein großes Potential von ZF, Untersaaten, präziserer mechanischer Unkrautkontrolle und Sensoren als Bestandteil von IPM in der Zuckerrübenproduktion nach.

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