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A study of integrated weed control strategies for establishing soybean (*Glycine max* L. Merr.) in the German production system

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1. General Introduction

Soybean (*Glycine max* (L.) MERR.) in 2016, was cultivated in 120 million hectares worldwide and it is one of the most frequently traded agriculture products. Only the last 5 decades, there is an increase of the global consumption by 234 million tonnes (Garrett et al. 2013). This increase can be explained by the multiple uses of soybean, including as a vegetable oil, biofuel and protein source in livestock feed (Boerema et al. 2016). Additionally, soybean plays an important role in the diet of humans worldwide and has the potential to fill the gap in protein nourishment in the near future (Hartman et al. 2011). The global soybean market is primarily supplied by the USA, Argentina and Brazil which account for 81% of global soybean production (Hartman et al. 2011). Europe is one of the major importers of soybean, which has shown a strong increase over the last 50 years. This increase has led to negative ecological and socio-economic effects and reduced natural capital in the production countries because of permanent losses of important ecosystems (Boerema et al. 2016). An increase in local soybean production could reduce these negative effects and increase protein self-sufficiency in Europe. For successful soybean cultivation, cultivars must be adapted to European climates. The genetic diversity and population structure of Canadian lines are a suitable match to European conditions and can be used as the basic starting material (Hahn and Würschum 2014). Breeding programmes have produced several registered cultivars for the European market in the last ten years. In addition to environmental conditions, weeds are a major detriment to soybean yield, although they can be controlled directly by chemical or mechanical treatments or indirectly by agricultural practices, such as crop rotation and soil tillage (Oerke 2006). The main weed species in European soybean fields are *Echinochloa crus-galli* (L.), *Chenopodium album* (L.), *Amaranthus retroflexus* (L.) and *Solanum nigrum* (L.) (Schroeder et al. 1993).

The use of herbicides can lead to a weed control efficacy of up to 99% and is therefore the most effective weed control measure (Foster et al. 1993). However, a few herbicides are registered for soybean in Germany; thus, specific herbicides may not be applicable for farmers engaged in soybean production (Gehring et al. 2014). Although the weed spectrum can be effectively controlled by a single application or a combination of different herbicides (Gehring et al. 2014). Herbicides can result in crop injury, crop damage and reduced crop yield when used at inappropriate rates or times or in mixtures with several active ingredients (Salzman and Renner 1992). Additionally, different cultivars have different specific tolerance levels to herbicides (Smith and Wilkinson 1974, Friesen and Wall 1986, Salzman and Renner 1992). Testing systems have been used to evaluate cultivars as a prerequisite for US market registration, and crop injury can be evaluated visually or by measuring the height, biomass and yield (Barrentine et al. 1976, Ladlie et al. 1976, Barrentine et al. 1982). However, visual estimations are subjective and not comparable to the results of other experiments (Andújar et al. 2010). Measurements of certain parameters, such as biomass, leaf area index, plant height and yield, occur late in the season and are time intensive. Sensor technologies are a helpful tool for evaluating plant health objectively, rapidly and early in the season. A number of sensors can detect crop injury via spectral analyses of the fluorescence excitation of plants (Brown and Noble 2005, Peteinatos et al. 2014). The new cultivars registered for the European market have not been thoroughly tested for herbicide tolerance, although certain cultivars have shown crop injury, particularly when exposed to the active ingredient metribuzin (Petersen 2014). Sensor-based screening of the cultivars to evaluate their tolerance levels would be helpful for preventing yield losses.

An alternative to the use of herbicides is the mechanical control of weeds. Different mechanical technologies have been used historically (Evans 2010). Harrowing, hoeing, horizontal and vertical rolling elements and flaming are examples of mechanical weeding methods (Bowman 1997). Hoeing leads to high weed control efficiency, particularly in the inter-row area, and it also lowers the risk of crop damage relative to harrowing (Dierauer and Stöppler-Zimmer 1994, Lötjönen and Mikkola 2000). However, weeds in the intra-row area are not sufficiently controlled by hoeing, and additional tools, such as harrow implements, finger weeders and torsion weeders, offer promising opportunities to resolve this problem (Van der Weide et al. 2008). Furthermore, precision steering technology (e.g., RTK-GNSS or camera steering systems) could be used to improve the accuracy of the intra-row elements and increase the effective weed control in the intra-row area while simultaneously reducing the risk of crop damage (Van der Weide et al. 2008).

In European soybean cropping systems, soil tillage is commonly performed. Soil tillage with a conventional plough is cost intensive and time consuming, and further negative effects include damage to the soil structure, reduction of water infiltration, increased risk of soil erosion and damage to the soil community (Gebhardt et al. 1985). Therefore, the amount of no-tillage soybean cropping area has increased in the major soybean-producing countries in recent decades (Hartman et al. 2011). In no-tillage systems, the input of non-selective herbicides has increased (Osteen et al. 2012) and results in the occurrence of herbicide-resistant weed species (Vila-Aiub et al. 2008). Cover crops can reduce the number of weeds during the non-productive period between two cash crops and have the potential to inhibit weed growth by releasing biochemical substances (Kunz et al. 2016). Cereal rye (*Secale cereale* L.) is often used as a cover crop before soybean cultivation because of its rapid development, high biomass production, and allelopathic potential (Reberg-Horton et al. 2005, Mirsky et al. 2009). However, cover crops must be controlled to prevent them from becoming a weed in the main crop. To avoid the need for non-selective herbicides, cover crops can be controlled mechanically using a roller-crimper (Ashford et al. 2000). Less information is available on no-tillage soybean cropping systems based on cover crops under European conditions.

1.2. Objectives of the thesis

The objectives of this thesis were to (i) detect crop injury by herbicides on different soybean cultivars using a chlorophyll fluorescence imaging sensor, (ii) evaluate the efficiency of chemical and mechanical weed control strategies, (iii) examine the benefits of precision farming technologies for mechanical weed control in the inter- and intra-row areas and (iv) investigate tillage, reduced tillage and no-tillage systems based on cover crops for their weed suppression efficiency in soybean.

1.3. Structure of the thesis

This work presents three papers published in the peer-reviewed journal *Weed Technology, Agronomy* and *Agriculture* and one review paper, published in *Julius-Kühn-Archiv*.

The first section presents the paper is titled “Utilization of Chlorophyll Fluorescence Imaging Technology to Detect Plant Injury by Herbicides in Sugar beet and Soybean” and was published in the journal *Weed Technology* and describes a new chlorophyll fluorescence imaging sensor to detect crop injury in soybean and sugar beet.

The second paper is titled "Chemical and mechanical weed control in soybean (*Glycine max*)" and was published in *Julius-Kühn-Archiv*, and it provides an overview of the efficiency of chemical and mechanical weed control in soybean under German cropping conditions.

The third paper is titled "Benefits of Precision Farming Technologies for Mechanical Weed Control in Soybean and Sugar Beet - Comparison of Precision Hoeing with Conventional Mechanical Weed Control" and was published in the journal *Agronomy*, and it describes precision farming technologies for mechanical weed control in the inter- and intra-row areas as well as conventional mechanical weed control methods in soybean production.

The fourth paper is titled "Weed Control Using Conventional Tillage, Reduced Tillage, No-Tillage, and Cover Crops in Organic Soybean" and was published in the journal *Agriculture*, and it presents the effect of different tillage systems on weed and soybean density as well as the impact on crop yield.

2. Publications

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

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Abstract

Sensor technologies are useful tools 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). Cultivars of both crops had a varied reaction on herbicides. In sugar beet, the average F_v/F_m of 9 different cultivars 1 d after treatment of desmedipham + phenmedipham + ethofumesate + lenacil was reduced by 56% compared to the nontreated control. In soybean, the application of metribuzin + 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 significantly 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 beneficial diagnostic tool to quantify phytotoxicity of herbicides on crop cultivars directly after herbicide application.

Nomenclature: Desmedipham; ethofumesate; flufenacet, N-(4-fluorophenyl)-N-(1-methylethyl)-2-[[5-(trifluoromethyl)-1,3,4-thiadiazol-2-yl]oxy]acetamide; lenacil; metamitron; metribuzin; phenmedipham; soybean, *Glycine max* (L.) Merr.; sugar beet, *Beta vulgaris* (L.) ssp. *vulgaris*.

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

2.2. Chemical and mechanical weed control in soybean (*Glycine max*)

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Abstract

In this study we investigated the possibility of chemical and mechanical weed control strategies in soybean. Soybean field experiments were conducted in 2013 and 2014 in Southern Germany. Five treatments including common herbicide mixtures and four mechanical weed control treatments, implementing a harrow and a hoe, were tested at different locations. In the herbicide experiments two treatments were applied by PRE emergence herbicides (Metribuzin, Clomazone, Dimethenamid and Metribuzin, Flufenacet, Clomazone) and another two treatments were sprayed with a combination of PRE + POST emergence herbicides (Metribuzin, Flufenacet, Thifensulfuron and Pendimethalin, Thifensulfuron, Bentazon, Cycloxydim). Furthermore, a POST herbicide treatment was implemented (Thifensulfuron, Bentazon, Thifensulfuron, Fluazifop-P-butyl). In the mechanical weed control experiments, treatments were: three times hoeing, PRE emergence harrowing plus three times hoeing, hoeing and harrowing in rotation or three times harrowing. In both experiments an untreated control was included. A 90% weed control efficacy and 23% yield increase was observed in the POST herbicide treatment. PRE + POST treatments resulted in 92% to 99% weed control efficiency and 15% yield increase compared to the untreated control. In the mechanical weed control experiments the combination of PRE emergence harrowing and POST emergence hoeing resulted in 82% weed control efficiency and 34% higher yield compared to the untreated control. Less weed control efficiency (72%) was observed in the harrow treatment, leading to 20% higher yield compared to the control.

The suitability of both strategies for implementation in “Integrated Weed Management” has been investigated.

Keywords: Harrowing, herbicide, hoeing, soybean, weed control efficacy.

2.3. 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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Abstract

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 carried out 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

2.4. Weed Control Using Conventional Tillage, Reduced Tillage, No-Tillage, and Cover Crops in Organic Soybean

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Abstract

Soybean field experiments in organic and conventional cropping systems were conducted to investigate the weed suppressing effects of different tillage systems and cover crop mulches at two locations in South West Germany during 2014 and 2015. The influence of three different tillage systems on weed control efficacy, soybean plant density and crop yield was examined. In the no-tillage system (NT), two different cover crops (rye and barley) were treated by a roller-crimper before soybean sowing. For the reduced tillage system (RT) shallow soil cultivation (7.5 cm depth) using a cultivator after cover crop harvest was performed, while the third system was conventional tillage (CT) with a plough (25 cm depth) without previous cover crops. Finally, CT system without weed control was used as control treatment (C).

Weed densities in the field experiments ranged from 1 to 164 plants m^{-2} with *Chenopodium album* (L.), *Echinochloa crus-galli* (L.) P. Beauv. and *Sonchus arvensis* (L.) as predominant weed species. No significant difference was found between the two cover crops. Highest cover crop soil coverage was measured in the NT treatment. Highest weed density (164 plants m^{-2}) was measured in the untreated control. CT, RT and NT reduced weed density up to 71%, 85% and 61% respectively, across both locations and years. Soybean plant density was reduced in NT (-36%) compared to CT (-18%). Highest crop yields up to 2.4 t ha^{-1} were observed in RT. Our work reveals the importance of cover crops for weed suppression in soybean cropping systems without herbicide application.

Keywords: Cover crop barley (*Hordeum vulgare* L.), cover crop rye (*Secale cereale* L.), conservation tillage, roller-crimper, soybean (*Glycine max* (L.) Merr.), organic no-tillage systems.

3. General Discussion

In this thesis, weed control strategies for local soybean (*Glycine max* (L.) MERR.) cultivation are presented and analysed. This chapter is structured into three main sections:

- detection and evaluation of crop injury after herbicide application
- mechanical weed control strategies in soybean
- different cultivation strategies (tillage, reduced tillage and no-tillage) for weed control in soybean.

The main outcomes of the field and greenhouse experiments are discussed, and an overview of future prospects is given.

3.1. Detection and evaluation of crop injury following herbicide application

The results of Section 2.1. are based on the Imaging PAM sensor, which is a useful instrument for evaluating photosystem II (PS-II) activity via measurements of the maximum quantum chlorophyll fluorescence. Crop injury can be detected by the PAM sensor before visual symptoms appear. The cultivars ‘Solena’, ‘SY Eliot’ and ‘Gallec’ were identified as tolerant to metribuzin, dimethenamid and clomazone. The ‘ES Mentor’ and ‘Sultana’ cultivars were sensitive to metribuzin but tolerant to dimethenamid and clomazone (Section 2.1.). The active ingredient metribuzin results in crop injury to different cultivars (Smith and Wilkinson 1974, Friesen and Wall 1986, Salzman and Renner 1992). In the USA, cultivars were screened through the mid-1990s for their sensitivity to metribuzin to produce a list of cultivars that are sensitive to specific metribuzin concentrations. With respect to herbicide sensitivity, cultivar-specific metabolism or degradation was found to be the reason for different tolerance levels (Smith and Wilkinson 1974). The screening of all cultivars permitted on the European market would be advisable because of different tolerance levels of the cultivars. Furthermore, the parameter “herbicide tolerance” should be included in the breeding process.

The active ingredients dimethenamid and clomazone caused less or no crop injury in the tested soybean cultivars (Section 2.1.). However, whether the active ingredients that do not react in the PS-II system can be detected by measuring PS-II activity remains unclear. In the study of Riethmuller-Haage et al. (2006), herbicide stress by ALS inhibitors on weeds could be identified by measuring the chlorophyll fluorescence shortly after herbicide application, which indicates that other modes of action (e.g., ALS inhibitors) in addition to PS-II inhibitors can be detected by measuring PS-II activity. However, whether the full stress effect can be quantified by this indirect measurement remains unclear. In the German market, pendimethalin is permitted and used by farmers. In future research, pendimethalin should be tested because of the sensitivity of certain cultivars as indicated by field experiments in the ‘common field trails Baden Württemberg’ from 2010 to 2015 (Gerhards 2015).

In this study, the Imaging PAM sensor was evaluated and found to be a robust tool for detecting plant injury by herbicides. However, certain limiting technical factors must be addressed. To measure the maximum quantum chlorophyll fluorescence, the sensor must detect the zero fluorescence level. Therefore, plants must be dark-adapted for at least 20 minutes before the maximum quantum yield can be measured (Kaiser et al. 2013). The requirement to cover the plants makes the measurements time intensive. Furthermore, the activity of PS-II can also be affected by other stress factors, e.g., nutrient deficiency, water stress and fungal infestation. Therefore, an untreated control plant must be used as a reference to evaluate the outcome. To improve the sensor system, these parameters should be evaluated and included in the system. The effect of these parameters can be considered during measurement to avoid the need for an untreated control plant. Furthermore, the sensor can be used to detect other stress factors because of their indirect impact on PS-II activity. Further research should be performed on these stress factors (e.g., nutrient deficiency, water stress or fungal infestation) as well as on other crops to identify injury from herbicides.

3.2. Mechanical weed control strategies in soybean

For successful mechanical weed management, (Bowman 1997) described three important factors. First: generate perfect growth conditions for the crops. Second: suppress weeds and keep them at a disadvantage. Third: accept weeds that do not negatively influence crop yield. To fulfil the second point, different mechanical technologies have historically been used (Evans 2010). Harrowing, hoeing, horizontal and vertical rolling elements and flaming are examples of mechanical weeding methods (Bowman 1997). Many adaptations and refinements of these techniques and tools have been developed and are currently on the market. The tools can be separated into two groups based on their area of application: the inter- and intra-row areas. In Section 2.2., harrowing (inter- and intra-row) and hoeing (inter-row) were investigated. Both techniques are well-known methods for mechanical weed control but have not been evaluated for weed control in soybean under German conditions.

Harrowing is effective before the two-leaf stage in dicot weeds and during the one-leaf stage in monocot weeds (Van der Weide et al. 2008). Therefore, pre-emergence harrowing is an effective strategy as shown in the results in Section 2.2.. To prevent crop damage, the working depth of the harrow tools should be no deeper than 2-3 cm and although the crop seed can have reached germination, it should not be past crop stage BBCH 04 (Van der Schans et al. 2006). In practise, depending on the weather and soil conditions, pre-emergence harrowing is a delicate, time-sensitive method of controlling weeds and characterised by a short time frame (Bowman 1997). Directly after emergence, soybean is sensitive to harrowing; however, later in the growth stage (> BBCH 11), crops are robust and post-emergence harrowing can be performed. In the experiments in Section 2.2., pre- and post-emergence harrowing reduced weed density and increased yield compared with the untreated control. Weed control efficacy and crop yield were slightly reduced compared with other mechanical strategies. Higher weed competition, damage to the leaf, and plant loss can explain the yield loss caused by harrowing. The impact on crop plants could be mitigated by increasing the sowing density of the soybean. Based on the high working speed and area efficiency, harrowing is an interesting tool for mechanical weed control for local soybean production.

Van der Weide et al. (2008) reported effective weed control in the inter-row area using hoeing implements. Inter-row hoeing has a low risk of crop damage if appropriate steering is performed. However, the development of the crop must be past BBCH 10 to identify the crop rows. Weeds located in the intra-row area will be not controlled as demonstrated in this thesis (Sections 2.2. and 2.3.), and there is a high potential for yield loss (Van der Weide et al. 2008). Depending on the driving speed and modality of the hoeing implements, soil can be moved into the crop row to cover the weeds. However, crops also become covered by loose soil, particularly during the first treatment. Covering crops with soil in the early developmental stages often results in a high reduction in plant numbers, e.g., in sugar beet. Conversely, in the experiments of this thesis, soybean showed good performance after it was covered by soil, even at an early growth stage (Section 2.3.).

Intra-row elements, such as torsion weeders, finger weeders and rotary hoes, represent additional options for controlling weeds in the intra-row area (Bowman 1997, Van der Schans et al. 2006). The weed control efficiency of torsion weeders strongly depends on the soil conditions. These tools work best in loose soil. Under compacted soil conditions, the elements are not able to penetrate beneath the soil surface (Cloutier et al. 2007). Additionally, soybean must be developed beyond growth stage BBCH 11 to avoid crop damage. Finger weeders are a well-known tool to control weeds in the intra-row area in vegetables, and they result in increased weed control in soybean cultivation (Section 2.3.). Finger weeders are more effective than torsion weeders against weeds at the two-leaf stage; however, the use of both weeders is suggested for small weed plants to ensure efficient removal (Cloutier et al. 2007, Van der Weide et al. 2008). The rotary hoe removes small and large weeds from the intra-row area and can be used under compacted soil conditions. Depending on the adjustment and driving speed, uprooting of soybean or damage to the leaves may occur (Buhler et al. 1992).

The disadvantage of these tools compared with harrowing is the need for precision steering to work close to the plants without causing crop damage (Van der Weide et al. 2008). Different technologies, such as RTK-GNSS, ultrasonic technology and camera systems, allow steering close to the crop row. In Section 2.3., the effect of an intra-row tool (finger weeder) steered by RTK-GNSS and a camera guiding system with a moveable frame was investigated. Both systems worked reliably in the experiments, although increased accuracy in the weed control efficiency compared with manual steering was not observed. However, the systems provide relief to the driver and enable extended working periods, which can result in increased efficiency. When using RTK-GNSS, the parallelism of the rows provides the option of hoeing independently of the sowing working width, which further can increase the working efficiency. Additionally, pre-emergence hoeing may suppress weeds in the early growth stages. The driving speed, working period and precision can be improved using automatic steering systems, thus indicating that hoeing is an effective treatment for weed control in soybean.

3.3. Different cultivation systems for weed control in soybean

The experiments presented in Section 2.4. demonstrate higher crop yields in the tillage and reduced tillage systems compared with the no-tillage system. Soil cultivation led to an increased emergence rate of soybean and resulted in a relatively higher yield in the tillage and reduced tillage systems. However, for both systems, additional weed control by hoeing was necessary to avoid yield losses. The no-tillage system based on cover crops has high weed suppression potential, particularly for the summer annual weed species. By integrating cover crops in crop rotation, the field is permanently covered by living plant material, which builds a green bridge between the previous main crop and soybean. Additionally, reduced nutrient losses, runoff and erosion, and increased soil organic matter and improved soil structure can be achieved by using cover crops (Freibauer et al. 2004, Liu et al. 2005, Baets et al. 2011, Gabriel et al. 2013). The no-tillage system can equalise peaks in the workload of the farmer and should be further investigated. To improve the success of the no-tillage system, the following parameters must be further researched:

- cover crop management
- cover crop treatment
- sowing technique.

Because of their high impact on the performance of the soybean, these factors are discussed in detail in the following paragraphs.

Mirsky et al. (2012) suggested a cover crop biomass greater than 8.000 kg ha^{-1} for effective weed suppression. Cultivars with rapid growth, high biomass potential and early sowing at high density should be a priority for achieving high biomass production and effective weed suppression. Furthermore, the availability of nutrients should not be limited so that the cover crop growth can support rapid development. In this study, rye and barley were used and identified as adequate crops. The emergence rate of soybean was enhanced more by barley than rye, although the weed density was higher in barley. However, significant differences were not observed between barley and rye. Excessive biomass production of the cover crop leads to reduced soybean development in the study by Smith et al. (2011). Thus, additional cover crops should be investigated, e.g., winter annual cereals, brassicaceae, vetch and other legumes and mixtures.

Different techniques for transforming the living cover crop into a mulch layer to prevent the cover crop from becoming a weed in the main crop have been presented in the literature. Ashford et al. (2000) compared the effectiveness of herbicides and rolling/crimping to control the cover crop and suggested a combination of a half dose of herbicide with the crimper. Additional studies have presented the roller as an economically and ecologically useful tool (Mirsky et al. 2009). The parameters weight and crimper aggressiveness can be changed by filling it with water and varying the driving speed. Different arrangements of the metal rail can also influence the effect because of the increase in weight per unit area. Additionally, the cover crops can be cut and carried or controlled by a mulching machine. Cut and carry systems require additional support by herbicides for weed control. However, sowing is facilitated by the reduced amount of residue on the soil surface. Mulching is a time- and cost-intensive strategy; therefore, it is not suitable for large-scale production (Creamer and Dabney 2002).

The mulch layer requires modifications to the sowing technique. The discs of the sowing machine must penetrate the mulch layer while simultaneously creating ideal seedbed conditions. Adequate pressure on the disc is necessary to penetrate the soil and place the seeds at the exact depth. Closure of the seed furrow following the sowing disc also requires additional tools. These requirements must be fulfilled by the sowing machine to achieve advantageous conditions. As an alternative to no-tillage, strip-till technology could be used. However, soil movement in the strip leads to the stimulation of new weeds. Theisen and Bastiaans (2015) presented a simple technical improvement for a specific sowing machine to reduce soil movement, which resulted in decreased weed emergence. This method could be adapted for strip-till technology to reduce the risk of weed emergence in the treated area. Strip-till treatment directly before sowing creates insufficient seedbed penetration because of the soil compaction and large soil fragments under the predominant conditions. Strip-tilling is only advisable at locations where soil tillage can be performed in the spring. Alternatively, two strip-till treatments, one in autumn and one in spring, could be performed to create better seedbed conditions. Adjustments to the sowing technique are important factors for improving the soybean emergence rate and crop yield in no-tillage soybean systems.

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Summary

Soybean (*Glycine max* L. Merr.) has expanded to become one of the most traded agriculture products worldwide in recent decades. The global soybean market is primarily supplied by the USA, Brazil and Argentina, which account for 80% of the global soybean production. Europe is one of the primary importing regions; however, the dependence on soybean imports has been critically assessed by the public. To reduce the dependency on soybean imports, increased local soybean production should be favoured. In addition to environmental conditions, weeds are a major limiting factor for soybean yield under German climate conditions. Weeds can be successfully controlled with herbicides, although crop injury frequently occurs after application. It is known that cultivars have different tolerance levels to herbicides which have been evaluated visually or by measuring the height, biomass and yield. Sensor-based screening would be helpful for a rapid evaluation of cultivar tolerance to herbicide application. Alternatively, mechanical weed control strategies can be applied. Since soybean production is currently introduced to the regional crop production, weed control efficiency of conventional mechanical tools (e.g., hoeing and harrowing) have to be evaluated. By using automatic guiding systems intra-row elements could be utilised to increase the weed control efficiency of mechanical hoeing. Other than that, agronomical practices such as the tillage system or cover crops influences the occurrence of weeds. The most common practise worldwide for soybean cultivation is the no-tillage system, which has not yet been investigated under local conditions. Therefore, different weed control strategies in soybean production were investigated according to the following major objectives of this thesis:

- Detection of crop injury by herbicides using a chlorophyll fluorescence imaging sensor for different soybean cultivars.
- Evaluation of the conventional mechanical strategies of hoeing and harrowing in soybean.
- Examination of the weed control efficiency in inter- and intra-row areas using RTK-GNSS precision steering and an optical camera guiding system for mechanical weed control in soybean.
- Evaluation of the efficiency of 'tillage', 'reduced tillage' and 'no- tillage' cultivation systems and the influence of cover crops on weed suppression in local soybean production.

The Imaging-PAM-sensor based on chlorophyll fluorescence imaging was utilised to investigate the response of different soybean cultivars to the application of herbicides. The measurements indicated significant differences with respect to injury to the cultivars after herbicide application. Herbicides containing the active ingredient 'metribuzin' resulted in significant differences in the level of crop injury depending on the cultivar. The active ingredients 'dimethenamid' and 'clomazone' resulted in less injury, independent of the cultivar. The PAM-sensor was able to detect stress symptoms 3 to 7 days before visual symptoms appeared. In the appropriate environment, this sensor can provide objective data to identify detrimental changes in photosystem II. However, additional research must be performed because chlorophyll fluorescence induction can be affected by external factors, such as water stress, lack of nutrition, pathogens, viruses, and environmental conditions, such as temperature. The PAM-sensor is a rapid and powerful tool for investigating crop injury by measuring chlorophyll fluorescence following herbicide application in soybean.

An investigation of hoeing and harrowing, which are conventional mechanical techniques for weed control, showed 78% and 72% weed control efficiency, respectively. In further experiments, the results of precision steering systems using RTK-GNSS and an optical camera guiding system additionally equipped with intra-row elements (e.g., finger weeders) were compared with the results of conventional hoeing. Mechanical weed control using automatic steering technology and an intra-row element (finger weeder) reduced the weed density by 89% compared with 68% in the conventional hoeing system. With respect to crop yields, statistical benefits of precision steering were not observed. However, the driving speed could be increased from 4 km h^{-1} in the conventional hoeing system to 10 km h^{-1} using the automatic steering systems. Automatic guided systems are useful tools for steering intra-row elements close to the crop row and therefore increase the weed control efficiency of mechanical hoeing in soybean production.

In an additional experiment, two cover crops species, rye (*Secale cereale* L.) and barley (*Hordeum vulgare* L.), were grown for preventive weed control in soybean production. The cover crops were transformed into a mulch layer using a roller-crimper immediately before soybean was sown using a no-tillage technique. For the reduced tillage treatment, the cover crops were cut and removed, and then shallow soil cultivation was performed prior to soybean sowing. Conventional tillage was performed to compare the systems with respect to their weed control efficiency, crop development and soybean yield. The results showed that the no-tillage system had a greater effect on suppressing summer annual weed species (*Chenopodium* *album* (L.), *Echinochloa crus-galli* (L.) P. Beauv. and *Amaranthus retroflexus* (L.)) than the tillage systems. Conventional tillage and reduced tillage showed increased suppression of the weed species *Matricaria inodora* (L.), *Stellaria media* (L.) Vill. and *Sonchus arvensis* (L.), which were present in the no-tillage system. However, in the conventional tillage and reduced tillage systems, an additional weed control treatment was necessary to suppress the summer annual weeds and ensure high yields. The cover crop rye resulted in weed control similar to that of barley in the no-tillage system. Despite the low weed density, the no-tillage system with a rolled cover crop showed a yield reduced of 47%, whereas the yield of the reduced tillage system was decrease by 23% compared with the conventional tillage system. Nevertheless, the no-tillage system with the rolled cover crops demonstrated high weed suppression potential under the local cultivation conditions and should be further improved to increase crop yields.

Zusammenfassung

In den letzten Jahrzehnten entwickelte sich die Sojabohne (*Glycine max* L. MERR.) zu einem der meist gehandelten Agrarprodukte der Welt. Die drei Hauptproduzenten sind USA, Brasilien und Argentinien, welche gemeinsam 80% des Marktes ausmachen. In Europa besteht ein großer Bedarf an Sojaprodukten, welcher hauptsächlich über Import gedeckt wird. Die Abhängigkeit von Importware und die damit verbundenen sozioökologischen und -ökonomischen Auswirkungen des Sojaanbaus in den Exportländern werden in der Öffentlichkeit kritisch gesehen. Eine Ausdehnung des heimischen Sojaanbaus kann der Abhängigkeit von Importware entgegenwirken.

Neben der Sortenanpassung an die klimatischen Bedingungen in Europa stellt die Unkrautkontrolle eine weitere große Herausforderung hierfür dar. Derzeit können die Unkräuter mit Hilfe der zugelassenen Herbizide erfolgreich bekämpft werden, wobei dies oftmals zu Schäden an der Kulturpflanze führt. Die zugelassenen Sojasorten zeigen unterschiedliche Kulturverträglichkeiten gegenüber den Herbiziden. Visuelle Bonituren, Messungen der Pflanzenhöhe, Biomasse- und Ertragserfassung dienen als Indikatoren zur Bewertung der Herbizidschädigung. Ein Sortenscreening mit Hilfe eines Sensors kann eine schnelle Evaluierung der Herbizidverträglichkeit der Kulturpflanze unterstützen. Alternativ zum Einsatz von Herbiziden können Unkräuter auch mechanisch kontrolliert werden. Da sich der heimische Sojaanbau noch im Anfangsstadium befindet, muss zuerst die Wirkung der klassischen mechanischen Geräte wie Hacke und Striegel geprüft werden. Durch den Einsatz von automatischen Lenksystemen können zusätzliche Hackelemente zur Bekämpfung der Unkräuter in der Reihe eingesetzt werden. Darüber hinaus spielen Bewirtschaftungspraktiken, wie die Bodenbearbeitung oder der Einsatz von Zwischenfrüchten, eine große Rolle für das Auftreten von Unkräutern. Global gesehen wird Soja überwiegend im Direktsaatverfahren angebaut, was unter mitteleuropäischen Bedingungen noch wenig erforscht wurde. Basierend auf diesen Verfahren zur Unkrautkontrolle leiten sich folgende Zielsetzungen der Arbeit ab:

- Erkennung von Herbizidstress an verschiedenen Sojasorten mit Hilfe eines Chlorophyllfluoreszenz-Sensors.
- Bewertung von Hack- und Striegelmaßnahmen zur mechanischen Unkrautbekämpfung im Sojaanbau.

- Beurteilung der Effizienz automatischer Lenksysteme (GNSS-RTK und eine Kamera geführte Hacke mit Verschieberahmen) Unkräuter zwischen und in der Reihe zu bekämpfen.
- Bewertung von wendender und reduzierter Bodenbearbeitung sowie Direktsaat und den Einfluss von Zwischenfrüchten auf das Unkrautaufkommen im Sojaanbau.

Zur Bewertung des Einflusses von Herbiziden auf die Pflanzengesundheit wurde mit dem Imaging-PAM-Sensor die Chlorophyllfluoreszenz verschiedener Sojasorten nach der Applikation untersucht. Die Ergebnisse zeigten signifikante Unterschiede nach der Messung mit dem Imaging-PAM-Sensor in Bezug auf den Herbizidstress der Sojapflanze. Nach der Herbizidapplikation mit dem Wirkstoff Metribuzin wiesen einige Sorten signifikante Unterschiede der Chlorophyllfluoreszenz im Vergleich zur Kontrolle auf. Die Wirkstoffe Dimethenamid und Clomazone führten bei allen Sorten zu einer geringeren Stressreaktion. Der Sensor konnte den Herbizidstress an den Kulturpflanzen 3 bis 7 Tage vor dem Auftreten von visuellen Symptomen messen. Unter gleichbleibenden Umweltbedingen werden Änderungen im Photosystem-II von dem PAM-Sensor zuverlässig erfasst. Es bedarf jedoch weiterer Untersuchungen, da die Chlorophyllfluoreszenz auch von externen Faktoren wie Wasserstress, Nährstoffmangel, Viruserkrankungen und Umweltbedingungen (z.B. Temperatur-schwankungen) beeinflusst werden kann. Der Imaging-PAM-Sensor ist ein zuverlässiges und nützliches Werkzeug, um Herbizidstress an Kulturpflanzen zu detektieren.

In den Versuchen zur mechanischen Unkrautkontrolle ergab die klassische Behandlung mit der Reihen-Hacke einen Bekämpfungserfolg von 78% und mit dem Striegel eine Reduktion der Unkräuter von 72% verglichen zur unbehandelten Kontrolle. In einem weiteren Experiment wurden die Precision Farming Technologien GNSS-RTK und eine Kamera gesteuerte Hacke mit Verschieberahmen eingesetzt. Die Systeme wurden mit zusätzlichen Werkzeugen (z.B. Fingerhacke) für die Unkrautkontrolle in der Reihe ausgestattet und die Ergebnisse mit einer konventionellen Hacke verglichen. Hierbei ergab sich für das automatisch geführte System mit Fingerhacke ein Unkrautbekämpfungserfolg von 89%, während konventionelles Hacken 68% Bekämpfungserfolg erzielte. In Bezug auf den Ertragszuwachs ergab sich keine signifikante Erhöhung durch den Einsatz von automatischen Lenksystemen, jedoch konnte dadurch die Fahrgeschwindigkeit von 4 km h^{-1} auf 10 km h^{-1} erhöht werden. Aufgrund ihrer exakten Führung entlang der Pflanzenreihe unterstützen automatische Lenksysteme den Einsatz von zusätzlich angebauten Werkzeugen.

In weiteren Versuchen im Rahmen dieser Arbeit wurden Roggen (*Secale cereale* L.) und Gerste (*Hordeum vulgare* L.) als Zwischenfrüchte zur vorbeugenden Unkrautkontrolle vor Soja angebaut. Unmittelbar vor der Aussaat der Sojabohnen mit einer Direktsaatmaschine wurden die Zwischenfrüchte mit einer Messerwalze niedergedrückt. In einer weiteren Variante wurden die Zwischenfrüchte von der Fläche abgefahren und die Stoppeln daraufhin flach bearbeitet (reduzierte Bodenbearbeitung). Um die Ergebnisse dieser beiden Systeme bezüglich Unkrautkontrolle, Kulturpflanzenentwicklung und Ertrag einordnen zu können, wurde eine Variante mit klassischer wendender Bodenbearbeitung (Pflug) angelegt. Die Ergebnisse zeigten eine deutlich gesteigerte Unterdrückung der Unkrautarten *Chenopodium album* (L.), *Echinochloa crus-galli* (L.) P. Beauv. und *Amaranthus retroflexus* (L.) in dem Direktsaatsystem verglichen mit den Varianten mit reduzierter oder wendender Bodenbearbeitung. Jedoch wies die Direktsaatvariante einen signifikanten Anstieg der Arten *Matricaria inodora* (L.), *Stellaria media* (L.) Vill.) und *Sonchus arvensis* (L.) auf. In den Varianten mit reduzierter oder wendender Bodenbearbeitung war eine zusätzliche Bekämpfung der vorwiegend sommerannuellen Unkräuter während der Vegetation notwendig, um die Erträge zu sichern. Im Direktsaatsystem zeigten die beiden eingesetzten Zwischenfrüchte Roggen und Gerste keine Unterschiede in ihrer unkrautunterdrückenden Wirkung. Trotz der teilweise höheren Unterdrückung der Unkräuter wies das Direktsaatsystem eine Ertragsreduktion von 47% auf. Die Variante mit reduzierter Bodenbearbeitung ergab einen Ertragsrückgang von 23% verglichen zum System mit wendender Bodenbearbeitung. Das Potenzial der vorbeugenden Unterdrückung von Unkräutern durch Zwischenfrüchte in einem Direktsaatsystem sollte zukünftig weiter untersucht werden, mit dem Ziel die Etablierung der Sojabohnen und somit den Ertrag zu steigern.

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Curriculum vitae

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