Development of a sensor-based harrowing system using digital image analysis to achieve a uniform weed control selectivity in cereals

Dissertation to obtain the doctoral degree of Agricultural Sciences
(Dr. sc. agr.)

Faculty of Agricultural Sciences
University of Hohenheim
Institute of Phytomedicine (360)

submitted by
Michael Spaeth
from Reutlingen

2021

This thesis was accepted as a doctoral dissertation in fulfillment of the requirements for the degree "doctor scientiarium agriculturae" (Dr. sc. agr. in Agricultural Sciences) by the Faculty of Agricultural Sciences at the University of Hohenheim on 07.07.2021.

Date of oral examination: 06.10.2021
Dean of Agricultural Faculty Prof. Dr. Ralf Thomas Vögele

Examination committee:
Head of the committee Prof. Dr. Martin Hasselmann
Supervisor and Reviewer Prof. Dr. Roland Gerhards
Co-Reviewer Prof. Dr. Dionisio Andujar Sánchez
Additional Examiner Prof. Dr. Hans W. Griepentrog

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 GENERAL INTRODUCTION

Cereals are grown on 73% of the world's agricultural land and constitute more than 60% of the global food production. They are an important part of the diet, providing proteins, carbohydrates for energy, minerals, and vitamins (Charalampopoulos *et al.*, 2002; Kumar & Anand, 2021). With over 600 million tons harvested annually, wheat (*Triticum aestivum*) is one of the three major cereal crops worldwide (Shewry, 2009). To be able to provide stable and high yields for an increasing population, crop protection has always been an important aspect of arable crops. Biotic factors, like weeds, animal pests, and pathogens, are permanently jeopardizing crop and food production. Among these factors, weeds are by far the most important in wheat production worldwide and the main cause for yield losses (Oerke, 2006). Weeds interfere with the crop plant through competition for the limited resources light, nutrients, water and growth space and through allelopathy. In that context, the weed density, weed species and the time of germination are fundamental factors that affect the level of competition. Weeds that emerge before or simultaneously with the crop will be more competitive than weeds which emerge during later stages of crop development. Not all weeds are equally competitive and the negative effects such as light, space, and nutrient reduction may differ substantially. Particular weed species are extremely competitive due to their growth habit, capability to disperse easily, longevity of their seeds and ability to grow in different crop environments. For example, *Chenopodium album* (L.) or *Cirsium arvense* (L.), the latter being capable of vegetative propagation, are often found in cereal cropping systems (Hettwer & Gerowitt, 2004; Bhaskar & Vyas, 1988) and represent such highly competitive weed species. Some weeds even display allelopathic abilities which may hinder the proper development of crop seedlings (Weston & Duke, 2003). In dry areas perennial weeds like *C. arvense* and *Convolvulus arvensis* (L.) are more competitive than annual weeds, due to their deep root system, and early vigour in spring (Sardana *et al.*, 2017; Swanton *et al.*, 2015). Persistent weed infestations interfere with harvesting, cause lodging, transfer diseases and pests, increase production costs as contaminated products require costly processing and cleaning, and can affect final product quality (Sardana *et al.*, 2017; Oerke, 2006; Swanton *et al.*, 2015). Estimated yield loss potential of weeds in wheat production can be as high as 23%, and for maize it can even be as high as 40.3% (Oerke, 2006; Oerke & Dehne, 2004). Therefore, effective weed control is considered one of the crucial prerequisites for a successful crop production (Gerowitt, 2003). The introduction of synthetic herbicides in the 1940-1950s revolutionized agriculture, and it has been the main method to control weeds in arable crops ever since. The lower labour intensity compared to mechanical weeding, along with high weed control efficacy, good crop quality and high yield quantities with low input costs led to a heavy reliance and dependence on herbicides and other pesticides (Powles und Shaner 2001; Abbas et al. 2018; Timmons 1970; Zimdahl 2015). However, during the last decades, increasing negative impacts of synthetic herbicides were recorded, like adverse effects on the environment and biodiversity, residues in the food chain, health risk and the strong increase in herbicide resistant weed populations (Hillocks 2012; Özkara et al. 2016; Damalas und Koutroubas 2016; Gaba et al. 2016).

Especially the resistant weed populations and the residues in food chain, led to support the call for alternative weed control strategies. Therefore, the European Commission (EC) directive 2009/128/EC was enacted to lower pesticide input in all EU member states. A catalogue of measures was compiled to guide farmers on how to adopt and design Integrated Pest Management (IPM) strategies (Hillocks, 2012). IPM is characterized by the minimized use of pesticides in combination with alternative methods to control pests, diseases and weeds. The aim is to promote biodiversity of animals and plants, protect human health and the environment. As a component of IPM, Integrated Weed Management (IWM) comprises the use of preventive cultural, mechanical, biological and bio-technological weed control measures as well as chemical solutions, such as herbicides (Swanton & Weise, 1991). The aim is to diversify weed management options through increased utilization of non-chemical control methods like mechanical weed control, in order to be less reliant on herbicides (Shaner, 2014). Mechanical weed control (MWC) can be used alone (pre-emergence e.g. ploughing or soil tillage, post-emergence e.g. hoeing) or in combination with herbicides, like a band sprayer to reduce the application rate, and therefore the herbicide input. Under optimal weather and field conditions, MWC can be as effective as a single herbicide application against weeds. (Home *et al.*, 2002; Wiltshire *et al.*, 2003; Spaeth *et al.*, 2020b; Riemens *et al.*, 2007) were able to confirm, that mechanical methods have a similar weed control efficacy as an herbicide application in cereals, sugar beet and lettuce.

The efficacy of weed control methods mainly depends on the soil, weather and crop growth conditions (Kurstjens & Kropff, 2001), but also, the experience and knowledge of the farmer have to be considered. Especially for hoeing or harrowing, a relation between weed control efficacy and the tolerable crop damage exists, which mainly depends on the experience of the farmer. Steering or tool adjustment mistakes are some of the farmer related factors that decrease yields (Home *et al.*, 2002). Different methods for mechanical weed control exist and it depends on the crop and often the soil or field conditions which tools are utilized for weeding. For example, harrows or rotary hoes treat the entire field and be used less the broad leaf crops such as cabbage or lettuce. Conventional hoes only treat the inter-row area and is mainly used for vegetable crops, maize or soya. Additionally for interrow hoeing, finger weeders and other In-row tools can be used to treat the intra-row area (Machleb *et al.*, 2020). But using hoes in cereals is limited due to the narrow row spacing. Therefore, harrowing plays a major role for mechanical weeding in cereals and legumes. In practical farming, the treatment intensity of a harrow is mostly set by visual assessment of the effect on the crop and the weeds in a test run until the desired weed control level is achieved. This treatment intensity is then applied throughout the entire field. Conventional harrows are flexible systems, and treatment intensity must be adjusted manually, and it is seldom done more than once per field (Rasmussen *et al.*, 2009; Jensen *et al.*, 2004). Thus, conventional harrows can never achieve optimal weeding results in the entire field due to the non-uniformly spatial distribution of weeds (Wiles *et al.*, 1992).

Adjusting the treatment intensity continuously to account for the heterogeneity of agricultural fields would lead to optimal performance of mechanical weeding. However, this is a task which cannot be realized manually because it is too labour and time intensive. Thus, to obtain a constant in field-specific mechanical treatment intensity, without disregarding the profitability of the operation, it is essential to integrate automation technology (Precision agriculture) such as sensors, in mechanical weeding. Sensor-technology is a part of Precision agriculture (PA) which aims at managing spatial and temporal variability to improve crop performance, economic conditions, and to adjust management to the unique condition found in each field while maintaining environmental stability (Bucci *et al.*, 2018; Bogue, 2017; Blackmore, 1994). Nowadays, there are a lot of commercial available agricultural machines that are routinely equipped with a range of sensors (Bogue, 2017; Machleb *et al.*, 2020). As an example, in field sprayers ultrasonic and imaging sensors are used to control the nozzles to avoid double application or the spraying of field margins. Especially in the crop production and protection sector, optical sensors (e.g. cameras) have become a crucial technology. Certain optical characteristics of plants allow the health or other aspects (e.g. species identification) of a crop to be determined. RGB-Cameras (400-750 nm) are used for visual inspection, elevation modelling and plant counting. Multispectral-Cameras (400-1000 nm) using NIR and RGB wavelengths are used for visual inspection, plant counting, soil properties, moisture analysis, crop health, stress analysis and water management. However, to be able to capture all the mentioned options, image analysis software and a decision-algorithm are needed. Due to optical imaging, it is feasible to realize even single crop plant treatments (Gobor 2013). All this saves the farmer time and facilitates work. For example, camera-guided hoeing is already an established system in wide row crops and was extensively tested during the past years. As a result, time and labour savings as well as stable yield levels can now be achieved (Kunz et al. 2018; Kunz et al. 2015; Tillett et al. 2002; Wiltshire et al. 2003).

In recent decades, there have been several approaches to continuously adjust the performance of the harrowing intensity on the heterogeneity of agricultural fields (Søgaard, 1998; Engelke, 2001; Rueda-Ayala *et al.*, 2013; Peteinatos *et al.*, 2018; Müter *et al.*, 2014; 2015). Søgaard (1998) was using a working depth sensor to vary the tine angle based on the current soil conditions in the field. The harrowing intensity was adjusted by modifying the implement's tine angle. The aim of the control system was to maintain a fixed working depth and therefore a steady harrow intensity. However, the author did not taken into account different crop growth stages, weed densities, and crop soil cover values. Rueda-Ayala *et al.* (2013; 2015; Peteinatos *et al.*) and Peteinatos *et al.* (2018) have taken weed density or soil density or both into account, using different combination of sensors like an electric soil density sensor, a bi-spectral camera, or an ultrasonic sensor and included the data in a decision algorithm for site-specific weed harrowing. Rueda-Ayala *et al.* (2015) adjusted the harrowing intensity in areas with high crop and weed densities more aggressively, while areas with lower densities were cultivated with a gentler treatment. Areas with very low densities or without weeds were not treated. However, the actual crop covering by soil was not considered in the decision algorithm, even though the burial is one of the main mechanisms for weed harrowing and can achieve a high crop damage using an aggressive intensity (Kurstjens & Kropff, 2001). Nevertheless, crop damage, was reduced by continuously adjusting the intensity to the variable field conditions, both in winter wheat and winter barley (Engelke, 2001; Rueda-Ayala *et al.*, 2013). Also, a higher WCE could be achieved when the harrowing intensity was adjusted automatically to the field conditions (Rueda-Ayala *et al.*, 2013). The automatic adjustment of harrowing intensity can avoid excessive crop damage and increase the weed control efficiency (Rueda-Ayala et al., 2013). One of the major disadvantages of these systems was that all adjustments were done based on previous calibrations or a priori decisions and correlations regarding weed density and harrowing intensity. None of the aforementioned systems was able to re-evaluate adjust the harrowing intensity based on the actual output during the harrowing treatment (Gerhards *et al.*, 2020b).They have shown the potential for harrowing automation, but the variety of information needed for a proper adjustment, might be the reasons for the lack of suitable systems for online control of intensity. A further approach to increasing selectivity for weed control would be to combine the camera sensors with artificial neural networks (ANNs). This could help to control the working intensity in real time and plant specific. Also, to estimate the beginning of weed control for different classes of acceptable yield losses and for modelling and predicting competition between weeds and crops, machine learning can be used (Monteiro *et al.*, 2021).

1.1 Objectives of the Thesis

The objectives of this thesis were:

- to develop, implement and test a decision algorithm based on continuous camera measurements of the crop coverage before and after harrowing;

- to test, if the online regulation system of harrowing intensity was capable to realize and adjust to the pre-set threshold values for CSC;

- to find the optimum CSC corresponding to the highest selectivity and yield in cereals;

- to evaluate WCE, CSC, crop density, crop biomass and grain yield of harrowing treatments with a continuous regulation of intensity and fixed intensities in winter wheat and spring oats.

1.2 Structure of the Thesis

This Dissertation is focused on sensor-based mechanical weed control technology. The first chapter (chapter 1) is a general introduction that focuses on the current problems and shows capabilities for sensor-technology in agriculture. Further on, this thesis includes four scientific articles (chapter 2), three of them are scientific papers that have been published or submitted in the peer-reviewed journals *Weed Research* and *Agronomy*. One manuscript is a patent published at the *Austrian-Patent-Office*. These scientific publications describe the realized sensor-based harrowing development and its application potential.

The first paper is a study, titled *"Automatic adjustment of harrowing intensity in cereals using digital image analysis"* and was published in the journal *Weed Research* in 2019. The design, assessments, and decision support system of the sensor-based harrow is described inside. Furthermore, the adjustment accuracy was measured in automatic mode and compared with manual adjustment control.

The second publication is a patent, titled "Verfahren und Bodenbearbeitungsgerät zum Striegeln" and was published in the *Austrian-Patent-Office* in 2019. It describes the current sensor-based harrow system in each detail and protects the development from being used, manufactured and marketed by third parties. The owner is the company: Thomas Hatzenbichler Agro-Technik GmbH, 9433 St. Andrä, Lavanttal (AT).

The third paper comprises an experimental study, titled *"Smart Harrowing—Adjusting the Treatment Intensity Based on Machine Vision to Achieve a Uniform Weed Control Selectivity under Heterogeneous Field Conditions"* and was published in the journal *Agronomy* in 2020. It describes the utilization of the current sensor-based harrow development at three field trials in two locations in southwest Germany for the first time. The effects of machine-based harrow intensity on the weed control efficacy, crop biomass, and grain yield were measured and analysed in cereals.

The fourth paper is titled *"Comparing sensor-based adjustment of weed harrowing intensity with conventional harrowing under heterogeneous field conditions"* and was submitted to *Weed Research* in 2021. It shows a comparison between the automatic adjustment of harrow intensity, with a conventional adjustment of the intensity. The effects on weed control efficacy, CSC, crop dry mass and grain yield were analysed.

The next chapter is a general discussion (chapter 3) including all findings of this research work, an outlook on how precision agriculture for crop protection will develop in the future, and then the dissertation closes with a detailed summary (chapter 4).

Apart from the peer-reviewed journal articles, included in the thesis, during the course of this thesis one more contribution to an international scientific conference was oral presented. This work was supplementary to the included articles, and therefore not included in the current thesis.

- Spaeth, M. and Gerhards, R. (2021). Comparison of Sensor-based Harrowing Technology (SenHa) with a conventional manual harrowing-system. In: *Proceedings of the 13th European Conference on Precision Agriculture Congress*.

2 PUBLICATIONS

2.1 Automatic adjustment of harrowing intensity in cereals using digital image analysis

R Gerhards*, M Spaeth*, M Sökefeld*, GG Peteinatos*, A Nabout* and V Rueda Ayala**

*University of Hohenheim, Department of Weed Science, 70593 Stuttgart, Germany

**NIBIO, Norwegian Institute of Bioeconomy Research, 4353 Klepp Stasjon, Norway

Correspondence:

Roland Gerhards, University of Hohenheim, Department of Weed Science (360 B), D-70599 Stuttgart, Germany. Tel: (+49) 711-459-22399

Email: Roland.gerhards@uni-hohenheim.de

Published in: Weed Research 2021, 61, 68-77

© 2021 The Authors.

Weed Research published by John Wiley & Sons Ltd on behalf of European Weed Research Society

The original publication is available at:

https://doi.org/10.1111/wre.12458

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

2.1.1 Summary

Precision farming technologies were implemented into a commercial harrow to increase selectivity of weed harrowing in spring cereals. Digital cameras were mounted before and after the harrow measuring crop cover. Crop soil cover (CSC) was computed out of these two images. Eight field experiments were carried out in spring cereals. Mode of harrowing intensity was changed in five experiments by speed, number of passes and tine angle. Each mode was varied in five intensities. In three experiments, only intensity of harrowing was changed. Weed control efficacy (WCE) and CSC were measured immediately after harrowing. Crop recovery was assessed 14 days after harrowing. Modes of intensity were not significantly different. However, intensity had significant effects on WCE and CSC. Cereals recovered from 10% CSC and selectivity was in the optimum range at 10% CSC. Therefore, 10% CSC was the threshold for the decision algorithm. If the actual CSC was below 10% CSC, intensity was increased. If the actual CSC was higher than 10%, intensity was decreased. Image analysis, decision support system and automatic control of harrowing intensity by hydraulic adjustment of tine angle were installed on a controller mounted on the harrow. The new system was tested in an additional field study. Threshold values for CSC were set at 10%, 30% and 60%. Automatic tine angle adjustment precisely realized the three different CSC values with variations of 1.5 to 3%. This development contributes to selective weed control and supports farmers during harrowing.

Keywords: Precision Farming, sensor technologies, mechanical weed control, site-specific harrowing

2.1.2 Introduction

Although chemical weed control still plays a dominant role in weed management strategies, there is a strong need for alternative measures and integrated management. Negative impacts on the environment and the risk of herbicide residues in the food chain as well as the strong increase of herbicide resistant weed populations support the call for alternative weed control strategies (Hillocks 2012). Among physical weed control measures, weed harrowing is very promising because of its high labor efficiency (Rasmussen 1992). However, the WCE of harrowing is not consistent in the literature. Field studies carried out in Norway in spring wheat showed a WCE of 26% after pre-emergence harrowing and 47% after post-emergence harrowing (Brandsaeter *et al.* 2012). They achieved the best weed control efficacy when pre- and post-emergent weed harrowing were combined (61%). However, those results were highly dependent on the trial site and varied between trial years. Rasmussen *et al*. (2008), Van der Weide *et al.* (2008) and Rasmussen *et al.* (2009) achieved 80-90% weed control efficacy against mostly annual broad-leaved weeds in spring cereals.

Harrowing is less effective against larger weeds, annual grasses (e.g. *Alopecurus myosuroides* Huds) and perennial weeds (e.g. *Cirsium arvense* L., *Elymus repens* L.) (Melander *et al*. 2012, Terpstra *et al.* 1981). Therefore, it is important to combine weed harrowing with other preventive and curative tactics of weed control, including crop rotations, tillage practices, cover cropping, hoeing and chemical weed control (Hillocks 2012). The weed control mechanism of harrowing is mainly due to soil burial, but also uprooting plays a role when weeds are small (Kurstjens and Kropff 2001, Leblanc *et al*. 2011).

The working mechanism of harrowing implies whole field cultivation and therefore, includes risk of crop damage. However, weed harrowing in cereals may also favor crop growth due to a combination of different effects such as soil loosening, reduction of evaporation, soil aeration, nutrient mineralization and inducing of tillering/shoot development (Steinmann, 2002). The intensity of harrowing can be regulated by modifying the driving speed, the number of consecutive passes and the tine angle (Rydberg, 1994; Rasmussen & Svenningsen, 1995). The challenge is to achieve a high degree of weed control while keeping crop damage as low as possible. The crop damage is mainly caused by covering plants with excessive amounts of soil (CSC = Crop Soil Cover) or by tearing off parts of the leafs (Rasmussen *et al*. 2009, Jensen *et al*. 2004).

Selectivity has been defined as the ratio between percentage of weed control and the percentage of CSC immediately after harrowing (Rasmussen *et al.* 2008). This definition does not consider recovering or new germination of weeds after treatment and crop recovery from harrowing. Re-growth of weeds or late germinating weeds may require repeated cultivations, especially in crops with low competitive ability (Van der Weide *et al*. 2008). CSC can be measured in real-time based on digital image analysis (Rasmussen *et al.* 2007, Weis *et al.* 2008, Rueda & Gerhards 2009).

Farmers mostly apply a constant harrowing intensity across the whole field, regardless of variations in crop cover, weed distribution and soil texture within the field. A constant harrowing intensity may cause crop damage in field sections with light and sandy soil textures and low crop cover. In parts of the field with heavy soils and high crop cover, treatment intensity may be too gentle causing insufficient weed control. Automatic adjustment of harrowing intensity can avoid excessive crop damage and increase WCE (Rueda Ayala *et al.* 2013). In recent decades, there have been several attempts to improve mechanical weed control by varying the harrowing intensity (Søgaard 1998, Engelke 2001, Rueda-Ayala *et al.* 2013, Müter *et al.* 2014, Rueda-Ayala *et al.* 2015). Rueda Ayala *et al.* (2013) mounted an electronic soil density sensor on a harrow tine to measure the draught force of the soil at a depth of 2-5 cm. Their decision algorithm decided to harrow more aggressively in areas with dense and heavy soil and with a reduced intensity in field sections with light soil. This principle has been implemented in commercial harrows. It resulted in higher WCE but caused lower crop coverage compared to uniform harrowing intensity. Søgaard (1998) varied the intensity of weed harrowing is by changing the working depth of the tines. However, the author did not take into account different crop growth stages and weed densities. Rueda-Ayala *et al.* (2013) and Peteinatos *et al.* (2018) measured the weed density before harrowing using a bispectral camera, and Rueda-Ayala *et al.* (2015) determined weed density with an ultrasonic sensor and included the data in a decision rule for site-specific weed harrowing (Rueda-Ayala *et al.* 2013, Rueda-Ayala *et al.* 2015). They applied the highest intensity of harrowing at locations with high weed density and reduced harrowing intensity in areas with medium and low weed infestation. However, other factors such as the crop coverage remaining immediately after treatment and the soil moisture were not considered in the decision rule.

To the current state, none of the developed decision algorithms have been precise enough to adjust tine angle in the new harrows with hydraulic variation on tine angle. Some systems have shown the potential for harrowing automation, but the variety of information needed for a proper adjustment, the complexity of the sensor- and steering systems and the costs associated with such systems might be the reasons for the lack of suitable systems for online control of intensity. Therefore, the objective of the study was to develop, implement and test a decision algorithm based on continuous camera measurements of the crop coverage before and after harrowing. An image analysis system was designed to calculate the actual CSC during harrowing. A controller had was installed on the harrow to analyze the images, compare the actual CSC with a preset threshold value and transfer the decision to the online hydraulic tine angle regulation system for adjusting the harrowing intensity. A Threshold value for CSC was derived from previous empirical data of eight field studies in spring cereals. An additional field study was carried out to test, if the online regulation system of harrowing intensity was capable to realize and adjust to the preset threshold values for CSC.

2.1.3 Materials and Methods

2.1.3.1 Field experiments 1-8

Eight field experiments were conducted in spring wheat, cv. Triso and spring barley, cv. Leandra on the University of Hohenheim Experimental Research Station for Organic Farming near Stuttgart, Germany located 435 m a.d.l.. Both cultivars can compensate plant losses by tillering in the vegetative growing stages. However, time between sowing of spring cereals and generative growth induced by photoperiodism is relatively short in Southwestern Germany. Therefore, seed rates were relatively high with 600 seeds m-2 for spring wheat and 400 seeds m-2 for spring barley. Row spacing was 20 cm for spring wheat and 15 cm for spring barley. Seeding depth was 2-3 cm. Soil type is a Stagnic Luvisol and soil texture is silty loam and loamy clay. The average annual precipitation is 700 mm and the average temperature 8.8 °C. The region is characterized by dry weather periods in spring. Experimental fields received no rainfall at least 3 days before harrowing and 3 days after harrowing.

Five experiments (Exps. 1-5) were implemented using a split-plot design with two factors and four repetition blocks (Table 2.1-1). The factor named ‘mode of intensity’ was arranged in the whole plot. This factor included three modes for varying the harrowing intensity: (I) increasing driving speed, (II) changing angle of tines and (III) increasing number of consecutive passes on the same day as cultivation. Each mode of intensity was used to create five intensity levels. In total, there were four increasingly more aggressive harrowing intensities and one untreated control (intensity zero). The factor ‘intensity level’ was arranged in the subplots. Each experiment from 1 to 5 comprised 60 plots (3 modes × 5 intensities × 4 replicates). Three further experiments (Exps. 6-8) were implemented using a randomized complete block design with four replicates. The study factor ‘harrowing intensity’ was set by varying tine angle in five steps (Table 2.1-1). Plots in exps. 6-8 were only 12 to 15 m long and 2.5 m wide.

Table 2.1-1: Details of harrowing experiments in spring cereals with different modes and levels of intensity.

Exp.	**Year**	**Crop/growth stage at harrowing**	**Plot size (m) width x length**	**Mode of intensity**		
				Speed [S] (km h^{-1})	**Passes [P]**	**Intensity/tine angle [A]**
1	2011	Spring wheat, 21	2.5 x 20	0, 3, 6, 9, 12	0, 1, 2, 3, 4	Light, medium, strong, very strong
2	2011	Spring wheat, 24	2.5 x 20	0, 3, 6, 9, 12	0, 1, 2, 3, 4	Light, medium, strong, very strong
3	2012	Spring wheat, 21	2.5 x 20	0, 3, 6, 9, 12	0, 1, 2, 3, 4	Light, medium, strong, very strong
4	2012	Spring wheat, 24	2.5 x 20	0, 3, 6, 9, 12	0, 1, 2, 3, 4	Light, medium, strong, very strong
5	2012	Spring wheat, 21	2.5 x 20	0, 3, 6, 9, 12	0, 1, 2, 3, 4	Light, medium, strong, very strong
6	2014	Spring wheat, 12	2.5 x 15	8	1	Light, medium, strong, very strong
7	2014	Spring wheat, 21	2.5 x 15	8	1	Light, medium, strong, very strong
8	2018	Spring barley, 21	3 x 12	8	1	10 °, 25 °, 40 °, 55 °, 70 °

Harrowing was done along crop rows with a 2.5 m wide harrow (Hatzenbichler, St. Andrä, Austria) with flexible tines (25 mm distance between tines, six rows of tines) and manual adjustment for tine angle and working depth. Since 2018, a hydraulic setting of the tine angle has been used. At the time of harrowing, the weed species were in the 2-6 leaf stage. The most abundant weed species were *Galium aparine* L. (cleavers), *Polygonum convolvulus* L. (wild buckwheat), *Raphanus raphanistrum* L. (wild radish), *Matricaria* spp. (Matricaria), *Capsella bursa-patoris* (L.) Med. (shepherd's purse), *Chenopodium album* L. (common lambsquarter), *Lamium purpureum* L. (red dead-nettle), *Myosotis arvensis* (L.) Hill. (field forget-me-not), *Polygonum arviculare* L. (common knotgrass), *Stellaria media* (L.) Vill. (chickweed) and *Thlapsi arvense* L. (field pennycress) with average total densities in the control plots before harrowing ranging from 68 - 812 weeds m^{-2}, which represents a medium to high infestation rate for spring cereals.

2.1.3.2 Assessments

Weed density and crop coverage were assessed before and immediately after harrowing. Crop coverage was again measured 14 days after harrowing. Weeds were counted in a 0.1 m^2 frame at four locations per plot. Crop cover was measured with two RGB cameras, model AD-130-GE (JAI Technology, China) mounted in the front and rear of the harrow at a frame rate of 4 fps from a height of 1 m above ground. Field of view was 0.2 m^2. Excessive Green Red Index (ExGR) was calculated out of the three layers of the processed Red (R), Green (G) and Blue (B) images according to Mink et al. (2018) to enhance the contrast between green vegetation and soil. The ExGR (1) is the difference of the Excessive Green index (ExG) (2) and the Excessive Red index (ExR) (3). A zero threshold was applied to create a binary image. Weeds were removed from the ExGR image based on size and shape of plants according to Weis et al. (2008) resulting in crop cover (Figure 2.1-1).

$$ExGR = ExG - ExR \tag{1}$$

$$ExG = \frac{2 * G - R - B}{G + R + B} \tag{2}$$

$$\mathrm{ExR} = \frac{1.4 * \mathrm{R} - \mathrm{B}}{R + B} \tag{3}$$

CSC is defined as the part of the crop that is covered by soil, after the treatment. Two images, presenting the crop coverage before and after harrowing provide the necessary information to measure % CSC.

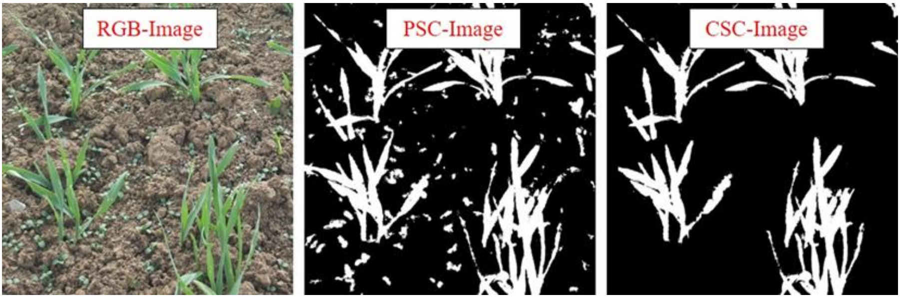

Figure 2.1-1: Left: RGB image; middle: Excessive Green image representing plant soil cover (PSC); right: binary image after morphological filtering showing crop soil cover (CSC).

Grain yields were recorded in experiments 1, 2, 6, 7, 8 in 2 x 10 m sub-plots in the center of the plot using a plot combine harvester (Zürn170, Zürn Harvesting GmbH & Co. KG, Schöntal-Westernhausen, Germany). Grain yield data are presented for 86 % dry weight.

2.1.3.3 Decision support system for automatic adjustment of tine angle by camera control

Empirical data of previous field studies (Tabbl 2.1-1) were analyzed to determine a threshold for crop soil cover (CSC) in the Decision Support System (DSS). This threshold was defined as the maximum CSC that the crops could compensate in all experiments 1-8 within 14 days after harrowing. Real-time adjustment of the harrowing intensity was achieved by varying the tine angle. In the DDS, actual CSC value was compared with the threshold value. Data analysis of experiments 1-8 was done as described in Rasmussen *et al*. (2008), modeling leaf cover index (L) and weed density (W) directly after harrowing, as function of the mode dependent intensity values. Crop resistance and weed control efficacy parameters were estimated for exponential decay functions

$$WCE = 100 * \left\{1 - \exp\left(-c * \left[-\frac{1}{b} * \ln\left(1 - \frac{CSC}{100}\right)\right]^{0.25}\right)\right\} \quad (4)$$

$$b = \frac{\ln L_0 - \ln L}{I} \quad (5)$$

$$c = \frac{\ln W_0 - \ln W}{I^{0.25}} \quad (6)$$

with WCE = weed control efficacy, CSC = crop soil cover, b (estimated from equation 5) representing crop resistance to intensity and c (estimated from equation 6) representing weed control efficacy in relation to intensity. W_0 is the weed density in untreated plots and W represents the weed density in treated plots, L is the leaf cover index in treated plots and L_0 equals leaf cover index in untreated plots. Harrowing intensity is represented by I.

Selectivity curve shows a steep increase of weed control efficacy up to approximately 10% CSC (Figure 2.1-2). Lower intensities (CSC) strongly reduce WCE and higher intensities (CSC) cause crop damage.

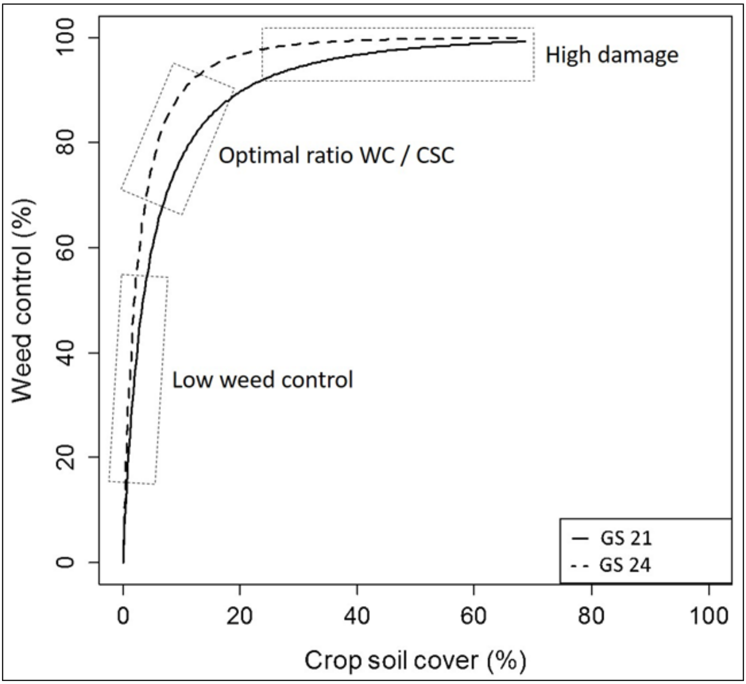

Figure 2.1-2: Selectivity curve for weed harrowing in spring wheat 2012 according to equation 4; GS 21 and GS 24 represent the crop growth stages “one tiller = 21” and “4 tillers = 24”.

If the actual CSC is higher than the preset threshold of 10%, the tine angle is decreased to avoid crop damage. If the CSC was lower than preset threshold, the tine angle was increased to achieve a higher weed control efficacy (Figure 2.1-3). The tine angle is adjusted in steps of 15° (Figure 2.1-4). Adjustment of tine angle was realized within less than 1 s.

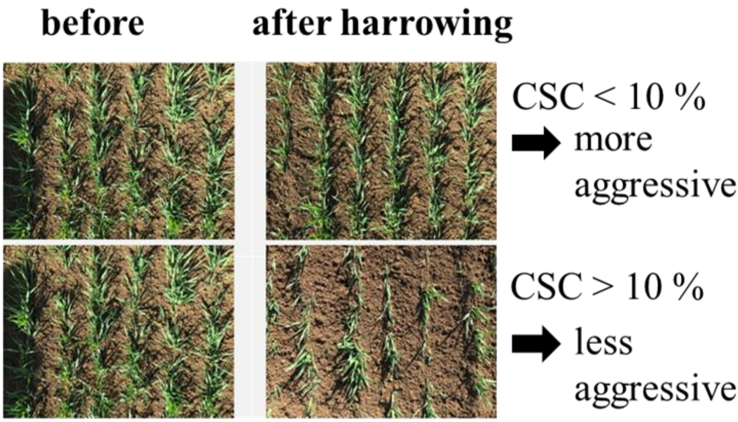

Figure 2.1-3: Example for the decision rules based on CSC calculated from two images before and after harrowing.

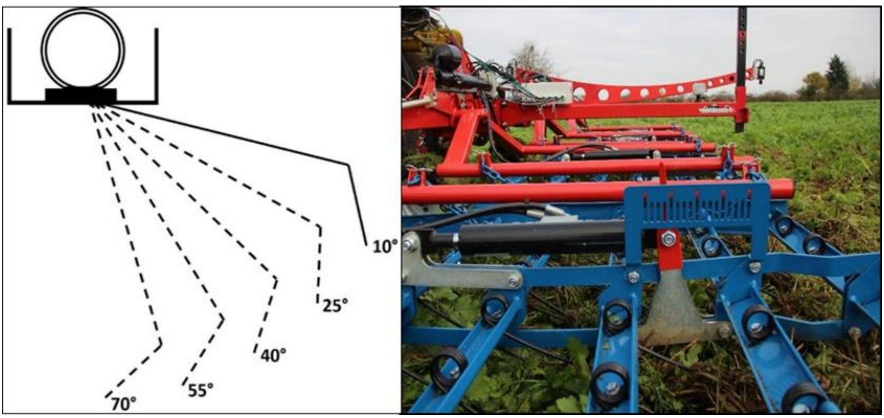

Figure 2.1-4: Left: illustration of five tine angles presenting five levels of harrowing intensity; right: photo of the position of the hydraulic cylinder, which is connected to a digital signal transferred to the controller.

2.1.3.4 Design and control system of the camera steered harrow

Cameras, DSS and controller were integrated in a 6 m wide harrow (Hatzenbichler, St. Andrä, Austria) with flexible tines (25 mm tine distance, 6 mm tine diameter, six rows of tines) and hydraulic adjustment of tine angle. The harrow is divided into four sections of 1.5 m. For this study, tine angle on all four sections were controlled equally. A gear divider ensured an even distribution of the oil flow to all four hydraulic cylinders. The captured images were transferred to an external Controller (Kontron S & T Group, Augsburg, Germany) on the harrow. The controller contained an image recognition software (IRS) and a decision support system (DSS). If the actual CSC was higher than the threshold, harrowing intensity was decreased. The adjustment of tine angle based on CSC measurement and the threshold was automatically executed by the actuator (Roboteq, Inc., Scottsdale, USA) on the harrow (Figure 2.1-5). The actuator controls of the hydraulic cylinders via solenoid valves. A movement of the hydraulic cylinder caused a proportional variation of the tine angle. The actuator of the controller records the positions of the hydraulic cylinders via a CANOpen interface on the cylinders to avoid that a signal for decreasing or increasing the tine angle is generated, when the cylinder was fully expanded or compressed. During each start of the automatic mode, the harrow is moving to the highest and lowest intensity points in order to recalibrate the distance sensor on the hydraulic cylinders. After any automatic adjustment of the tine angle, the current harrow position is updated in the controller. A controlling board was designed to allow a manual and automatic mode of the harrow (Figure 2.1-6).

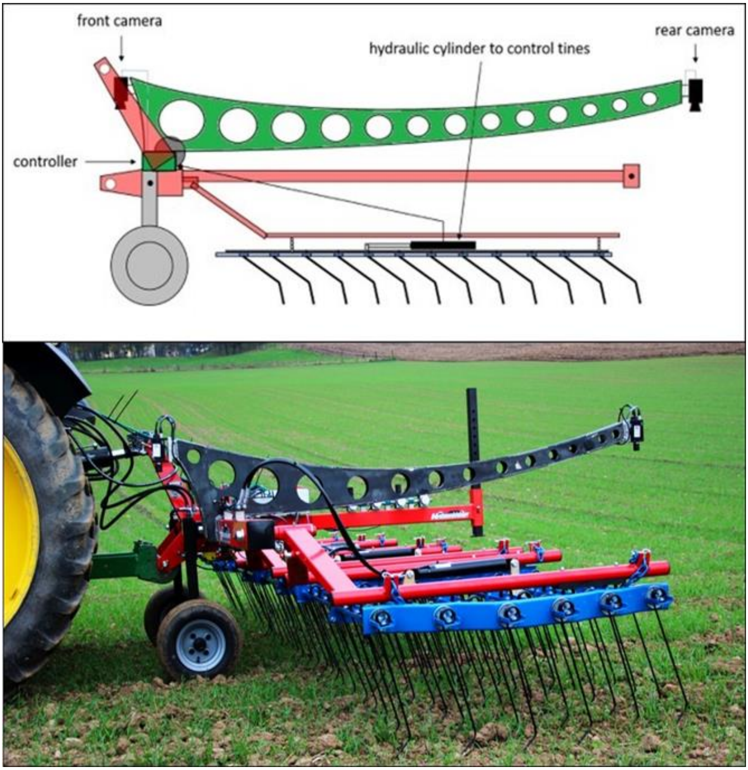

Figure 2.1-5: Design and picture of the harrow containing automatic adjustment of tine angle.

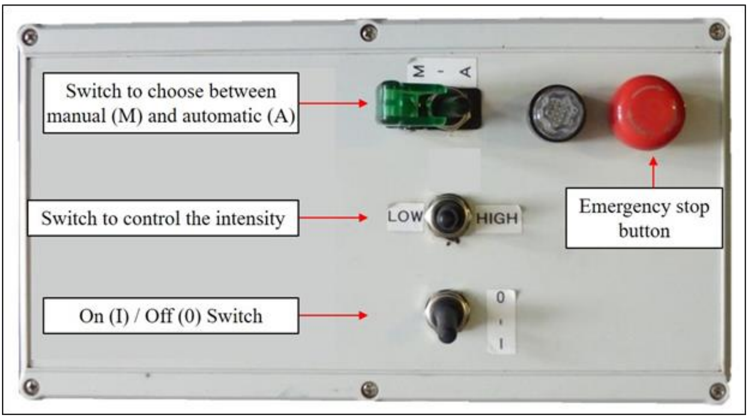

Figure 2.1-6: The controlling board of the harrow actuator.

2.1.3.5 Description of field experiment 9

The ninth field experiment was conducted in winter wheat at Hirrlingen near Tübingen in autumn 2019 to test the accuracy of automatic tine angle control of the Hatzenbichler harrow. Winter wheat was at 2-3 leaf stage at the time of harrowing. The trial was a 2 × 3 factorial arrangement in a randomized complete block design with three replicate blocks. The first factor was the mode of tine angle control: a manual and an automatic control. In the manual mode, tine angle was set in the field border next to the experiment and then kept constant for the complete treatment. In the automatic mode, intensity was continuously adjusted according to the actual CSC and the threshold value. The second factor represented the intensity of harrowing with three levels (light, medium, strong) (Table 2.1-2).

Table 2.1-2: Description of the treatments in the winter wheat experiment.

Treatment code	Mode of control	Intensity
Auto 10%	Automatic	light: 10% CSC threshold
Auto 30%	Automatic	medium: 30% CSC threshold
Auto 60%	Automatic	strong: 60% CSC threshold
Man_I	Manual	light: tine angle 10 °
Man_II	Manual	medium: tine angle 40 °
Man_III	Manual	strong: tine angle 70 °

The experiment contained 18 plots with a size of 25 m × 6 m, each. The driving speed was constantly 8 km h^{-1}. Harrowing was done along crop rows. CSC (for verification of conformity with the thresholds) was calculated taking ten images before and after harrowing at random positions in the plot with a digital RGB-camera (Panasonic DMC-TZ41) according to equation (7).

$$CSC = 100 * \frac{(L_0 - L)}{L_0} \quad (7)$$

L_0 represents crop coverage before harrowing and L is the crop coverage measured after harrowing.

2.1.3.6 Data analysis

All data were analysed using the R Studio software (Version 1.0.136, RStudio Team, Boston, MA, USA). Regression analysis was applied for data of experiments 1-8 as described in Rasmussen et al. (2008), modelling leaf cover and weed density directly after treatment as function of the mode-independent intensity values. To compare growth stages and the different modes of intensity (MOI), selectivity at 80% weed control was used. Leaf cover, weed density were log-transformed to achieve normal distribution and variance homogeneity of the data and make regression parameter estimation possible. The log-transformation was necessary in any case to fit exponential equations with linear mixed-effects models. Intensity, MOI and growth stage were assigned as fixed effects and block and interactions block × MOI × growth stage as random effects. Lack-of-fit tests were conducted to test model fit and non-significant factors or interactions were reduced from the model. Residuals were inspected and outliers were removed to improve model fit. The delta method was used to calculate 95% confidence intervals (95% CI) for CSC.

An analysis of variance (ANOVA) was performed for the data of experiment 9 and crop recovery data followed by a Tukey-HSD (Honestly Significant Difference) test of the means at $\alpha \leq 0.05$. An ANOVA was used because harrowing intensities 0-5 were categorical predictor variables. Prior to the analysis, the data were tested for homogeneity of variance and normal distribution of the residuals.

2.1.4 Results

2.1.4.1 Results experiments 1-8

Lack-of-fit test showed that equations 5 and 6 described well ($P > 0.05$) data for the leaf cover index and weed density reduction, respectively for experiments 1-5. No statistical difference was found for the mode of intensity (MOI) for all calculated parameters ($P>0.05$). (Tab. S1, Figs. S1, S2). Crop resistance parameter was 0.271 in exps. 1 and 2, 0.276 in exps. 3 and 4 and 0.203 in exp. 5. Weed control parameter c was 2.329 in exps. 1 and 2, 2.011 in exp. 3, 2.832 in exp. 4 and 1.93 in exp. 5. CSC at 80% WCE was equal regardless if intensity was varied by speed, number of passes or tine angle in experiments 1-5 (Figs. S1, S2). Therefore, mode of intensity by speed and number of passes was skipped from the experiments 5-8. Intensity was further on only changed by tine angle in experiments 6-8.

Level of intensity had a strong impact on selectivity. In all experiments, we observed an exponential increase of WCE at low to medium intensities. As expected, higher intensities increased the CSC, but based on equations 4 and 5, WCE at higher intensities is flatting out towards a plateau. Therefore, selectivity decreased at high intensities. Harrowing was slightly more selective, when the cereals had 4 tillers (BBCH 24) compared to earlier treatments at 2-leaf stage and beginning of tillering (BBCH 21) (see Figure 2.1-2).

In average, 58% WCE was achieved at 5% CSC (lowest intensity), 75% WCE at 10% CSC and 82% at 20% CSC. Higher than 10% CSC, the benefit (WCE) of increasing intensity was lower due to the cost of crop damage (CSC) (Table 2.1-3). This was one reason for selecting 10% CSC as threshold in the decision algorithm.

We observed in all eight experiments that crop coverage increased faster in the treated plots compared to the untreated control. Within 14 days after harrowing, crop coverage was always higher at intensities causing 10% CSC than in the untreated plots. The lowest crop recovery was observed in experiment 2 with 12 % CSC. In experiment 8, spring barley could even compensate 41% CSC within 14 days (Table 2.1-3, Figure 2.1-7). This result indicates that harrowing stimulated crop growth during vegetative development, if intensity was not too high. The fact, that the crop could compensate 10% CSC in all experiments was a second argument for selecting 10% CSC as threshold in the decision rule of automatic tine angle adjustment.

Table 2.1-3: Weed control efficacy (WCE) at 5, 10 and 20 crop soil cover (CSC) and maximum CSC that the crop compensated 14 days after harrowing.

Exp.	% WCE at 5% CSC	% WCE at 10% CSC	% WCE at 20% CSC	Max. % CSC tolerated
1	70	78	80	15
2	82	88	91	12
3	58	79	83	28
4	78	84	90	35
5	30	63	81	14
6	26	57	62	15
7	41	63	72	21
8	77	89	96	41
Mean	58	75	82	23

Harrowing intensity had no significant effect on grain yield. Grain yields were also not significantly different from the untreated control (Table 2.1-4). It was observed that yields at low harrowing intensity were slightly higher than the untreated controls. Highest intensities of harrowing often resulted in lowest yields.

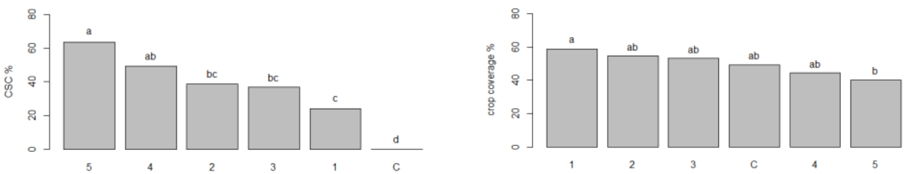

Figure 2.1-7: Crop Soil Cover (CSC) directly after harrowing in spring barley in experiment 8 (left) and crop cover 14 days after harrowing (right); C = untreated control, 1-5 = harrowing intensity with 1 = lowest intensity.

Table 2.1-4: Average grain yields (t ha^{-1}) in relation to harrowing intensity

Exp.	Crop	Untreated	Light	Medium	Strong	Very strong
1	Spring wheat	4.8 a	5.0 a	5.2 a	4.8 a	4.7 a
2	Spring wheat	4.0 a	4.9 a	4.7 a	5.0 a	5.1 a
6	Spring wheat	3.2 a	3.4 a	3.6 a	3.3 a	3.1 a
7	Spring wheat	3.3 a	3.5 a	3.7 a	3.3 a	3.0 a
8	Spring barley	6.5 a	7.2 a	7.6 a	7.1 a	6.1 a

2.1.4.2 Results experiment 9

Automatic tine angle control was more precise than using the manual settings. In the three treatments of automatic adjustment, average CSC varied only 1.5% (Auto 10%) to 3.5% (Auto 30% and Auto 60%) from the preset threshold value. The three automatic treatments differed significantly from each other (Figure 2.1-8). The standard error for the automatic modes was 5% for the Auto 10% treatment and 8% for Auto 30% and 17% for Auto 60%, while the standard error in the three manual modes was 18-20%.

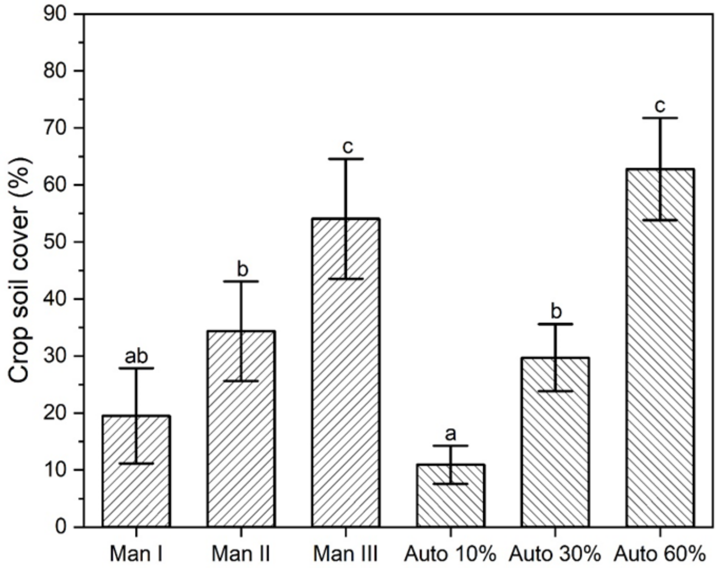

Figure 2.1-8: Mean crop soil cover (CSC) and standard errors measured in winter wheat at Hirrlingen 2019 after harrowing in three manual settings and with three automatic thresholds for CSC. Means with the same letter are not statistically different according to HSD-Test at $\alpha \leq 0.05$. Man I = low manual adjustment of tine angle (10 °), Man II = medium manual adjustment of tine angle (40 °), Man III = high manual adjustment of tine angle (70 °), Auto 10% = CSC threshold in image recognition software (IRS) is 10%, Auto 30% = CSC threshold in IRS is 30%, Auto 60% = CSC threshold in IRS is 60%.

2.1.5 Discussion

This This paper presents a new approach combining digital image analysis with an online control system of automatically adjusting the harrowing intensity in cereals for post-emergent weed control. Different from previous works (Søgaard, 1998; Engelke, 2001; Rueda-Ayala et al., 2013; Rueda-Ayala et al., 2015; Müter et al., 2014), the automatic regulation system is less dependent of the crop growth stage, driving speed and soil texture. This working flexibility facilitates the practical use of the new system. It supports famers with little practical experience in weed harrowing to apply the constant intensity.

The decision algorithm is based on the selectivity model by Rasmussen & Svenningsen (1995), Rasmussen et al. (2008) and Rasmussen et al. (2009) with a threshold for maximum % CSC. The aim of this approach was to avoid harrowing intensities that could damage the crop. In other decision algorithms adjusting harrowing intensity to weed density (Rueda-Ayala et al., 2015; Peteinatos et al., 2018) or soil resistance (Rueda Ayala et al.; 2013) the risk of crop damage was higher, because those systems allowed a higher CSC than 10% to obtain a targeted 80% weed control.

The effects of harrowing on crop and weeds are probably very complex or not fully understood, both for pre- and post-emergent treatments. The model by Rasmussen et al. (2008) and Rasmussen et al. (2009) relates the positive effect (weed control) to the negative impact (crop soil cover) measured immediately after post-emergent harrowing. Apart from weed control, harrowing may have additional positive effects on crop development such as the mobilization of nitrogen in the soil (Steinmann, 2002) and the induction of crop-tillering (Rueda-Ayala et al., 2011). In the present study, spring cereals compensated and partly overcompensated 12-41% burial of crop leaves by soil during harrowing. Within two weeks after harrowing, crop coverage in the treated plots was equal or higher than in the untreated control. Rasmussen et al. (2008) observed similar results with a compensation of 2-31% CSC, Rasmussen et al. (2009) measured 18-24% CSC tolerance and Rasmussen et al. (2010) found 23-33% CSC compensation. Concluding from these results, a threshold of maximum 10% CSC seems to be in the range of optimal selectivity.

The automatic system of harrow adjustment performed correctly and robust under heterogeneous field conditions. In the automatic mode, CSC measured from separate images before and after harrowing corresponded well to the threshold value set in the controller with a lower standard deviation than for manual control. Deviation of the achieved to the threshold

CSC value varied from 1.5 to 3%. Standard error increased at higher preset thresholds in the automatic regulation due to the extremely high burial of crop leaves by soil at highest harrowing intensity. However, it was lower compared to the manual adjustment. The benefit of an automatic adjustment of harrowing intensity is higher in fields with heterogeneous crop development. A constant manual setting would damage the crop in areas with poor development and reduce weed control efficacy in field sections with strong crop growth. Rueda-Ayala et al. (2013) and Engelke (2001) also observed a higher weed control efficacy and a precise adjustment to site-specific variations of field conditions with an automatic intensity regulation of the harrows in fields with heterogeneous soils.

This study cannot highlight easy- and difficult-to-control weed species with a harrow. Grasses and perennial weed species that showed low control rates in Melander et al. (2012) and Terpstra et al. (1981) did not occur in our experiments. Control efficacy against annual broadleaves did not clearly differ between species. It rather depended on growth stage. Small cotyledon weeds were controlled better than larger weeds.

More field studies are needed in spring cereals and in winter cereals to test the current threshold under different environments. Brandsaeter et al. (2012), Rasmussen et al. (2010), Rueda Ayala et al. (2011) and Kurstjens & Perdok (2000) reported that weed control efficacy and crop response to weed harrowing strongly vary between site and year. More focus should also be given to the crop response of harrowing concerning crop density, biomass, tillering, ear development, height and yield. One farmer involved in this study increases seed density of cereals and legumes by 10% when post-emergent harrowing is planned.

Technical improvements can increase the performance of the presented system. A separate control of each segment of the harrow with one pair of cameras before and after the tines would take into account smaller variations of crop cover and increase the precision of the treatment. However, it would also increase the costs. The hydraulic adjustment of tines is relatively slow. It takes approximately one s to adjust the tine angle. New harrows use pneumatic variation systems of tine angle (e.g., Air-Flow-Harrow (Hatzenbichler, St. Andrä, Austria). They can adjust the tine angle within 0.1s. This would decrease the reaction time of the harrow and make proper adjustment at common driving speeds of 12 km h-1. The information of weed coverage (PSC – CSC) from the digital images has so far not been included in the decision algorithm. It would be possible to reduce the threshold of CSC in areas with no weeds and increase it in high-density patches. Therefore, this idea needs further investigations. A major benefit of the current development is its simplicity and robustness. Variations of tine angle are made based on one simple parameter (CSC) that can be assessed online using low-cost RGB-cameras.

2.1.6 Acknowledgments

We are grateful to Hans Back, Felix Möcklinghoff, Lisa Engelhardt and Tobias Schiller for conducting field studies and analyzing data in their Bachelor and Master theses. The authors acknowledge the technical support of Hatzenbichler providing a commercial 6 m wide harrow with hydraulic adjustment of tine angle for our studies.

2.1.7 References

Brandsaeter, L.O., Mangerud, K. andRasmussen, J. (2012) Interactions between pre- and post-emergence weed harrowing in spring cereals. *Weed Research,* 52, 338–347.

Engelke, B. (2001) Entwicklung eines Steuersystems in der ganzflächig mechanischen Unkrautbekämpfung [Development of a self-adjusting system for broadcast mechanical weed control]. Dissertation, Christian-Albrechts-Universität zu Kiel, Göttingen, Germany.

Hillocks, R.J. (2012) Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. *Crop Protection,* 31, 85–93.

Jensen, R.K., Rasmussen, J. and Melander, B. (2004) Selectivity of weed harrowing in lupin. *Weed Research,* 44, 245–253.

Kurstjens, D.A.G. and Perdok, U.D. (2000) The selective soil covering mechanism of weed harrows on sandy soil. *Soil and Tillage Research,* 55, 193–206.

Kurstjens, D.A.G. and Kropff, M.J. (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research,* 41, 211–228.

Leblanc, M. L., Cloutier, D. C., Cloutier, D. C., & Leblanc, M. L (2011) Mechanical weed control in cereal crops in Eastern Canada. Physical Weed Control: Progress and Challenges. *Canadian Weed Science,* 6, 35–42.

Melander, B., Holst, N., Rasmussen, I.A. and Hansen, P.K. (2012) Direct control of perennial weeds between crops – Implications for organic farming. *Crop Protection,* 40, 36–42.

Mink, R., Dutta, A., Peteinatos, G.G. et al. (2018) Multi-temporal site-specific weed control of *Cirsium arvense* (L.) Scop. and *Rumex crispus* L. in maize and sugar beet using Unmanned Aerial Vehicle based mapping. *Agriculture,* 8, 65.

Müter, M., Damerow, L. and Schulze Lammers, P. (2014) Kameragesteuerte mechanische Unkrautbekämpfung in Pflanzenreihen. *Landtechnik,* 69, 120-124.

Peteinatos, G., Gierer, F. and Gerhards, R. (2018) Precision harrowing using a bispectral camera and a flexible tine harrow. *Julius-Kühn-Archiv,* 385–389.

Rasmussen, J. (1992) Testing harrows for mechanical control of annual weeds in agricultural crops. *Weed Research,* 32, 267–274.

Rasmussen, J. and Svenningsen, T. (1995) Selective Weed Harrowing in Cereals. *Biological Agriculture & Horticulture,* 12, 29–46.

Rasmussen, J., Nørremark, M. and Bibby, B.M. (2007) Assessment of leaf cover and crop soil cover in weed harrowing research using digital images. *Weed Research,* 47, 299-310.

Rasmussen, J., Bibby, B.M. and Schou, A.P. (2008) Investigating the selectivity of weed harrowing with new methods. *Weed Research,* 48, 523–532.

Rasmussen, J., Nielsen, H.H. and Gundersen, H. (2009) Tolerance and Selectivity of Cereal Species and Cultivars to Postemergence Weed Harrowing. *Weed Science,* 57, 338–345.

Rasmussen, J., Mathiasen, H. and Bibby, B.M. (2010) Timing of post-emergence weed harrowing. *Weed Research,* 50, 436–446.

Rueda-Ayala, V. P. and Gerhards, R. (2009) Selectivity of weed harrowing with sensor technology in cereals in Germany. In E. van Henten, D. Goense & C. Lokhorst, (Eds.) Precision Agriculture '09, vol. 7, pp. 339–348. 7th European Conference on Precision Agriculture (ECPA), Wageningen, The Netherlands: Wageningen Academic Publishers.

Rueda-Ayala, V.P., Rasmussen, J., Gerhards, R. and Fournaise, N.E. (2011) The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat. *Weed Research,* 51, 478–488.

Rueda-Ayala, V., Weis, M., Keller, M., Andújar, D. and Gerhards, R. (2013) Development and testing of a decision making based method to adjust automatically the harrowing intensity. *Sensors (Basel, Switzerland),* 13, 6254–6271.

Rueda-Ayala, V., Peteinatos, G., Gerhards, R. and Andújar, D. (2015) A non-chemical system for online weed control. *Sensors, 15,* 7691-7707

Rydberg, T. (1994) Weed Harrowing—the Influence of Driving Speed and Driving Direction on Degree of Soil Covering and the Growth of Weed and Crop Plants. *Biological Agriculture & Horticulture,* 10, 197–205.

Søgaard, H.T. (1998) Automatic Control of a Finger Weeder with Respect to the Harrowing Intensity at Varying Soil Structures. *Journal of Agricultural Engineering Research,* 70, 157–163.

Steinmann, H.-H. (2002) Impact of harrowing on the nitrogen dynamics of plants and soil. *Soil and Tillage Research,* 65, 53–59.

Terpstra, R. and Kouwenhoven, J.K. (1981) Inter-row and intra-row weed control with a hoe-ridger. *Journal of Agricultural Engineering Research,* 26, 127–134.

Van der Weide, R.Y., Bleeker, P.O., Achten, V.T.J.M., Lotz, L.A.P., Fogelberg, F. and Melander, B. (2008) Innovation in mechanical weed control in crop rows. *Weed Research,* 48, 215–224.

Weis, M., Ritter, C., Gutjahr, C., Rueda Ayala, V., Gerhards, R. and Schölderle, F. (2008) Precision Farming for weed management: techniques. *Gesunde Pflanzen,* 60, 171-181.

2.2 Patent - Verfahren und Bodenbearbeitungsgerät zum Striegeln

österreichisches patentamt

AT 16504 U2

2019-11-15

Gebrauchsmusterschrift

Anmeldenummer:	GM 67/2019	Int. Cl.: ***A01B 35/20***
Anmeldetag:	27.06.2019	***A01B 39/28***
Beginn der Schutzdauer:	15.11.2019	***A01B 79/00***
Veröffentlicht am:	15.11.2019	

Gebrauchsmusterinhaber:

Thomas Hatzenbichler Agro-Technik GmbH 9433 St. Andrä im Lavanttal (AT)

Erfinder:

Gerhards Roland Dr. 73066 Uhingen (DE)

Peteinatos Gerassimos Dr. 70599 Stuttgart (DE)

Sökefeld Markus Dr. 53111 Bonn (DE)

Spaeth Michael 72800 Eningen unter Achalm (DE)

Nabout Adnan Dr. 40670 Meerbusch (DE)

Original publication is available at:

https://worldwide.espacenet.com/patent/search/family/068502073/publication/AT16504U2?q=AT16504U2&queryLang=en%3Ade%3Afr

Verfahren und Bodenbearbeitungsgerät zum Striegeln

Ein als Striegel ausgebildetes Bodenbearbeitungsgerät (1) besitzt ein Traggestell (2), an dem verschwenkbar Striegelzinken (4) angeordnet sind. Zum Verstellen des Striegelwinkels (14) ist ein Antrieb (5) vorgesehen. Beim Striegeln werden die Striegelzinkel (4) kontinuierlich so ausgerichtet, dass die Striegelzinken (4) beim Überschreiten eines Schwellenwertes für den Pflanzenverschüttungsgrad steiler und beim Unterschreiten des Schwellenwertes flacher gestellt werden. Für das laufende Ermitteln des Pflanzenverschüttungsgrades werden von zwei Kameras (8, 10) aufgenommene Bilder analysiert und mit dem Schwellenwert verglichen. Die als Pflanzenverschüttungsgrad ausgewerteten Bilder können hinsichtlich Aufnahmezeitpunkt und -ort gespeichert werden.

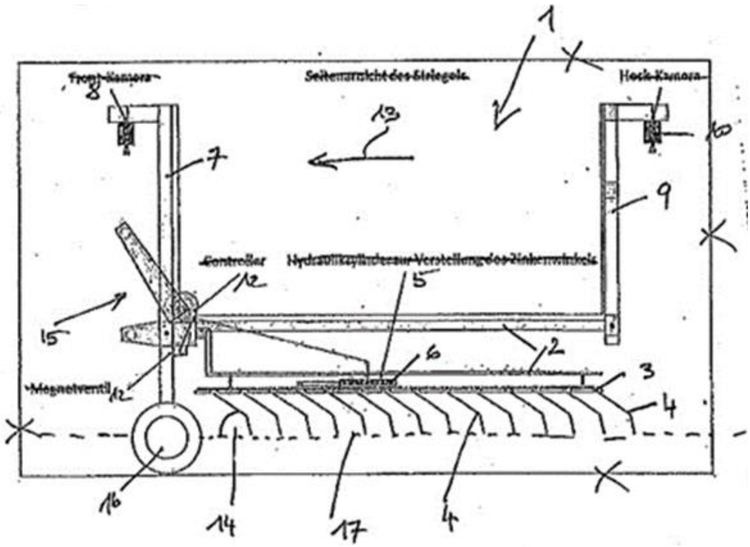

Figure 2.2-1: Seitenansicht ein erfindungsgemäßes Bodenbearbeitungsgerät (Striegel) Beschreibung

[0001] Die Erfindung betrifft ein Verfahren und ein Bodenbearbeitungsgerät zum Striegeln.

[0002] Geräte zum Striegeln, die auch als „Striegel" bezeichnet werden, sind bekannt. Beispielsweise wird auf den im Prospekt „Hatzenbichler AUSTRIAN-AGRO-TECHNIK" gezeigten und beschriebenen „Original-Striegel" verwiesen. Dieser bekannte Striegel besitzt ein Traggestell mit mehreren Holmen, an denen Striegelzinken befestigt sind. Die Striegelzinken umfassen einen dreifach gewundenen Abschnitt, sodass die Zinken beim

Bearbeiten des Bodens zum Entfernen von Unkraut aus Feldern mit Kulturpflanzen, wie Getreide, Soja, Mais, Sonnenblumen, Erdbeeren, Zuckerrüben, Raps und dgl., federnd eingesetzt werden können.

[0003] Ein weiteres Bodenbearbeitungsgerät ist aus EP 1 961 283 B1 bekannt. Dieses bekannte Bodenbearbeitungsgerät, das zum Pflegen der Bodenflächen von Kulturpflanzungen bestimmt ist, besitzt ein Traggestell und mehrere, an dem Traggestell verschwenkbar angeordnete Striegelzinken. Weiters ist eine den Striegelzinken zugeordnete Verstelleinrichtung vorgesehen, mit der die über Schraubenfedern bewirkte Vorspannung der Striegelzinken eingestellt werden kann. Problematisch bei dem aus EP 1 961 283 B1 bekannten Bodenbearbeitungsgerät ist es, dass die Striegelzinken über Schraubenfedern vorgespannt werden, was nicht nur ein erheblicher Aufwand, sondern auch störanfällig ist.

[0004] Bekannt ist weiters ein Bodenbearbeitungsgerät mit mehreren Striegelzinken, bei welchem die Striegelzinken an Hebeln befestigt sind, die über Träger an Holmen des Traggestells verschwenkbar gelagert sind. Durch Anliegen der Hebel an Anschlägen, die an den Holmen vorgesehen sind, ist die Wirkstellung der Striegelzinken definiert. Die Striegelzinken werden durch ihnen zugeordnete Federn in Form von Pneumatikzylindern in ihre Wirkstellung vorgespannt.

[0005] Das Striegeln im Nachlauf bekämpft einjähriges Unkraut in Kulturpflanzungen. Bodenbearbeitungsgeräte bekämpfen beim Striegeln Unkraut, indem Unkraut mit Erdreich verschüttet, herausgerissen oder entwurzelt wird. Problematisch ist dabei, dass durch das Striegeln auch Kulturpflanzen (z.B. Getreide, Leguminosen) beeinflusst werden. Großsamige Kulturpflanzen sind häufig stärker verwurzelt als kleinsamiges Unkraut, so dass zum Entwurzeln und Verschütten von Unkraut beim Striegeln eine geringere Intensität ausreicht, um Unkraut erfolgreich zu bekämpfen.

[0006] Es ist beim Striegeln darauf zu achten, dass die von der Ausrichtung der Striegelzinken abhängige Intensität des Einwirkens der Striegelzinken des Bodenbearbeitungsgerätes (Striegel) so gewählt wird, dass selektiv nur Unkraut, nicht aber Kulturpflanzen beeinflusst werden, und sich Kulturpflanzen vom Striegeln erholen können. Das Erholen von Kulturpflanzen ist ebenfalls ein wichtiger Parameter für die Wahl der Intensität des Striegelns.

[0007] Der Zeitpunkt des Striegelns hat Einfluss auf den Erfolg des Bekämpfens von Unkraut. Die Selektivität und der Erfolg des Bekämpfens von Unkraut durch Striegeln sind in der Regel in frühen Entwicklungsstadien von Kulturpflanzen höher. Bei Wintergerste ist Striegeln im

BBCH- Code-Stadium 12 (2-Blatt) erfolgreicher als im BBCH-Code-Stadium 24 (4 Bestockungstriebe).

[0008] Allerdings ist die Selektivität annähernd gleich, wenn die Intensität des Striegelns angepasst wird. Vorteilhaft wird das Striegeln ausgeführt, wenn die Kulturpflanzen weiterentwickelt sind als das Unkraut.

[0009] Die Intensität des Striegelns kann durch die Ausrichtung der Striegelzinken, insbesondere durch Wahl des Striegelwinkels - also des Winkels, den die Striegelzinken mit dem zu bearbeitenden Boden einschließen durch die Geschwindigkeit, mit welcher das Bodenbearbeitungs- gerät bewegt wird, und/oder durch die Zahl der Überfahrten geändert und angepasst werden.

[0010] Der Erfindung liegt die Aufgabe zugrunde, ein Verfahren und ein Bodenbearbeitungsgerät zum Striegeln zur Verfügung zu stellen, bei welchen die Ausrichtung der Striegelzinken und damit die Intensität des Striegelns den jeweiligen Erfordernissen, insbesondere selbsttätig (automatisch), angepasst werden kann.

[0011] Gelöst wird diese Aufgabe erfindungsgemäß mit einem Verfahren, das die Merkmale von Anspruch 1, und mit einem Bodenbearbeitungsgerät, dass die Merkmale von Anspruch 11 aufweist.

[0012] Bevorzugte und vorteilhafte Ausgestaltungen des erfindungsgemäßen Verfahrens und Bodenbearbeitungsgerätes sind Gegenstand der Unteransprüche.

[0013] Die Erfindung stellt eine neue Technik zum vorzugsweisen kameragesteuerten Regeln der Intensität des Striegelns zur Kontrolle (Bekämpfen) von Unkraut in Kulturpflanzungen (Getreide, Leguminosen) dar. Die richtige Intensität des Striegelns wird in Echtzeit über das Ändern der Ausrichtung der Striegelzinken (des Zinkenwinkels) verwirklicht. Die Regelgröße für die passende Ausrichtung der Striegelzinken (des Zinkenwinkels) ist ein Pflanzenverschüttungsgrad („PSC"). Dabei kann vorgesehen sein, dass der Pflanzenverschüttungsgrad (PSC) mit Hilfe von Bildern, die von auf den zu bearbeitenden Boden gerichteten Kameras, bezogen auf die Arbeitsrichtung vor und nach dem Bodenbearbeitungsgerät, erzeugt werden, ermittelt wird.

[0014] Beispielsweise wird der Pflanzenverschüttungsgrad (PSC) unter Anwenden der Formel

$$PSC = 100 \times \left(\frac{L_o - L}{L_0}\right) \quad (1)$$

ermittelt, wobei L_0 die Pflanzenbedeckung vor dem Striegeln und L die Pflanzenbedeckung nach dem Striegeln bedeutet.

[0015] Im Rahmen der Erfindung kann so vorgegangen werden, dass der erfasste Pflanzenverschüttungsgrad (PSC) mit einem Schwellenwert für den Pflanzenverschüttungsgrad (PSC) verglichen wird, wobei bevorzugt ist, dass ein Schwellenwert im Bereich 5 bis 25% gewählt wird und insbesondere 20% beträgt.

[0016] Im Rahmen des erfindungsgemäßen Striegelns können die Striegelzinken bei einem Pflanzenverschüttungsgrad (PSC), der über dem Schwellenwert liegt, steiler im Sinne einer Vergrößerung des Striegelwinkels gestellt werden, und die Striegezinken bei einem Pflanzenverschüttungsgrad (PSC), der unter dem Schwellenwert liegt, flacher im Sinne einer Verkleinerung des Striegelwinkels gestellt werden.

[0017] Im Rahmen der Erfindung kann vorgesehen sein, dass zum Erfassen der Bilder Kameras, wie full-frame RGB-Kameras (Vollbild RGB Kameras), verwendet werden, die beispielsweise in einer Höhe von 1,2 m über dem Boden angebracht sind. Dabei ist es bevorzugt, wenn eine Kamera im Frontanbau des Bodenbearbeitungsgerätes und eine weitere Kamera im Heck des Bodenbearbeitungsgerätes angeordnet ist.

[0018] Bei der Erfindung kann vorgesehen sein, dass aus jeweils einem Bild beider Kameras der Pflanzenverschüttungsgrad (PSC) berechnet und mit dem Schwellenwert verglichen wird. Der Schwellenwert entspricht einem bestimmten Wert des Pflanzenverschüttungsgrades.

[0019] Dabei kann vorgesehen sein, dass die Ausrichtung der Striegelzinken und damit die Intensität des Striegelns geändert, nämlich erhöht oder verringert wird, je nachdem, ob der Schwellenwert überschritten oder unterschritten wird. Bevorzugt ist es, wenn die auf den Schwellenwert gestützte Entscheidung auf Grundlage von je sechs Bildpaaren getroffen wird.

[0020] Die Erfindung erlaubt es, den jeweiligen Pflanzenverschüttungsgrad bildanalytisch zu quantifizieren, wobei die erfassten und ermittelten Werte für den Pflanzenverschüttungsgrad mit dem Schwellenwert verglichen werden.

[0021] Bei dem erfindungsgemäßen Verfahren wird in einer bevorzugten Ausführungsform ein digitales Bildanalyseverfahren vorwendet, das kontinuierlich den Pflanzenverschüttungsgrad, der von dem Bodenbearbeitungsgerät bewirkt wird, größenmäßig erfasst. Der Pflanzenverschüttungsgrad wird zum Einstellen der Intensität des Striegelns durch Ändern der Ausrichtung der Striegelzinken verwertet.

[0022] Ein bei dem erfindungsgemäßen Verfahren in einer Ausführungsform verwendbarer Rechner, der als Expertensystem (decision-algorithm) dient, ermittelt und verwirklicht für jede Position die beste Ausrichtung (Stellung) der Striegelzinken (Einstellung des Zinkenwinkels) im Sinne der höchsten Selektivität.

[0023] Nachstehend werden weitere Merkmale und Einzelheiten der Erfindung anhand von in den Zeichnungen schematisch dargestellten Ausführungsbeispielen erläutert. Es zeigt:

[0024] Figure 2.2-2 in Seitenansicht ein erfindungsgemäßes Bodenbearbeitungsgerät

[0025] Figure 2.2-2 Beispiele für ein RGB-Bild (links) und ein ausgewertetes Binärbild (rechts)

[0026] Figure 2.2-3 eine Heckansicht des Bodenbearbeitungsgerätes und

[0027] Figure 2.2-3 eine Draufsicht auf das Bodenbearbeitungsgerät.

[0028] Ein erfindungsgemäßes Bodenbearbeitungsgerät 1 („Striegel") besitzt ein Traggestell 2, an dem mehrere Holme 3 vorgesehen sind. An den Holmen 3 sind Striegelzinken 4 angebracht. An dem Traggestell 2 sind vorne Stützräder 16 und eine Dreipunktaufhängung 15 vorgesehen.

[0029] Zum Ändern der Ausrichtung der Striegelzinken 4 sind die Holme 3 im Traggestell 2 um die Längsachsen der Holme 3 verdrehbar gelagert. Zum Verdrehen der Holme 3 und damit zum Schwenken der Striegelzinken 4 ist ein Antrieb 5 vorgesehen. Dieser Antrieb 5 kann Hydraulikzylinder umfassen.

[0030] Durch Betätigen des Antriebes 5 werden die Striegelzinken 4 geschwenkt, so dass deren Stellung zu dem zu bearbeitenden Boden, also der Striegelwinkel 14, geändert wird.

[0031] An dem Bodenbearbeitungsgerät 1 ist, bezogen auf die vorgegebene Arbeitsrichtung (Pfeil 13 in Fig. 1), über einen Träger 7 vorne eine auf den Boden 17 gerichtete Kamera 8, insbesondere eine full-frame RGB-Kamera, angebracht.

[0032] Eine weitere Kamera 10, die ebenfalls eine full-frame RGB-Kamera sein kann, ist über einen zweiten Träger 9 am Heck des Bodenbearbeitungsgerätes 1 angebracht und ebenfalls auf den zu bearbeitenden Boden 17 gerichtet.

[0033] Das Bodenbearbeitungsgerät 1 umfasst eine Steuereinheit 12, über die der Antrieb 5 zum Verschwenken der Striegelzinken 4 angesteuert wird.

[0034] Die Steuereinheit 5 ist funktionell mit einem Rechner verbunden. Insbesondere sind die Steuereinheit 5 und der Rechner zu einer Einheit kombiniert. Der Rechner dient als „Expertensystem" und vergleicht den erfassten Pflanzenverschüttungsgrad mit einem vorgegebenen Schwellenwert. Der Schwellenwert ist der Wert für die Bedeckung der Pflanzen, welche die Kulturpflanzen tolerieren oder überkompensieren können, d.h. bis zu dem Schwellenwert nehmen die Kulturpflanzen durch das Striegeln keinen Schaden.
[0035] Der Striegelwinkel 14, den die Striegelzinken 4 mit dem zu bearbeitenden Boden 17 einschließen, wird kontinuierlich in Abhängigkeit von dem Pflanzenverschüttungsgrad (PSC) geändert.
[0036] Der Pflanzenverschüttungsgrad (PSC) wird nachfolgender Formel berechnet:

$$PSC = 100 \times \left(\frac{L_o - L}{L_0}\right) \qquad (2)$$

[0037] In dieser Formel bedeutet L_0 die Pflanzenbedeckung (Bedeckung der Kulturpflanzen und des Unkrautes mit Erdreich) vor dem Striegeln und L die Pflanzenbedeckung nach dem Striegeln. Auf Grundlage, der von der Kamera 8 aufgenommenen Bilder wird der Wert von L_0 ermittelt. Auf Grundlage, der von der Kamera 10 aufgenommenen Bilder wird der Wert von L ermittelt.
[0038] Die Werte für L_0 und L werden aus den Farbbildern der Kameras 8 und 10 berechnet, indem aus zu Image ExGR transformierten Bildern (automatisch) Binärbilder erzeugt werden, worauf die weißen Bildpunkte relativ zum Gesamtbild ermittelt werden.
[0039] Wenn ein Pflanzenverschüttungsgrad (PSC) zwischen 5 und 25%, insbesondere von 20% (= Schwellenwert des PSC) ermittelt wird, wird die Ausrichtung der Striegelzinken 4 (der Zinkenwinkel 14) nicht geändert. Falls der Pflanzenverschüttungsgrad (PSC) über dem Schwel- lenwert liegt, beispielsweise größer als 20% ist, wird der Zinkenwinkel 14 vergrößert, d.h. die Striegelzinken 4 werden „steiler" gestellt, so dass sie weniger intensiv wirken.
[0040] Wenn der Pflanzenverschüttungsgrad (PSC) unter dem Schwellenwert liegt, beispielsweise kleiner als 20% ist, wird der Zinkenwinkel 14 verringert, so dass die Striegelzinken 4 mit dem zu bearbeitenden Boden einen kleineren Winkel einschließen und „flacher" sind, so dass sie stärker wirken.

[0041] Es ist erkannt worden, dass Getreide vom 3-Blattstadium bis Mitte der Bestockung die Fähigkeit hat, einen Pflanzenverschüttungsgrad von 20% zu kompensieren. Bei einem Pflanzenverschüttungsgrad von 20%, also beim bevorzugten Schwellenwert, beträgt der Erfolg beim Bekämpfen von Unkraut ungefähr 80%.

[0042] Die an dem Bodenbearbeitungsgerät 1 angebrachten Kameras 8 und 10 nehmen beispielsweise Bilder mit einer Frequenz von sechs Bildern pro Sekunde auf. Jedes Bild wird zu „Excessive Green-Red" (Image ExGR) transformiert (Formeln 1 bis 3). ExGR ist eine Rechenoperation an Standard-Farbbildern (vgl. Meyer, G.E.; Hindmann, T.W.; Laksmi, K. Machine Vision Detection Parameters for plant Species Identification. In Proceedings of the Precision Agriculture and Biological Quality, Boston, MA, USA, 3-4 November 1999; Volume 3543, pp. 327-335. Woebbecke, D.M.; Meyer, G.E.; Von Bargen, K.; Mortensen, D.A. Color indices for weed identification under various soil, residue, and lighting conditions. Trans. ASAE 1995, 38, 259-269. Meyer, G.E.; Neto, J.C.; Jones, D.D.; Hindman, T.W. Intensified fuzzy clusters for classifying plant, soil, and residue regions of interest from color images. Comput. Electron. Agric. 2004, 42, 161-180.

[0043] Hamuda, E.; Glavin, M.; Jones, E.A survey of image processing techniques for plant extraction and segmentation in the field. Comput. Electron. Agric. 2016, 125, 184-199.) Durch die Farbanalyse ExGR werden die spektralen Eigenschaften lebender Pflanzen verstärkt und die spektralen Eigenschaften des Bodens und toter Pflanzengewebe (Mulch) abgeschwächt. Das Ergebnis ist ein höherer Kontrast zwischen Pflanze und Bildhintergrund.

Dies vereinfacht über eine automatische Grauwertschwelle das Erstellen von Binärbildern. Damit wird, unabhängig von den äußeren Aufnahmebedingungen, der Kontrast zwischen Pflanzen und Boden verstärkt.

$$Image_{ExGR} = Image_{ExG} - Image_{ExR} \tag{3}$$

$$Image_{ExR} = \frac{1.4 \times Image_{red} - Image_{blue}}{Image_{red} + Image_{blue}} \tag{4}$$

$$Image_{ExG} = \frac{2 \times Image_{green} - Image_{red} - Image_{blue}}{Image_{red} + Image_{red} + Image_{blue}} \tag{5}$$

[0044] Die in den vorstehenden Gleichungen verwendeten Begriffe sind in den genannten Literaturstellen erläutert.

[0045] Anschließend werden aus den zu „ExGR“ transformierten Bildern über Grauschwellen Binärbilder (Pflanze - Boden) erzeugt, von welchen eines beispielhaft in Figure 2.2-2 rechts wiedergegeben ist. Vgl. Gerhards R, Nabout A, Sökefeld M, Kühbauch W, Nour-Eldin (1993) Automatische Erkennung von acht Unkrautarten mit Hilfe digitaler Bildverarbeitung und Fouriertransformation. J. Agron. & Crop Science 171, 321-328. Gerhards R, Christensen S (2003) Real-time weed detection, decision making and patch spraying in maize (Zea mays L.), sugarbeet (Beta vulgaris L.), winter wheat (Triticum aestivum L.) and winter barley (Hordeum vulgare L.). Weed Research 43, 1-8.

[0046] Bei dem erfindungsgemäßen Bodenbearbeitungsgerät 1 („Striegel") kann vorgesehen sein, dass die Bildaufnahme, die Bildverarbeitung und das Ermitteln der jeweils besten Ausrichtung der Striegelzinken in dem als „Expertensystem" dienenden Rechner (Vergleich des jeweiligen Pflanzenverschüttungsgrades mit dem vorgegebenen Schwellenwert) in einem Mikro- Kontroller mit grafischer Oberfläche ausgeführt werden.

[0047] Die Steuereinheit 12 ist im Ausführungsbeispiel auf dem Bodenbearbeitungsgerät 1 montiert. Die Steuereinheit 12 steuert den Antrieb 5 zum Ändern der Ausrichtung (Stellung) der Striegelzinken 4. Beispielsweise werden (Magnet-)Ventile, über welche die als Antrieb 5 zum Verstellen der Striegelzinken 4 dienenden Hydraulikzylinder 6 mit Hydraulikmedium beaufschlagt werden, betätigt.

[0048] Im Rahmen der Erfindung ist es bevorzugt, dass der Zinkenwinkel 14 einheitlich für die gesamte Breite des Bodenbearbeitungsgerätes 1, also im Beispiel Figure 2.2-3 für alle Teile mit je 1,5 m Breite des Bodenbearbeitungsgerätes 1, eingestellt wird.

[0049] Der aktuelle Zinkenwinkel 14 (Ausrichtung der Striegelzinken 4 zum zu bearbeitenden Boden) wird elektronisch angezeigt und wird der Steuereinheit („Kontroller") als Eingangsgröße aufgegeben.

[0050] Das erfindungsgemäße Verfahren und das erfindungsgemäße Bodenbearbeitungsgerät 1 erlauben es, das Striegeln an jeder Position im Feld mit der höchsten Selektivität auszuführen. Damit werden Schäden an Kulturpflanzen vermieden und der Erfolg des Bekämpfens von Unkraut wird erhöht.

[0051] Durch die beim erfindungsgemäßen Bodenbearbeitungsgerät 1 vorgesehene Anpassung der Ausrichtung der Striegelzinken 4 kann die Heterogenität landwirtschaftlicher

Pflanzen berücksichtigt werden, und das Bodenbearbeitungsgerät 1 ist zum Striegeln in verschiedenen Entwicklungsstadien von Kulturpflanzen erfolgreich einsetzbar.

[0052] Zusammenfassend kann ein Ausführungsbeispiel der Erfindung wie folgt beschrieben werden:

[0053] Ein als Striegel ausgebildetes Bodenbearbeitungsgerät 1 besitzt ein Traggestell 2, an dem verschwenkbar Striegelzinken 4 angeordnet sind. Zum Verstellen des Striegelwinkels 14 ist ein Antrieb 5 vorgesehen. Beim Striegeln werden die Striegelzinken 4 kontinuierlich so aus- gerichtet, dass die Striegelzinken 4 beim Überschreiten eines Schwellenwertes für den Pflanzenverschüttungsgrad steiler und beim Unterschreiten des Schwellenwertes flacher gestellt werden. Für das laufende Ermitteln des Pflanzenverschüttungsgrades werden von zwei Kameras 8, 10 aufgenommene Bilder analysiert und mit dem Schwellenwert verglichen. Die als Pflanzenverschüttungsgrad ausgewerteten Bilder können hinsichtlich Aufnahmezeitpunkt und -ort gespeichert werden.

Ansprüche

1. Verfahren zum Striegeln, bei dem ein Bodenbearbeitungsgerät verwendet wird, das schwenkbare Striegelzinken, die in den Boden eingreifen, um Pflanzen mit Erdreich zu verschütten, aufweist, dadurch gekennzeichnet, dass der Pflanzenverschüttungsgrad (PSC) erfasst und die Ausrichtung der Striegelzinken in Abhängigkeit vom Pflanzenverschüttungsgrad (PSC) geändert wird.
2. Verfahren nach Anspruch 1, dadurch gekennzeichnet, dass der Pflanzenverschüttungs- grad (PSC) mit Hilfe von Bildern ermittelt wird, wobei die Bilder von auf den zu bearbeiten- den Boden gerichteten Kameras, bezogen auf die Arbeitsrichtung, vor und nach dem Bearbeitungsgerät erzeugt werden.
3. Verfahren nach Anspruch 1 oder 2, dadurch gekennzeichnet, dass der Pflanzenverschüttungsgrad (PSC) unter Anwenden der Formel

$$PSC = 100 \times \left(\frac{L_o - L}{L_0}\right) \tag{6}$$

ermittelt wird, wobei L_0 die Pflanzenbedeckung vor dem Striegeln und L die Pflanzenbedeckung nach dem Striegeln bedeutet.

4. Verfahren nach einem der Ansprüche 1 bis 3, dadurch gekennzeichnet, dass der erfasste Pflanzenverschüttungsgrad (PSC) mit einem Schwellenwert für den Pflanzenverschüttungsgrad (PSC) verglichen wird.
5. Verfahren nach Anspruch 4, dadurch gekennzeichnet, dass ein Schwellenwert im Be- reich 5 bis 25% gewählt wird und insbesondere 20% beträgt.
6. Verfahren nach Anspruch 4 oder 5, dadurch gekennzeichnet, dass die Striegelzinken bei einem Pflanzenverschüttungsgrad (PSC), der über dem Schwellenwert liegt, steiler im Sinne einer Vergrößerung des Striegelwinkels gestellt werden, und dass die Striegelzinken bei einem Pflanzenverschüttungsgrad (PSC), der unter dem Schwellenwert liegt, flacher im Sinne einer Verkleinerung des Striegelwinkels gestellt werden.
7. Verfahren nach einem der Ansprüche 1 bis 6, dadurch gekennzeichnet, dass die von den Kameras aufgenommenen Bilder zu Excessive Green Red (ExGR) transformiert und an- schließend über Graussschwellen Binärbilder erzeugt werden, wobei die Formeln

$$Image_{ExGR} = Image_{ExG} - Image_{ExR} \quad (7)$$

$$Image_{ExR} = \frac{1.4 \times Image_{red} - Image_{blue}}{Image_{red} + Image_{blue}} \quad (8)$$

$$Image_{ExG} = \frac{2 \times Image_{green} - Image_{red} - Image_{blue}}{Image_{red} + Image_{red} + Image_{blue}} \quad (9)$$

   angewendet werden.
8. Verfahren nach Anspruch 7, dadurch gekennzeichnet, dass auf Grundlage der Binärbilder die Werte L_0 und L der Pflanzenbedeckung berechnet werden, wobei weiße Bildpunkte relativ zum Gesamtbild ermittelt werden.
9. Verfahren nach einem der Ansprüche 1 bis 8, dadurch gekennzeichnet, dass die Ausrichtung der Striegelzinken kontinuierlich geändert wird.
10. Verfahren nach einem der Ansprüche 1 bis 9, dadurch gekennzeichnet, dass die Ausrichtung der Striegelzinken auf einer Anzeigeeinrichtung angezeigt wird.

11. Bodenbearbeitungsgerät (1) zum Durchführen des Verfahrens nach einem der Ansprüche 1 bis 10, mit einem Holme (3) umfassenden Traggestell (2), mit mehreren an Holmen (3) des Traggestelles (2) angeordneten Striegelzinken (4) und mit wenigstens einem Holmen (3) zugeordneten Antrieb (5) zum Verdrehen von Holmen (3), wobei die Ausrichtung der Striegelzinken (4) durch Verdrehen von Holmen (3) veränderbar ist, dadurch gekennzeichnet, dass an dem Traggestell (1) wenigstens zwei Kameras (8, 10) vorgesehen sind, die zum Erfassen des Pflanzenverschüttungsgrades auf den zu bearbeitenden Boden (17) gerichtet sind und dass eine Steuereinheit (12), vorgesehen ist, die den Antrieb (5) für das Verdrehen von Holmen (3) ansteuert, um die Ausrichtung der Striegelzinken (4) in Abhängigkeit vom Pflanzenverschüttungsgrad zu ändern.
12. Bodenbearbeitungsgerät nach Anspruch 11, dadurch gekennzeichnet, dass ein Rechner vorgesehen ist, in welchem der Pflanzenverschüttungsgrad auf Grundlage der von den Kameras (8, 10) erfassten Bilder ermittelt und mit einem vorgegebenen Schwellenwert verglichen wird.
13. Bodenbearbeitungsgerät nach Anspruch 12, dadurch gekennzeichnet, dass der Rechner mit der Steuereinheit (12) kombiniert ist.
14. Bodenbearbeitungsgerät nach einem der Ansprüche 11 bis 13, dadurch gekennzeichnet, dass der Antrieb (5) zum Verdrehen von Holmen (3) beim Überschreiten und beim Unterschreiten des Schwellenwertes des Pflanzenverschüttungsgrades (PSC) zum Ändern der Ausrichtung der Striegelzinken (4) aktivierbar ist.
15. Bodenbearbeitungsgerät nach einem der Ansprüche 11 bis 14, dadurch gekennzeichnet, dass eine Kamera (8) an dem Traggestell (2), bezogen auf die Arbeitsrichtung (Pfeil 13), vorne und die andere der Kameras (10) hinten angeordnet sind.
16. Bodenbearbeitungsgerät nach einem der Ansprüche 11 bis 15, dadurch gekennzeichnet, dass die Kameras (8, 10) am Traggestell (2) über Träger (7, 9), die von dem Traggestell (2) auf der den Striegelzinken (4) gegenüberliegenden Seite abstehen, angeordnet sind.

17. Bodenbearbeitungsgerät nach einem der Ansprüche 11 bis 16, dadurch gekennzeichnet, dass als Kameras (8, 10) RGB-Kameras, insbesondere full-frame RGB-Kameras, vorgesehen sind.
18. Bodenbearbeitungsgerät nach einem der Ansprüche 11 bis 17, dadurch gekennzeichnet, dass ein Anzeigegerät vorgesehen ist, auf dem der Striegelwinkel (14), den die Striegelzinken (4) mit dem zu bearbeitenden Boden (17) einschließen, angezeigt ist.

Hierzu 2 Blatt Zeichnungen

Fig. 1

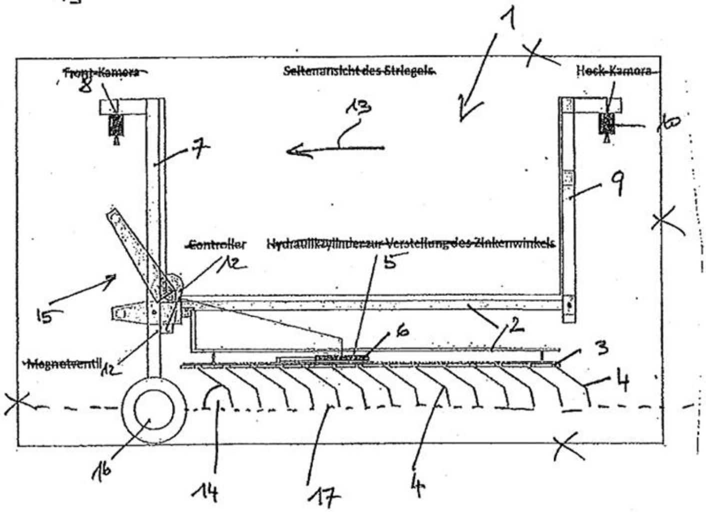

Fig. 2

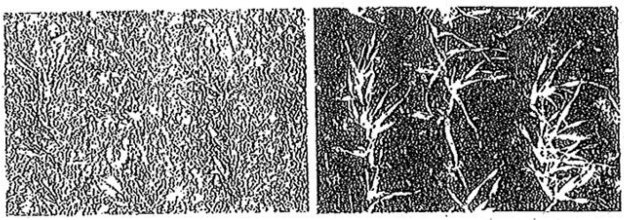

Figure 2.2-2: Fig 1, Seitenansicht ein erfindungsgemäßes Bodenbearbeitungsgerät (Striegel). Fig 2, beispiele für ein RGB-Bild (links) und ein ausgewertetes Binärbild (rechts)

Fig.3

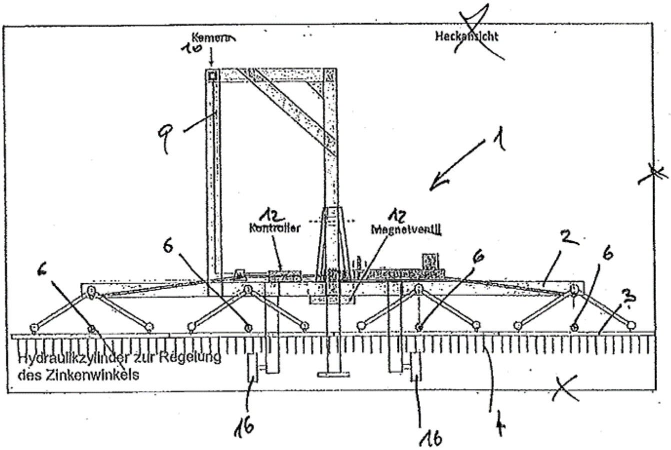

Fig.4

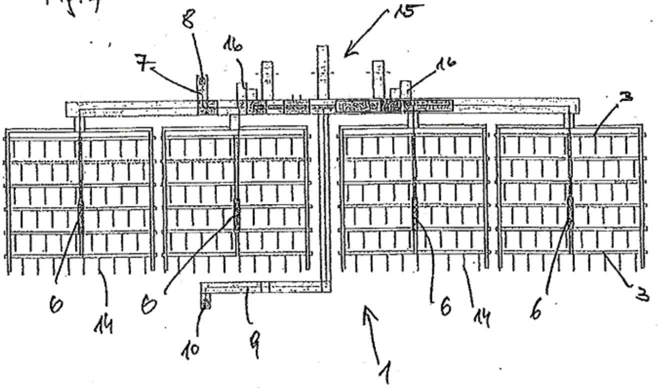

Figure 2.2-3: Fig.3, eine Heckansicht des Bodenbearbeitungsgerätes von Fig. 1 und Fig. 4, eine Draufsicht auf das Bodenbearbeitungsgerät von Fig. 1

2.3 Smart Harrowing—Adjusting the Treatment Intensity Based on Machine Vision to Achieve a Uniform Weed Control Selectivity under Heterogeneous Field Conditions

Michael Spaeth *, Jannis Machleb, Gerassimos G. Peteinatos, Marcus Saile and Roland Gerhards

Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany; Jannis_Machleb@uni-hohenheim.de (J.M.); G.peteinatos@uni-hohenheim.de (G.G.P.); Marcus.saile@uni-hohenheim.de (M.S.); Roland.gerhards@uni-hohenheim.de (R.G.)

*****Correspondence: Michael.spaeth@uni-hohenheim.de; Tel.: +49-711-459-22930

Published in: Agronomy (2020), 10(12), 1925.
© 2020 by the authors. Licensee MDPI, Basel, Switzerland
The original publication is available at:
https://doi.org/10.3390/agronomy10121925

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

2.3.1 Abstract

Harrowing is mostly applied with a constant intensity across the whole field. Heterogeneous field conditions such as variable soil texture, different crop growth stages, variations of the weed infestation level, and weed species composition are usually not considered during the treatment. This study offers a new approach to sensor-based harrowing which addresses these field variations. Smart harrowing requires the continuous adaptation of the treatment intensity to maintain the same level of crop selectivity while ensuring a high weed control efficacy. Therefore, a harrow was equipped with a sensor-system to automatically adjust the angle of the harrow tines based on a newly developed decision algorithm. In 2020, three field experiments were conducted in winter wheat and spring oats to investigate the response of the weed control efficacy and the crop to different harrowing intensities, in Southwest Germany. In all experiments, six levels of crop soil cover (CSC) were tested. The CSC determines the balance between crop damage and weed removal. Each experiment contained an untreated control and an herbicide treatment as a comparison to the harrowing treatments. The results showed an increase in the weed control efficacy (WCE) with an increasing CSC threshold. Difficult-to-control weed species such as *Cirsium arvense* L. and *Galium aparine* L. were best controlled with a CSC threshold of 70%. However, 70% CSC caused up to 50% crop biomass loss and up to 2 $t \cdot ha^{-1}$ of grain yield reduction. With a CSC threshold of 20% it was possible to control up to 98% of *Thlaspi arvense* L. The highest crop biomass, grain yield, and selectivity were achieved with an CSC threshold of 20–25% at all locations. With this harrowing intensity, grain yields were higher than in the herbicide plots and a WCE of 68–98% was achieved. Due to the rapid adjustment of tine angle, the new sensor-based harrow allows users to apply the most selective harrowing intensity in every location of the field. Therefore, it can achieve equal weed control efficacies as using herbicide applications.

Keywords: digital farming; digital image analysis; mechanical weeding; precision farming

2.3.2 Introduction

Concerns about negative side-effects of herbicides on ground and surface water, biodiversity, human health and residues in the food chain and the increasing problem of herbicide resistant weed species are major factors for an increasing interest in non-chemical weed control methods (Lotz et al., 2002; Melander et al., 2005). Mechanical weed control methods such as harrowing and hoeing, are very promising alternatives to chemical weed control. However, the success of mechanical weeding highly depends on the crop, the present weed species composition, the growth stages of the weeds and soil- and weather conditions. Harrowing can achieve 80-90 % weed control efficacy (WCE) against mostly annual broad-leaved weeds in spring cereals (spring barley, oat and triticale) (Rasmussen et al., 2008; Van der Weide et al., 2008; Rasmussen et al., 2009). Inter-row hoeing with no-till sweeps and goosefoot blades controlled up to 89% of the weeds in spring barley (Machleb et al., 2018) Under favorable soil conditions, mechanical weeding can achieve almost the same weed control efficacy as herbicides. Sensor based weed control can improve the aforementioned efficacies resulting in comparable to herbicide treatments outcome. Light and friable soils combined with dry and sunny weather are ideal conditions for harrowing (Home et al., 2002). Wet soil is less favorable for harrowing and weeds have better chances to recover (Kurstjens & Kropff, 2001). Harrowing mainly uproots and buries weeds with soil (Kurstjens & Kropff, 2001). Only a small proportion (less than 10%) of weeds is pulled out of the soil (Kurstjens & Kropff, 2001). It is most efficient, if the weeds had developed only cotyledons and the first true leaf's (Van der Weide et al., 2008).

The selectivity is a suitable parameter to determine the success of weed harrowing. It is defined as the percentage ratio of WCE and crop soil cover (CSC) (Rasmussen et al., 2008). CSC is the percentage of the crop canopy which is covered by soil immediately after harrowing (Rasmussen et al., 2008). Harrowing intensity can be regulated by changing the tine angle in relation to the field surface, the pressure of the tines onto the soil, the tractor driving speed and the number of passes (Rydberg, 1994; Rasmussen & Svenningsen, 1995). Hereby, the treatment intensity must fit to the crop development. Crop plants in the early development stages (e.g. winter wheat in the 3-leaf stage) should be harrowed with a lower intensity than crops in more advanced development stages during tillering to avoid excessive crop plant losses (Rasmussen et al., 2010). It must be considered that harrowing provides a physical stress for the plants and the frost tolerance of the crop plants can be decreased for a limited time (Findlay et al., 1996). However, apart from weed control, harrowing might have several positive effects on the crop including soil loosening, aeration of the soil, increasing soil temperatures and water infiltration, mineral nitrogen-content, and induction of tillering (Steinmann, 2002).

In practical farming, mostly treatment intensity is set by visual assessment of harrowing effect on crop and weeds in a test stripe. Then, a constant treatment intensity is applied throughout the entire field. The treatment is usually not adjusted during the application unless severe crop damage or failure of weed control efficacy becomes very obvious (Rasmussen et al., 2009; Jensen et al., 2004) A constant treatment intensity of the harrow would damage the crop in areas with very light soil and retarded crop growth stage. It would reduce WCE in areas with well-developed crops and high weed infestation levels. Site-specific harrowing with a camera-controlled adjustment of tine angle automatically increases intensity at locations with high density, weed patches and high crop coverage. It reduces the intensity of harrowing in areas with poor crop development low weed density (Søgaard, 1998). To increase the selectivity of harrowing, a balance between crop damage and weed control must be established. Thus, the variability in soil coverage and weed control must be constantly adjusted. For this study, the selectivity has been defined as the relationship between the percentage of weed control and CSC directly after harrowing (Rasmussen et al., 2008). New emergence of weeds was not considered after the treatment. Crops with a low competitiveness against weeds should be cultivated repeatedly (Van der Weide et al., 2008).

In recent decades, different sensor-based harrow developments were performed by (Søgaard, 1998; Rueda-Ayala et al., 2015; Rueda-Ayala et al., 2013; Engelke, 2001; Müter et al., 2014; Peteinatos et al., 2018; Gerhards et al., 2020). In a previous study, Engelke (2001) developed a sensor-based harrow that used a photo-optical sensor to detect the weed density in front of the tractor. A camera measured the actual value and compared it to a preset threshold. A quantitative determination was done between the weed density and soil. Afterwards the harrow adapted automatically to the previously recorded field conditions. Other systems such. Peteinatos et al. (2018) developed a sensor-based harrow and measured the weed density before the application using a bi-spectral camera. In a different study, Søgaard (1998) showed the possibilities of automatically adjusted depth control of the tines. For our approach, Gerhards et al. (2020) demonstrated the possibilities of sensor-based harrowing by simultaneously controlling several parameters like weed density, soil conditions and driving speed, by only measuring the burial before and after the treatment. This simplicity of the system offers a great advantage compared to others. The objective of this study was to test different harrowing intensities based on preset CSC threshold in the decision algorithm of the sensor-based harrow. It was measured how different CSC values influenced WCE, crop biomass, grain yield and selectivity. The sensor-based harrow was capable to realize a constant CSC in heterogenous field by constantly adjusting the tine angle with a hydraulic control system. It was aimed to find the optimum CSC corresponding to the highest selectivity and yield in two spring oats fields and one winter wheat field. It was hypothesized that (1) maximum WCE was already reached at CSC of less than 30 % and higher CSC did not increase WCE anymore. The second hypothesis was that strong harrowing intensities causing 70 % CSC could control difficult-to-control weed species, patches of species such as *Cirsium arvense*. and *Galium aparine*. which usually survive post-emergence harrowing. The third hypothesis was that highest grain yields were achieved with medium CSC thresholds.

2.3.3 Material and Methods

2.3.3.1 Experimental Sites and details

In 2020, three field experiments were conducted in winter wheat and spring oats at two locations of the University of Hohenheim in Southwest Germany to test the sensor-based harrow under heterogeneous field conditions. The first location, Oberer Lindenhof (48.47° N, 9.30° E), is a conventional farm, situated near Eningen, at an altitude of 720 m above sea level. The second location is a conventional farm at Hirrlingen (48.41° N, 8.89° E) with an elevation of 423 m above sea level. The average annual rainfall for both research locations was similar with 790 mm in Eningen and 796 mm in Hirrlingen. During the vegetation period, average temperatures were 1.5 °C higher than average and 80 mm less precipitation was recorded at both locations. Two experiments were carried out in Hirrlingen, one in winter wheat (*Triticum aestivum* L., cv. Patras) and one in spring oats (*Avena sativa* L., cv. Armani). Sowing density was 300 viable seeds m^{-2} in winter wheat and 350 viable seeds m^{-2} in oats. Winter wheat was sown on 10 October 2019 and oats on 15 March 2020. The third field trial near Eningen was sown with 350 viable seeds m^{-2} in oats. (A. sativa, cv. Armani) on 24 March 2020. The row distance was 150 mm in all three experiments. The soil texture was a silty loam at both locations. Details of the experiments are presented in Table 2.3-1.

Table 2.3-1: Details of harrowing experiments in Hirrlingen and Eningen with different mechanical and herbicide treatments in 2020.

Details	**Hirrlingen (48.41° N, 8.89° E) Winter Wheat**	**Hirrlingen (48.41° N, 8.89° E) Spring Oats**	**Eningen (48.47° N, 9.30° E) Spring Oats**
Sea level	423 m	423 m	720 m
Long-term average Precipitation	790 mm	790 mm	796 mm
Long-term average temperature	7.8 °C	7.8 °C	8.5 °C
Soil composition	Clay 53%, Sand 7%, Silt 40%	Clay 56%, Sand 11%, Silt 33%	Clay 43%, Sand 23%, Silt 35%
Crop variety	cv. Patras	cv. Armani	cv. Armani

Sowing	10 October 2019	15 March 2020	24 March 2020
Seed density	300 seeds m^{-2}	350 seeds m^{-2}	350 seeds m^{-2}
Mechanical application	19 March 2020	06 May 2020	8 May 2020
Herbicide application	16 March 2020	16 May 2020	19 May 2020
Harrow driving speed	8 km h^{-1}	8 km h^{-1}	8 km h^{-1}
Harvesting	03 August 2020	03 August 2020	28 August 2020

All three trials were set up as a randomized complete block design with four repetitions and six treatment intensities, one untreated control, and an herbicide treatment across the entire plot. The plot size was 6 × 25 m. Table 2.3-2 provides an overview of the treatments and their respective descriptions.

Table 2.3-2: Treatment descriptions, time of treatment, and crop growth stage of the field trials at Hirrlingen and Eningen in 2020. CSC means crop soil cover, defined as the percentage of the crop canopy that is covered by soil immediately after harrowing. WW-H, SO-H means Winter Wheat-Hirrlingen, Spring Oats-Hirrlingen, respectively, and SO-E means Spring Oats Eningen.

Treatment	**Treatment Acronym**	**Time of Treatment (DAS *)**	**Crop Growth Stage (BBCH **)**
Untreated control	CON	-	-
Herbicide	HERB	WW-H 158, SO-H 63, SO-E 56	BBCH 14
Crop soil cover of 5%	CSC_5%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 15%	CSC_15%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 20%	CSC_20%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 25%	CSC_25%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 45%	CSC_45%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24
Crop soil cover of 70%	CSC_70%	WW-H 161, SO-H 53 SO-E 48	BBCH 21-24

* DAS = Day After Sowing, ** BBCH = Biologische Bundesanstalt, Bundessortenamt und chemische Industrie.

In the herbicide treatment, Concert SX (Cheminova Deutschland GmbH, metsulfuron 38.4 g kg^{-1} a.i. and thifensulfuron 384.5 g kg^{-1} a.i.) was applied with a plot sprayer in oats at Hirrlingen and Eningen at crop stage Biologische Bundesanstalt, Bundessortenamt und Chemische Industrie (BBCH) 14. In winter wheat Atlantis Flex + Biathlon 4D (Bayer CropScience Deutschland GmbH, propoxycarbazone 67.5 g kg^{-1} a.i. and mesosulfuron 43.8 g kg^{-1} a.i. + BASF SE, tritosulfuron 714 g kg a.i., and florasulam 54 g kg a.i.) was also applied with a plot sprayer. The mechanical treatments were performed at crop stage BBCH 21–24. Due to the high clay content, it was important to have ideal soil moisture and friable soil conditions for the mechanical cultivation with the harrow. In the untreated control, no weed control method was carried out. The untreated plots were driven by the tractor in the same manner as for all mechanical treatments but with the harrow raised. Harrowing was performed parallel to the crop rows with a driving speed of 8 km h^{-1}.

2.3.3.2 Description of the Sensor-based Harrow (SenHa)

The treatments were performed with a 6 m wide harrow (Hatzenbichler, St. Andrä, Austria) with flexible tines (25 mm distance between the tines, six tine rows, tine bending 120 °, 6 mm tine diameter, 380 mm tine length, and protected spring winding); see Figure 2.3-1. The maximum force that each tine could apply was 50 newtons, with a decrease of 0.67 newtons $degree^{-1}$. The automatic adjustment of the harrowing intensity was achieved by controlling the hydraulic cylinders responsible for changing the tine angle and by using digital image analysis, as described in (Gerhards *et al.*, 2020b). The harrow was composed of four 1.5 m sections. All the sections received the same signal that was calculated based on the digital image analysis method. Thus, the tine angle was always equal for each harrow section. A gear divider ensured an even distribution of the oil flow to all four hydraulic cylinders. The main function of the machine vision elements was to continuously measure the plant soil cover in front and behind the harrow. Weeds were removed from the images using a morphological filter of object size. Then, crop coverage was calculated. The difference in crop soil coverage between the front camera (before harrowing) and the row camera (after harrowing) is defined as crop soil cover (CSC). CSC was continuously measured during harrowing. The actual CSC value was then compared with a preset threshold value in the image analysis software (IRS). If the actual CSC was higher than the preset threshold, the tine angle was decreased to avoid crop damage. If the CSC was lower than the preset threshold, the tine angle was increased to achieve a higher weed control efficacy. The concept and the importance of the harrow tine angle is depicted in Figure 2.3-1. The angle α describes the angle of each harrow tine during the treatments. Reducing alpha results in a less intense (reduced pressure on tine) treatment, whereas an increase in alpha causes a more aggressive (increased pressure on tine) treatment. The pressure on the tine working part is a linear response equal to the change of alpha. It is important to note that alpha is always measured in relation to the harrow and not in relation to the ground; see Figure 2.3-1.

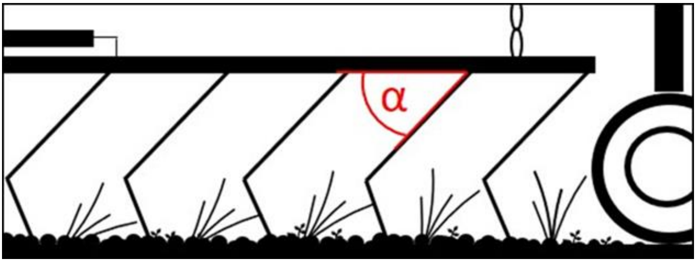

Figure 2.3-1: The concept of adjusting the harrow tine angle α based on the image analysis software (IRS). α is always measured in relation to the harrow, not to the ground.

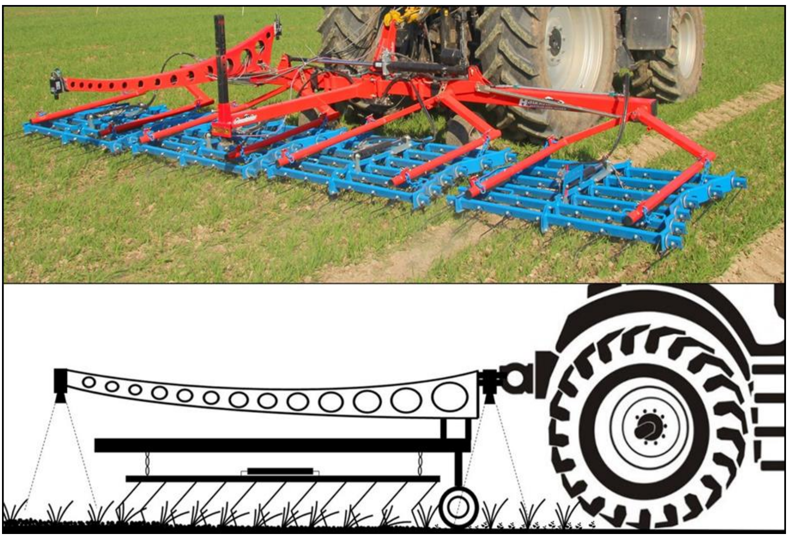

Figure 2.3-2: In the top image, the sensor-based harrow used in winter wheat in spring 2020. The design of the harrow with the field of view from both cameras, containing the automatic adjustment of the tine angle, in the bottom image.

2.3.3.3 Data Collection

All measurements, the biomass cut, and the harvesting of grains was performed only in the 10 center rows to reduce possible border effects. At the time of harrowing, the weed species were in the 2–6-leaf stage. All field measurements and agronomic operations were performed identically. At both research locations, weed plants per m^{-2} were counted for each plot three days prior to harrowing and the herbicide application. Three days after harrowing, weed plants were counted again for the mechanical treatments at Eningen and Hirrlingen. After a waiting period of two weeks, weed plants were also counted for the herbicide treatment in all trails. Weed counts were conducted using a frame of 1/10 m^2. Four random counts were performed in each plot. The percentage of weed control efficiency was calculated in each plot separately, because of the heterogeneity of the trial. An above ground biomass cut of 1 m^2 was performed at BBCH 49 in the spring oats at Eningen and Hirrlingen, and in the winter wheat at Hirrlingen at BBCH 59. The plant matter was separated into weed and crop plants. The fresh crop weight was measured shortly after taking the biomass cuts (data not shown). The plant material was then placed in a drying chamber for 48 h at 80 °C. After the drying process, the dry mass of the crop and weed plants was weighed and recorded for each plot. To assess the grain yield (t ha^{-1}), each plot was harvested at a size of 10 m × 1.25 m. Marginal effects were excluded by a core harvest. The harvest was undertaken using plot combine harvesters (Wintersteiger, Ried im Innkreis, Austria). The oat and winter wheat plots were harvested on 03 August 2020 at Hirrlingen and the spring oats on 26 August 2020 at Eningen.

2.3.3.4 Data Analysis

The data were analyzed with the R Studio software (Version 1.0.136, RStudio Team, Boston, MA, USA). Prior to the analysis, the data were tested for homogeneity of variance and normal distribution of the residues. An analysis of variance (ANOVA) was performed, and the means of each observation were compared with a Tukey-Honest Significant Difference (HSD) test at $\alpha \leq 0.05$. The model used was the following:

$$Y_{ik} = \mu + a_i + b_k + e_{ik} \tag{1}$$

where Y_{ik} is the result (e.g., grain yield) of treatment i at block k. μ is the general mean, a_i is the yield attributed to treatment i, while b_k is the block effect of block k, and e_{ik} is the residual error of that specific plot. CSC (%) was calculated in accordance with Rasmussen *et al.* [10] as:

$$CSC = \frac{100 \times (L_0 - L)}{L_0} \quad (2)$$

were L_0 represents crop coverage before harrowing and L is the crop coverage measured after harrowing. The weed control efficacy (*WCE*) was calculated according to Rasmussen, J. [22] as:

$$WCE = 100\% - \frac{\mathrm{d}s}{0.01 \times \mathrm{d}u} \quad (3)$$

where *ds* is the weed density (weeds m^{-2}) after application of the treatments and *du* is the weed density (weeds m^{-2}) in the same treatment plot before the application.

2.3.4 Results

2.3.4.1 Weed density and the five most common weed species in each trial

The highest weed density before harrowing was measured in spring oats in Eningen with 140 weeds m^{-2}, followed by spring oats in Hirrlingen with 110 weeds m^{-2} and winter wheat in Hirrlingen with 70 weeds m^{-2}. The five most abundant weed species before harrowing with their frequency are listed in Table 2.3-3. In general, there were more difficult-to-control weed species in Hirrlingen including *Galium aparine* in winter wheat with a frequency of 29% and *Cirsium arvense* in spring oats with a frequency of 28%. In spring oats in Eningen, the most problematic weed species was *Polygonum aviculare* L. with a frequency of 17%.

Table 2.3-3: The average weed densities and the frequencies of the five most abundant weed species in the field experiments in Hirrlingen and Eningen.

Location	Crop	Weed Density Weeds m^{-2}	Weed Species
Eningen	Spring oats	140	*Thlaspi arvense* L. (field pennycress) 33% *Veronica persica POIR.* (birdeye speedwell) 23% *Polygonum aviculare* L. (common knotgrass) 17% *Chenopodium album* L. (lamb's quarters) 10% *Capsella bursa-pastoris* L. (shepherd's purse) 7%
Hirrlingen	Winter wheat	70	*Galium aparine.* (cleavers) 29% *Veronica persica POIR.* (birdeye speedwell) 21% *Lamium purpureum* L. (red dead-nettle) 12% *Capsella bursa-pastoris* L. (shepherd's purse) 11% *Stellaria media* L. (chickweed) 9%
Hirrlingen	Spring oats	110	*Cirsium arvense* (creeping thistle) 28% *Polygonum aviculare* (common knotgrass) 19% *Thlaspi arvense* L. (field pennycress) 18% *Chenopodium album* L. (lamb's quarters) 14% *Veronica persica POIR.* (birdeye speedwell) 10%

2.3.4.2 Weed control efficacy in spring oats and winter wheat in Hirrlingen and Eningen

A reduction of the weed density was observed for all chemical and non-chemical treatments at every trial location (see Figure 2.3-3a–c). The herbicide treatment achieved a WCE between 98 and 100% over all experiments. A similar result (WCE 98%) was obtained when harrowing was performed with a CSC threshold of 20% in spring oats in Eningen (Figure 3a). The treatment with the lowest CSC threshold (CSC of 5%) also had the lowest reduction of weed density at all locations. Nonetheless, WCE of the 5% CSC treatment ranged from 30% in oats in Hirrlingen (Figure 2.3-3b) to 63% in oats in Eningen (Figure 2.3-3a).

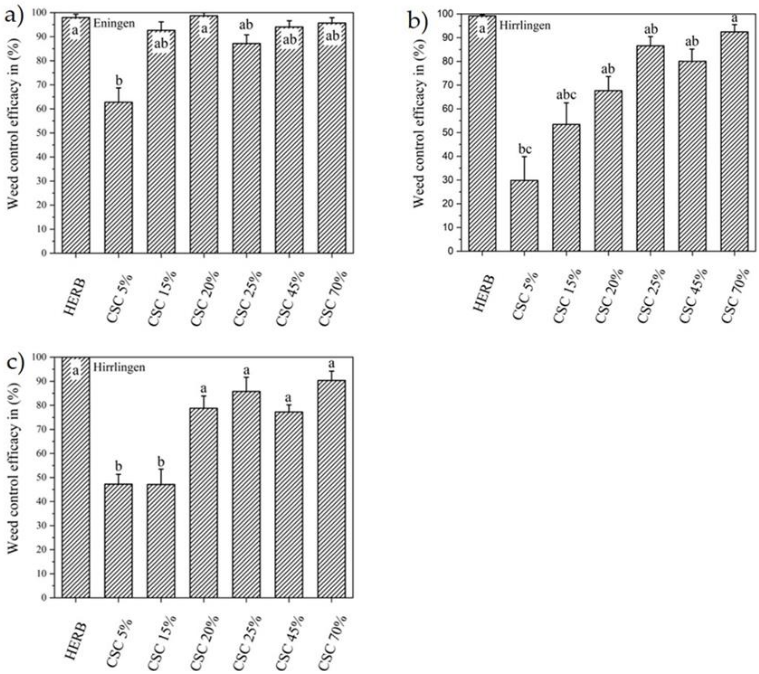

Figure 2.3-3: Weed control efficacy (WCE%) recorded in oats in Eningen (a), in oats in Hirrlingen (b), and in winter wheat in Hirrlingen (c). WCE for harrowing was measured directly after treatment. Herbicide efficacy was assessed 14 days after application. Means with the same letter are not significantly different according to an HSD-test at $\alpha \leq 0.05$. HERB = herbicide application, crop soil cover (CSC) 5, 15, 20, 25, 45, and 70% = crop burial by 5, 15, 20, 25, 45, and 70% soil respectively.

The WCE did not differ in the treatments with a CSC threshold of 15, 25, 45, and 70% (Figure 2.3-3a) in Eningen. It varied between 87% at CSC of 25% and 95% at the CSC threshold of 20%. The variants with a CSC threshold of 45% and 70% were between these extremes. There was a continuous increase in the WCE in oats in Hirrlingen from the 5% CSC treatment (30% WCE) to 86% WCE in the 25% CSC treatment. With a threshold of 45% CSC, WCE decreased slightly to 80% but did not differ from the aforementioned mechanical treatments. The highest value of WCE was achieved with the threshold of 70% CSC (WCE 90%). The CSC threshold of 70% resulted in WCE equal to that of the herbicide application. In winter wheat in Hirrlingen, the highest WCE of 100% was achieved with the herbicide application. The highest WCE with harrowing was measured for the CSC threshold of 70% (91% WCE). The threshold for CSC of 5% and 15% controlled 47% of the weeds. In the range of 20 to 25% CSC threshold, WCE was 78–86%.

Table 2.3-4: Weed densities before and after treatment and weed control efficacy (WCE %) in spring oats in Eningen and Hirrlingen and in winter wheat in Hirrlingen. Means with the same letter are not significantly different according to an HSD-test at $\alpha \leq 0.05$.

Location	**Crop**	**Treatment**	**before Harrowing (Weeds m^{-2})**	**after Harrowing (Weeds m^{-2})**	**WCE (%)**	**Significance p < 0.05**
Eningen	Spring oats	Control	140	135	-	-
		Herbicide *	122	2	98	a
		CSC_5%	57	21	63	b
		CSC_15%	116	6	95	ab
		CSC_20%	106	2	98	a
		CSC_25%	111	14	87	ab
		CSC_45%	86	6	93	ab
		CSC_70%	71	3	96	ab
Hirrlingen	Spring oats	Control	82	82	-	-
		Herbicide *	70	1	99	a
		CSC_5%	68	48	30	bc

		CSC_15%	80	37	53	abc
		CSC_20%	92	30	68	ab
		CSC_25%	60	8	86	ab
		CSC_45%	148	30	80	ab
		CSC_70%	81	6	92	a
Hirrlingen	Winter wheat	Control	46	45	-	-
		Herbicide *	57	0	100	a
		CSC_5%	60	32	47	b
		CSC_15%	56	30	47	b
		CSC_20%	52	11	79	a
		CSC_25%	29	4	86	a
		CSC_45%	30	7	77	a
		CSC_70%	50	5	90	a

* Herbicide weed control efficacy was measured 14 days after application.

2.3.4.3 Crop dry biomass in spring oats and winter wheat in Hirrlingen and Eningen

Crop dry mass was lowest in the untreated control and the harrowing variant with 70% CSC threshold (Figure 2.3-4a–c). The highest amount of dry matter at all locations was achieved at a CSC threshold of 15% with values ranging from approx. 400 to 490 g m^{-2}. In the lowest intensity of 5% CSC threshold, 210–245 g m^{-2} dry crop mass was observed.

In Eningen (Figure 2.3-4a), the highest oats dry mass was observed for the CSC threshold of 15%, with a total amount of 408 g m^{-2}. Similarly, high dry biomass was achieved for the CSC threshold of 20% and 25% (400 and 393 g m^{-2}). A reduction of crop dry mass was observed for the herbicide application. It had only 323 g m^{-2} dry crop mass. The highest intensity of harrowing (CSC threshold of 70%) and the untreated control had the lowest crop dry biomass of 265 and 249 g m^{-2}.

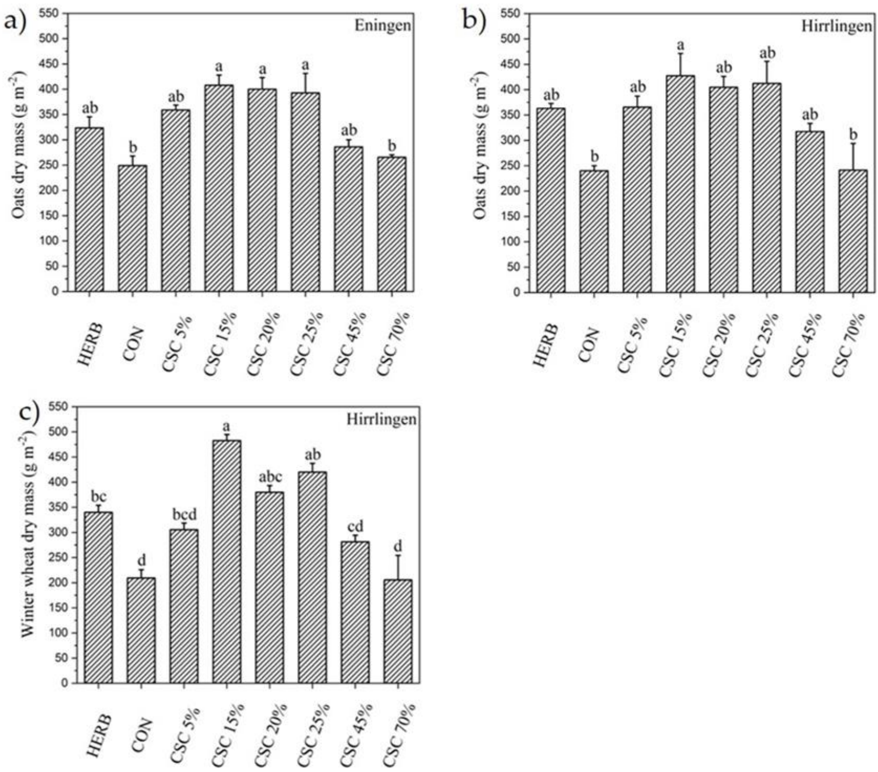

Figure 2.3-4: Dry crop mass (g m^{-2}) recorded in oats in Eningen (a), in oats in Hirrlingen (b), and in winter wheat in Hirrlingen (c). The measurements were made at BBCH 49 in spring oats and BBCH 59 in winter wheat. Means with the same letter are not significantly different according to an HSD-test at $\alpha \leq 0.05$. CON = untreated control, HERB = herbicide application, crop soil cover (CSC) 5, 15, 20, 25, 45, and 70% = crop burial by 5, 15, 20, 25, 45, and 70% soil respectively.

In spring oats in Hirrlingen the dry matter did not differ significantly between the treatments with a CSC threshold of 5, 20, 25, and 45%. The untreated control achieved the lowest crop dry biomass of 240 g m^{-2}, followed by a CSC threshold of 45% with 317 g m^{-2}. The CSC threshold of 25% resulted in the highest crop dry biomass of 412 g m^{-2}.

At the winter wheat trial in Hirrlingen the highest crop dry mass (Figure 2.3-4c) was achieved at CSC threshold of 15% (482 g m^{-2}). Similar to the other experiments, the CSC threshold of 70% and the untreated control had the lowest crop dry mass with 205 g m^{-2} for CSC threshold of 70% and 209 g m^{-2} for the untreated control. The highest crop dry biomass was observed with 15% CSC threshold.

2.3.4.4 Grain yield in oat and winter wheat in Hirrlingen and Eningen

The highest grain yields (7.3 t ha^{-1}) in oats in Eningen were recorded in the herbicide treatment and the harrowing treatment with CSC of 25% (Figure 2.3-5a). Only in these two treatments were yields significantly higher than in the untreated control with 5.9 t ha^{-1}. In oats in Hirrlingen, the herbicide treatment and the harrowing intensities at 15%, 20%, and 25% CSC had significantly higher yields with 6.6–7.0 t ha^{-1} than the untreated control with only 3.4 t ha^{-1}. In the other treatments (CSC threshold of 5%, 45%, and 70%), the yields ranged from 4.6 to 5.0 t ha^{-1}. Similar results were measured in winter wheat in Hirrlingen. The herbicide treatment and the CSC threshold of 20% and 25% achieved the highest grain yields with approximately 8.5 t ha^{-1}. The untreated control plot had the lowest grain yield of 6.5 t ha^{-1}, followed by the CSC threshold of 5% with 6.8 t ha^{-1}. The grain yield of other mechanical treatments varied from 7.5 (CSC threshold of 70%) to 8.4 t ha^{-1} (CSC threshold of 15%).

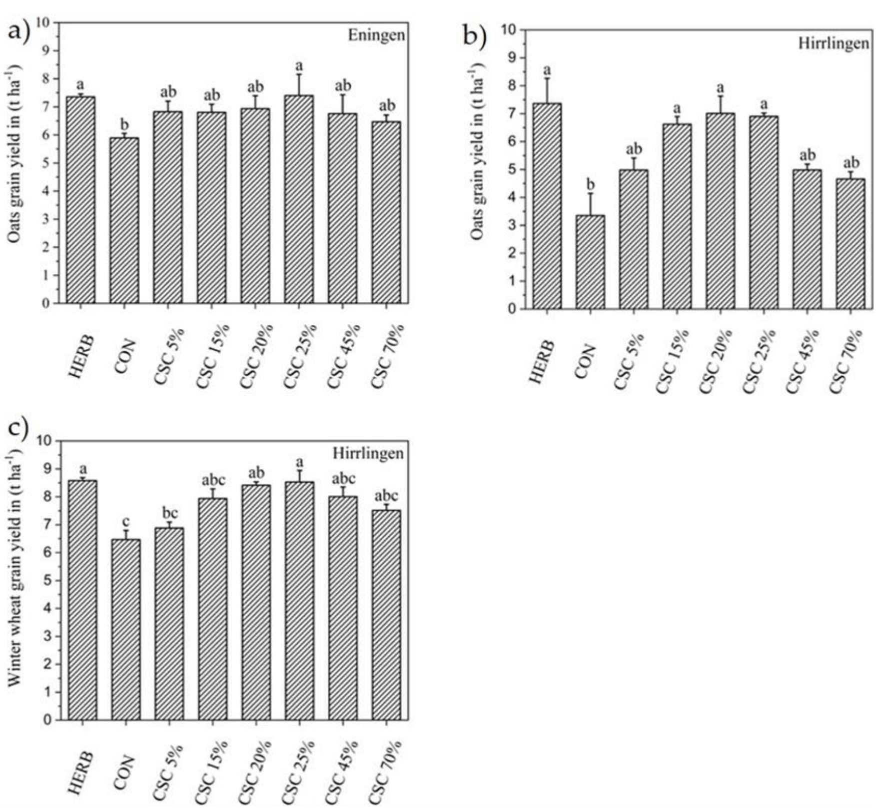

Figure 2.3-5: Grain yield (t ha^{-1}) recorded in oats in Eningen (a), in oats in Hirrlingen (b), and in winter wheat in Hirrlingen (c). Means with the same letter are not significantly different according to an HSD-test at $\alpha \leq 0.05$. CON = untreated control, HERB = herbicide application, crop soil cover (CSC) 5, 15, 20, 25, 45, and 70% = crop burial by 5, 15, 20, 25, 45, and 70% soil respectively.

2.3.5 Discussion

This study presents a new approach to mechanical weeding with a sensor-based harrow for post-emergence weed control in cereals. Different harrowing intensities were applied to determine weed control efficacy and crop response. Tine angle was adjusted to heterogeneous, site-specific field conditions to achieve a constant CSC. This work is an improvement of previous studies on weed harrowing (Rasmussen et al., 2008; Home et al., 2002; Søgaard, 1998; Rueda-Ayala et al., 2015; Rueda-Ayala et al., 2013; Engelke, 2001). It uses a simple image analysis algorithm to continuously adjust harrowing intensity taking the actual CSC as parameter for deciding if intensity needs to be decreased or increased (Gerhards et al., 2020). CSC has been identified as suitable measure for selectivity of weed harrowing (Rasmussen et al., 2008; Rasmussen et al., 2009; Rydberg, 1994). Similar to Rasmussen et al. (2008; 2009), we set a threshold for % CSC that should not be increased during harrowing to avoid yield loss due to crop damage. With the two RGB-cameras continuously measuring crop coverage before and after harrowing, we could realize a constant CSC close to the threshold set even under heterogeneous field conditions. Other systems such Peteinatos et al. (2018) used a bispectral-camera to detect and separate weeds and crop in the field to adjust the intensity of the harrow. However, that algorithm was based on images prior to harrowing and could not react on variable field conditions. In a different approach, three parameters (soil density, weed density and CSC) were measured to increase the selectivity of harrowing (Rueda-Ayala et al., 2013; Rueda-Ayala et al., 2015; Engelke, 2001). However, those algorithms were too complex for making online-decisions on harrowing intensity. The simplicity of the presented system is a great advantage for the practical application and commercial use in cereal production. The presented system is independent on the crop growth stage, driving speed, tine pressure and soil texture (Gerhards et al., 2020). It depends only on CSC. The results of this study show that it is meaningful to increase the CSC threshold in high density weed patches and locations with difficult-to-control weed species such as *G. aparine* and *C. arvense* and to tolerate a higher crop burial in these patches. However, with the current system a steady CSC threshold was applied.

Soil burial is the main effect of post-emergence harrowing (Home et al., 2002). Efficacy of mechanical weed control strongly depends on weather conditions and the weed species composition and weed growth stages (Home et al., 2002; Kurstjens & Kropff, 2001). Up to 97% of *Lepidium sativum* L. and *Chenopodium quinoa* Willd. were covered by harrowing

(Home et al., 2002). With the new sensor-based harrow presented, 98% WCE against *Thlaspi arvense* and *Veronica persica* was achieved in oats at Eningen with a CSC threshold of 20%. At Hirrlingen, a CSC threshold of 70% was needed in oats to achieve 90% WCE. This was probably due to the more problematic weed species such as *C. arvense* and *Polygonum aviculare* that were more tolerant to weed harrowing. In winter wheat, also a threshold of 70% CSC was necessary to control 90% of the major weed species *G. aparine*. Although a threshold of 25% CSC was found to result in highest grain yield, it might be advantageous in aggregated high-density patches of problematic weed species to increase harrowing intensity for higher WCE. Controversially, areas with few or no weeds could be treated with a CSC threshold lower than 25% to avoid crop damage.

In this study, the mechanical weeding at Eningen and Hirrlingen achieved equal results in WCE and grain yield to the herbicide treatment. Several studies reported that under optimum conditions mechanical weeding was as effective as herbicides (Van der Weide et al., 2008; Wiltshire et al., 2003; Riemens et al., 2007). In our case, also better or similar yield results were achieved with a crop-adapted burial intensity of maximum 25% CSC. This facilitation of automatic adjustment control to the heterogeneous field conditions provides both, organic and conventional farmers the opportunity to avoid crop damage and reduce weed density. Furthermore, it is independent of the manufacturer of the harrow implement and can be adapted to every hydraulically adjustable harrow.

Innovations in automated mechanical weed control have increased WCE and selectivity. However, mechanical weeding still needs to be combined with preventive weed control methods such as rotating autumn sown crops with spring crops, ploughing, false seed-bed preparation to reach equal WCE as herbicide treatments. Machleb et al. (2020) provides an overview of commercial sensor-based mechanical weed control systems in agriculture. Sensor-based inter-row hoeing systems with an automatic side-shift control are state of the art and commercially available. Studies such Kunz et al. (2018) showed that with a camera steered hoe an average reduction of weed density by 85% in maize could be achieved. However, it was quite difficult to control the weeds in the intra-row space without damaging the crop. Therefore, the herbicide application achieved a higher WCE. For sufficient WCE between und in the crop rows, the authors suggested a combination of inter-row hoeing and band herbicide spraying in the intra-row space. In a different approach Kunz et al. (2015), automatic hoe guidance achieved WCE of up to 89% in soybeans % and 87% in sugar beet.

For cereals, this study demonstrates that sensor-based harrowing provides a new approach to whole field cultivation, achieving up to 98% WCE without harming the crops. Sensor-based mechanical weed control systems aim on achieving a sustainable alternative for integrated crop protection, with results similar to the herbicide applications. In previous studies, Gerhards et al. (2020) achieved a WCE of up to 96% at 20% CSC, Rasmussen et al. (2009) reported a WCE of at least 80% by CSC of approx. 20% and Brandsaeter et al. (2012) achieved a weed control efficacy of 84% by combining pre- and post-emergence harrowing by using a manual controlled harrow. In our experiment, in a field of 1.5 ha, the system performed well, during the entire experiment. Furthermore, due to adjusting the harrow intensity to heterogeneous, site-specific field conditions by using a CSC threshold between 15-25%, the damage due to crop burial was reduced compared to harrowing with a constant intensity. Crop biomass and grain yield was highest at a CSC threshold of 15-25% at both locations. Harrowing might even promote crop growth as it was found for winter wheat by (Engelke, 2001) and for winter wheat and barley by (Rueda-Ayala et al., 2013).

The outdoor agricultural environment presents complexities that make automation challenging. The systems utilized must be able to operate in an unstructured agricultural environment, but still be able to perform uniformly and robustly throughout the treatment (Bechar & Vigneault, 2016). These complexities include but are not limited to variable light conditions, both regarding the light intensity and its direction in comparison to the implement. Machine vision systems for field use need to be designed to be robust to sunlight variations (McCarthy et al., 2010). In our sensor-based harrow the cameras did not have an automatic shutter regulation, therefore the exposure settings had to be adjusted manually. In cases of high exposure, the captured images were overexposed and therefore misleading, while when the implement was shadowed, the images were underexposed making it hard for the algorithm to detect the coverage of the plants. In order to regulate the lighting effects, powerful external illumination that would eliminate the shadow effects and regulate the light conditions or a closed canopy could be installed (Bechar & Vigneault, 2016). Improvements should be made in the generation of field images due to these variating conditions (Arroyo et al., 2016; Riehle et al., 2020). Plant identification, in order to increase the harrowing intensity on difficult to control weed species, can also be considered.

2.3.6 Conclusion

Automatic adjustment of harrowing with a maximum crop soil cover of 25% resulted in grain yields equal to those of herbicide application and average weed control efficacy of 80%. This automatic harrow provides an opportunity for integrated weed control and reduction of herbicide use. Furthermore, it might be a solution to decrease the risk of herbicide resistance and an effective tool to control problematic weeds such as *G. aparine*. More investigations are needed to better understand the effects of harrowing on cereal development in addition to direct weed control. Study is needed to determine how weeds and crops recover from harrowing, if crop growth can be stimulated by harrowing mainly during tillering, and if new weeds are induced to germinate after harrowing.

2.3.7 Author Contributions

All authors contributed extensively to this work. Michael Spaeth, Jannis Machleb and Marcus Saile organized the setup of the experiment, analyzed the data, evaluated the results and drafted the manuscript. Roland Gerhards and Gerassimos Peteinatos helped in the concept of sensor-based harrowing, designing the experiment, the drafting and revision of the paper.

2.3.8 Funding

This research received no external funding.

2.3.9 Acknowledgments

We are grateful to Hatzenbichler for the technical support and for providing a commercial 6 m wide harrow with hydraulically adjustable tine angle for this study.

2.3.10 References

Arroyo, J., Guijarro, M. and Pajares, G. (2016) An instance-based learning approach for thresholding in crop images under different outdoor conditions. *Computers and Electronics in Agriculture*, 127, 669–679.

Bechar, A. and Vigneault, C. (2016) Agricultural robots for field operations: Concepts and components. *Biosystems Engineering*, 149, 94–111.

Brandsaeter, L.O., Mangerud, K. and Rasmussen, J. (2012) Interactions between pre- and post-emergence weed harrowing in spring cereals. *Weed Research*, 52, 338–347.

Engelke, B. (2001) *Entwicklung eines Steuersystems in der ganzflächig mechanischen Unkrautbekämpfung [Development of a self-adjusting system for broadcast mechanical weed control]*. PhD thesis, Christian-Albrechts-Universität zu Kiel Göttingen, Germany.

Findlay, S., Carreiro, M., Krischik, V. and Jones, C.G. (1996) Effects of Damage to Living Plants on Leaf Litter Quality. *Ecological Applications*, 6, 269–275.

Gerhards, R., Späth, M., Sökefeld, M., Peteinatos, G.G., Nabout, A. and Rueda Ayala, V. (2020) Automatic adjustment of harrowing intensity in cereals using digital image analysis. *Weed Research*, 61, 68–77.

Home, M.C.W., Tillett, N.D., Hague, T. and Godwin, R.J., *et al.* (2002) An experimental study of lateral positional accuracy achieved during inter-row cultivation. In: *Proceedings 2002 of the 5th EWRS Workshop on Physical and Cultural Weed Control* (Eds D.C. Cloutier) (11-13 March, Pisa, Italy). 101–110 Pisa, Italy: EWRS.

Jensen, R.K., Rasmussen, J. and Melander, B. (2004) Selectivity of weed harrowing in lupin. *Weed Research*, 44, 245–253.

Kunz, C., Weber, J. and Gerhards, R. (2015) Benefits of Precision Farming Technologies for Mechanical Weed Control in Soybean and Sugar Beet—Comparison of Precision Hoeing with Conventional Mechanical Weed Control. *Agronomy*, 5, 130–142.

Kunz, C., Weber, J.F., Peteinatos, G.G., Sökefeld, M. and Gerhards, R. (2018) Camera steered mechanical weed control in sugar beet, maize and soybean. *Precision Agriculture*, 19, 708–720.

Kurstjens, D.A.G. and Kropff, M.J. (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research*, 41, 211–228.

Lotz, L.A.P., Van der Weide, R.Y., Horeman, G.H. and Joosten, L.T.A., *et al.* (2002) Weed management and policies: from prevention and precision technology to certifying individual farms. In: *Proceedings of the 12th EWRS Symposium Wageningen 2002* (Papendal, The Netherlands. European Weed Research Society.).

Machleb, J., Kollenda, B., Peteinatos, G.G. and Gerhards, R. (2018) Adjustment of Weed Hoeing to Narrowly Spaced Cereals. *Agriculture*, 8, 54.

Machleb, J., Peteinatos, G.G., Kollenda, B.L., Andújar, D. and Gerhards, R. (2020) Sensor-based mechanical weed control: Present state and prospects. *Computers and Electronics in Agriculture*, 176, 105638.

McCarthy, C.L., Hancock, N.H. and Raine, S.R. (2010) Applied machine vision of plants: a review with implications for field deployment in automated farming operations. *Intelligent Service Robotics*, 3, 209–217.

Melander, B., Rasmussen, I.A. and Bàrberi, P. (2005) Integrating physical and cultural methods of weed control— examples from European research. *Weed Science*, 53, 369–381.

Müter, M., Damerow, L. and Schulze Lammers, P. (2014) Kameragesteuerte mechanische Unkrautbekämpfung in Pflanzenreihen. *Landtechnik*, 69, 3.

Peteinatos, G., Gierer, F. and Gerhards, R. (2018) Precision harrowing using a bispectral camera and a flexible tine harrow. In: *Proceedings of the 28. Deutsche Arbeitstagung über Fragen der Unkrautbiologie und -bekämpfung* (Eds H. Nordmeyer, L. Ulber) (27-01 March, Braunschweig). 385–389. Braunschweig: JKI.

Rasmussen, J., Bibby, B.M. and Schou, A.P. (2008) Investigating the selectivity of weed harrowing with new methods. *Weed Research*, 48, 523–532.

Rasmussen, J., Mathiasen, H. and Bibby, B.M. (2010) Timing of post-emergence weed harrowing. *Weed Research*, 50, 436–446.

Rasmussen, J., Nielsen, H.H. and Gundersen, H. (2009) Tolerance and Selectivity of Cereal Species and Cultivars to Postemergence Weed Harrowing. *Weed Science*, 57, 338–345.
Rasmussen, J. and Svenningsen, T. (1995) Selective Weed Harrowing in Cereals. *Biological Agriculture & Horticulture*, 12, 29–46.
Riehle, D., Reiser, D. and Griepentrog, H.W. (2020) Robust index-based semantic plant/background segmentation for RGB- images. *Computers and Electronics in Agriculture*, 169, 105201.
Riemens, M.M., Van der Weide, R.Y. and BLEEKER, PO & LOTZ, LAP (2007) Effect of stale seedbed preparations and subsequent weed control in lettuce (cv. Iceboll) on weed densities. *Weed Research*, 47, 149–156.
Rueda-Ayala, V., Peteinatos, G., Gerhards, R. and Andújar, D. (2015) A non-chemical system for online weed control. *Sensors*, 15, 7691–7707.
Rueda-Ayala, V., Weis, M., Keller, M., Andújar, D. and Gerhards, R. (2013) Development and testing of a decision-making based method to adjust automatically the harrowing intensity. *Sensors*, 13, 6254–6271.
Rydberg, T. (1994) Weed Harrowing—the Influence of Driving Speed and Driving Direction on Degree of Soil Covering and the Growth of Weed and Crop Plants. *Biological Agriculture & Horticulture*, 10, 197–205.
Søgaard, H.T. (1998) Automatic Control of a Finger Weeder with Respect to the Harrowing Intensity at Varying Soil Structures. *Journal of Agricultural Engineering Research*, 70, 157–163.
Steinmann, H.-H. (2002) Impact of harrowing on the nitrogen dynamics of plants and soil. *Soil and Tillage Research*, 65, 53–59.
Van der Weide, R.Y., Bleeker, P., Molema, G.J., Lotz, L.A.P., Fogelber, F. and Melander, B. (2008) Innovation in mechanical weed control in crop rows. *Weed Research*, 48, 215–224.
Wiltshire, J.J.J., Tillett, N.D. and Hague, T. (2003) Agronomic evaluation of precise mechanical hoeing and chemical weed control in sugar beet. *Weed Research*, 43, 236–244.

2.4 Comparing sensor-based adjustment of weed harrowing intensity with conventional harrowing under heterogeneous field conditions

Michael Spaeth[1], Matthias Schumacher[1] and Roland Gerhards[1]

[1]University of Hohenheim, Department of Weed Science, 70593 Stuttgart, Germany

Correspondence

Michael Spaeth, University of Hohenheim, Department of Weed Science (360 B), D-70599 Stuttgart, Germany. Tel: (+49) 711-459-22938 Email: michael.spaeth@uni-hohenheim.de

Published in: Agronomy (2021), 11(8), 1605.
© 2021 by the authors. Licensee MDPI, Basel, Switzerland
The original publication is available at:
https://doi.org/10.3390/agronomy11081605

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

2.4.1 Abstract

Setting the right intensity is crucial for the success of post-emergence weed harrowing in cereals. The percentage of crop soil cover (CSC) correlates with the selectivity of weed harrowing. Therefore, real-time camera-based measurements of CSC offer a novel approach to automatically adjust the intensity of harrowing. The intensity of harrowing is varied by hydraulic steering of the tine angle. Five field experiments in cereals were conducted at three locations in southwestern Germany in 2019 and 2020 to measure the effect of camera-based harrowing (2020) and conventional harrowing on weed control efficacy (WCE), crop density, and grain yield. For this purpose, pair-wise comparisons of three fixed harrowing intensities (10°, 40°, and 70° tine angle) and three predefined CSC thresholds (CSC of 10%, 20%, and 60%) were realized in randomized complete block designs. Camera-based intensity adjustment resulted in more homogeneous CSC across the whole plot (6–16% less standard deviation variation) compared to conventional fixed settings of the tine angle. Crop density, WCE, crop biomass, and grain yield were significantly higher for camera-based harrowing than for conventional harrowing. WCE and yields of all automatic adjusted harrowing treatments were equal to the herbicide control plots. Camera-based harrowing provides a robust technology for effective weed management with a lower risk of crop damage than conventional harrowing.

Keywords:

Decision support system, digital farming, machine vision, organic farming, site-specific

2.4.2 Introduction

The current problems with herbicide resistant weeds (Busi et al., 2013), the adverse effects of herbicides on the environment, their residues in the food chain (Hillocks, 2012) and the decline of agrobiodiversity (Marshall, 2001) can be associated with the frequent use of herbicides. Mechanical weed control methods including harrowing and hoeing can reduce the reliance on chemical weed control and provides an efficient alternative to herbicides.

Among mechanical weed control treatments, harrowing achieves a high labor-efficiency and up to 90% weed control efficacy (WCE) can be achieved against annual dicotyledonous weed species, if weed plants are relatively small compared to crops and soil is dry during and after harrowing (Rasmussen, 1992; (Brandsaeter et al., 2012; Rasmussen et al., 2008; Van der Weide et al., 2008; Rasmussen et al., 2009). However, WCE can also be as low as 40% if the environmental conditions are less favorable and mostly grass weeds and perennial species occur (Brandsaeter et al., 2012). Under less favorable conditions, maximum WCE reached 62% if pre- and post-emergence harrowing were combined (Brandsaeter et al., 2012).

The working mechanism of harrowing implies a whole field cultivation within and between crop rows and therefore, it needs to be balanced between maximum weed control and minimal crop damage. The selectivity, described as the ratio between percentage WCE and percentage of crop soil cover (CSC) immediately after harrowing (Rasmussen, 1991; Rasmussen & Svenningsen, 1995) is a suitable parameter to evaluate the success of post-emergence harrowing. If the intensity of weed harrowing is too low, WCE and CSC are both low and consequently, selectivity is also low. If the intensity is two high, WCE and CSC are high, which causes again a low selectivity. A high selectivity in cereals is only achieved, if CSC remains constantly in the range around 20%, which the crop can compensate by higher growth rates after harrowing (Rasmussen et al., 2009; Gerhards et al., 2020). The intensity of weed harrowing can be varied by changing the tine angle, driving speed and the number of passes across the field (Rydberg, 1994; Rasmussen et al., 2008; Rasmussen & Svenningsen, 1995). The problem of conventional harrowing is that the intensity is usually set once at the beginning of the treatment. The initial intensity is then kept constant for the whole field. Under heterogenous field conditions, however, conventional harrowing with a fixed intensity may cause crop damage at locations with light soils and less crop coverage and low WCE in areas with high crop coverage and heavy soils. Therefore, harrow intensity needs to be adjusted continuously to achieve high selectivity over the entire field. Several studies were conducted to develop sensor-based technologies for the automatic adjustment of the harrowing intensity (Rueda-Ayala et al., 2013; Engelke, 2001; Peteinatos et al., 2018; Spaeth et al., 2020). Peteinatos et al. (2018) selected weed density measured by bi-spectral cameras to define the optimum harrowing intensity. Rueda-Ayala et al. (2015) assessed soil resistance and plant coverage with ultrasonic sensors to adjust the harrowing intensity. Engelke (2001) and Rueda-Ayala et al. (2013) showed that crop damage in winter wheat and spring barley were reduced, while WCE and crop biomass were increased by continuously adjusting harrowing intensity to variable field conditions. In a recent study, Gerhards et al. (2020) implemented an online control system based on real-time RGB-cameras to realize a constant CSC by hydraulic adjustment of the harrow tine angle.

The objectives of this study were to evaluate WCE, CSC, crop density, crop biomass and grain yield of harrowing treatments with a continuous regulation of intensity and fixed intensities in winter wheat and spring oats. It was investigated, if camera-based harrowing can compensate for field heterogeneity and realize a preset CSC value across the whole plot. It was also studied to which extend spring oats and winter wheat can tolerate different CSC values directly after harrowing without yield loss. The hypotheses tested were that camera-based harrow adjustment i) reduces variations in CSC across the plots, ii) increases WCE and selectivity compared to conventional harrowing with a fixed intensity and iii) results in similar yields to the standard herbicide treatments.

2.4.3 Materials and Methods

2.4.3.1 Experimental sites and design

Three Three field experiments, two in winter wheat (*Triticum aestivum*) cv. Porthus and one in spring oats (*Avena sativa*) cv. Apollon, were conducted in 2019. The experiments were located in Southwestern Germany in Hirrlingen (48.4 °N, 8.89 °E) at an elevation of 423 m above sea level and in Klein Hohenheim (KHH) (48.73 °N, 9.20 °E) with an altitude of 400 m above sea level. In 2020, two additional trials were performed in winter wheat cv. Patras and in spring oats cv. Armani at Hirrlingen and Oberer Lindenhof in Eningen (48.47 °N, 9.30 °E) at an altitude of 720 m above sea level.

Hirrlingen and Oberer Lindenhof are conventional farms and KHH is managed as an ecological farm. The average annual rainfall for Hirrlingen is 796 mm, 690 mm in KHH and 790 mm in Eningen. The average yearly temperature for Hirrlingen is 8.6 °C, in KHH 10.1 °C and in Eningen 6.8 °C (due to higher altitude). In 2019, KHH received 140 mm less rainfall than the average and temperature were 0.9 °C higher than the mean. Precipitation in Hirrlingen 2019 were slightly higher than the average (823 mm) and temperature was almost equal to the long-term average (10.2 °C). In 2020, average temperature at Eningen was 2.1 °C higher than the long-term mean and annual rainfalls were 20 mm higher than the mean.

Tillage before sowing was repeated within all experiments. First, the soil was ploughed (30 cm), followed by a seedbed preparation with a rotary hoe. Cereals were sown in conventional densities and row distance was 150 mm in all five field trials (Table 2.4-1). The soil texture was classified as a silty loam at all three locations. Silt content was slightly higher in KHH (Table 2.4-1).

Table 2.4-1: Year, location, crop with cultivar, sowing date (YYYY-MM-DD), seed rate and soil texture of all five experiments in 2019 and 2020.

Year	Location	Crop	Sowing date	Seed rate (Seeds m^{-2})	Soil texture
2019	Hirrlingen,	Winter wheat, cv. Porthus	2019-10-06	300	49% Clay, 6% Sand, 45% Silt
2019	Hirrlingen,	Spring oats, cv. Apollon	2019-03-01	350	45% Clay, 11% Sand, 44% Silt
2019	KHH,	Spring oats, cv. Apollon	2016-02-26	400	24% Clay, 11% Sand, 65% Silt
2020	Hirrlingen,	Winter wheat, cv. Patras	2020-10-10	300	53% Clay, 7% Sand, 40% Silt
2020	Eningen,	Spring oats, cv. Armani	2020-03-24	350	43% Clay, 23% Sand, 35% Silt

All five trials were set up as a randomized complete block design with four repetitions. In 2019, the three experiments contained five treatments and in 2020, eight treatments were tested in both experiments. The plot size in all trials was 6 × 25 m, with the longer side of the plots in the sowing direction of the crop. The treatments consisted of an untreated control (CON), a herbicide control treatment (HERB) (Hirrlingen and Eningen) or manual weeding (KHH), three conventional (2019 and 2020), and three automatic harrowing treatments (2020). The tine angle in the automatic treatments were adjusted continuously during harrowing according to three pre-set CSC values of 10%, 20%, or 60%. The conventional treatments had three fixed levels of tine angles (Man_I = low tine angle 10°, Man_II = medium tine angle 40°, and Man_III = strong tine angle 70°) that were adjusted once by hand in a strip next to the experimental plots and were not changed during the treatment. A tine angle of 10° corresponded to 10% CSC, a tine angle of 40° corresponded to 20% CSC, and the most aggressive conventional tine angle of 70° was related to 60% CSC. That allowed a pair-wise comparison of conventional and camera-based harrowing. Table 2.4-2 summarizes the treatments in the harrowing experiments in cereals with their different levels of intensity.

Table 2.4-2: Overview of the harrowing treatments with their different intensity level, and relative crop stage at harrowing in the experiments in spring oats and winter wheat in Hirrlingen, KHH and Eningen in 2019 and 2020. Man_I = low conventional adjustment of tine angle (10 °); Man_II = medium conventional adjustment (tine angle 40 °); Man_III strong conventional adjustment (tine angle 70 °); CSC 10% = threshold for automatic adjustment with 10% crop soil burial; CSC 20% = threshold for automatic adjustment with 20% crop soil burial; CSC 60% = threshold for automatic adjustment with 60% crop soil burial.

Year	Location	Crop and growth stage at harrowing	Mechanical treatment Intensity level	
			Conventional	Automatic
2019	Hirrlingen	Winter wheat cv.	Man_I	-
		Porthus	Man_II	
		BBCH 26-28	Man_III	
2019	Hirrlingen	Spring oats	Man_I	-
		cv. Apollon	Man_II	
		BBCH 26-28	Man_III	
2019	KHH	Spring oats	Man_I	-
		cv. Apollon	Man_II	
		BBCH 21-23	Man_III	
2020	Hirrlingen	Winter wheat cv.	Man_I	CSC 10%
		Patras	Man_II	CSC 20%
		BBCH 21-24	Man_III	CSC 60%
2020	Eningen	Spring oats	Man_I	CSC 10%
		cv. Armani	Man_II	CSC 20%
		BBCH 21-24	Man_III	CSC 60%

The control plots were left untreated for the entire growing season. However, it was ensured that the untreated control also received the same number of passes with the tractor wheels as the mechanical and herbicide treatments. Manual weeding in KHH was performed by pulling out weeds by hand several times until cereals started shooting. During weeding the person walked along the tractor tracks in order to avoid crop plant damage. Therefore, soil disturbance was reduced to a minimum. Weed harrowing in winter wheat and spring oats was done in one pass during tillering of the crop (BBCH 21-24) in early March. Harrowing was performed parallel to the crop rows with a driving speed of 8 km h^{-1}. At the time of harrowing, the majority of the weed species had developed 2-4 true leaves. Soil was relatively dry during and at least three days after harrowing without any rainfall in this period. The herbicides were applied shortly before tillering at crop growth stage BBCH 14-18. The herbicide application in Hirrlingen and Eningen was carried out with a plot sprayer (Schachtner-Fahrzeug- und Gerätetechnik, Ludwigsburg, Germany) equipped with flat jet nozzles (Lechler, AD 120-02) at a pressure of 2.4 bar and a speed up to 6.0. In spring oats, metsulfuron and thifensulfuron (Concert SX, 38.4 g a.i kg^{-1} + 384.5 g a.i. kg^{-1}, WG, Cheminova plc) at the recommended field rate of 0.1 kg ha^{-1} was sprayed. In winter wheat, florasulam and tritosulfuron (Biathlon 4D + 1.0 kg ha^{-1} Dash E.C., 54 g kg^{-1} + 714 g kg^{-1}, WG, BASF plc) at the recommended field rate of 0.07 kg ha^{-1} and propoxycarbazone and mesosulfuron (Atlantis Flex + 0.6 L ha^{-1} Biopower, 67.5 g a.i. kg^{-1} and 43.8 g a.i. kg^{-1}, WG, Bayer CropScience plc) at the recommended field rate of 0.2 L ha^{-1} was applied.

2.4.3.2 Camera-controlled harrowing technology

The conventional and automatic harrow treatments were performed with a 6 m wide harrow (Hatzenbichler, St. Andrä, Austria) with flexible tines (6 mm tine diameter, 25 mm distance between the tines, six tine rows, 380 mm tine length, and protected spring winding). The adjustment of the harrowing intensity was achieved by a hydraulic regulation of the tine angle. In automatic mode, the hydraulic cylinder is regulated by a controller containing a decision support system for the continuous adjustment of tine angle based on a threshold value for CSC. Tine angle is increased if the actual CSC is lower than the threshold to increase WCE, and tine angle is decreased if the actual CSC is higher than the threshold to avoid crop damage. CSC is measured online using two RGB cameras mounted before and behind the harrow calculating crop coverage (Gerhards et al., 2020) (Figure 2.4-1).

Figure 2.4-1: The sensor guided harrow in action, plus the hydraulic cylinder, which is used to adjust the tine angle to the actual field conditions.

The CSC (%) was calculated in accordance with (Rasmussen et al., 2008) as:

$$CSC = \frac{100 \cdot (L_0 - L)}{L_0} \quad (1)$$

where L_0 represents crop coverage before harrowing and L is the crop coverage measured after harrowing.

2.4.3.3 Data collection

Data assessment was performed identically in all field experiments. Weed density, crop density, CSC, and crop biomass were measured only in the 10 centre rows, in order to avoid border effect outliers.

CSC for pair-wise comparison of harrowing treatments were calculated by taking five images at random positions in the plots before harrowing and at the same position directly after harrowing with a digital RGB camera (Panasonic DMC-TZ41). The CSC value was calculated, according to the Equation (7) in (Gerhards et al., 2020). Images were taken from a height of 80 cm, providing a field of view of 100 × 83 cm.

Weed density was counted four random times per plot using a quadrate frame of 0.1 m^2. Weed counts were taken one day before treatment, immediately after harrowing, three and 14 days after treatment. WCE was calculated according to (Rasmussen, 1991) as:

$$WCE = 100\ \% - \frac{\mathrm{d}s}{0.01 \cdot \mathrm{d}u} \quad (2)$$

where ds is the weed density (weeds m^{-2}) directly after application and du is the weed density in the same plot before the application. WCE for the herbicide application was calculated using the counts before and 14 days after treatment. Crop density was counted four times at random positions in each plot along one meter of crop row directly after treatment.

The above-ground plant biomass of 1 m2 in each plot was cut shortly before flowering. The plants were separated into crops and weeds and then placed in a drying chamber for 48 h at 80 °C. Only data for dry crop biomass are shown, because weed biomass was close to zero in all treatments and locations.

Grain yield was recorded in sub-plots of 10 m × 1.25 m using a plot combine harvester (Wintersteiger, Ried im Innkreis, Austria). Similar to the biomass cut, in order to avoid marginal effects, the harvest was focused on the center eight lines of every treatment. The grain yield data presented have been corrected for 86% dry weight.

2.4.3.4 Data Analysis

Data were analyzed with the statistical software R (Version 3.4.3, R Foundation for Statistical Computing, Vienna, Austria). Prior to analysis, the data was tested for homogeneity of variance and normal distribution of the residuals by utilizing residual plots (“residual vs predicted” plot and quantile-quantile plot). An analysis of variance (ANOVA) was performed according to the following linear model:

$$Y_{ik} = \mu + a_i + b_k + e_{ik} \quad (3)$$

where Y_{ik} is the measured result (grain yield, dry biomass and WCE) of treatment i at block k. μ denotes the general mean and a_i represents the fixed effects of treatment i, while b_k and e_{ik} represent the random effects of the k^{th} block and the residual error for each plot, respectively. Due to the significant interactions between year and treatments, and between location and treatments, the factors year and location were analyzed separately. For each experiment (location per year), the model was then calculated separately. Means of fixed effects were compared with a Tukey-HSD test at $\alpha \leq 0.05$. Standard deviations of CSC were used to demonstrate the effect of camera-based adjustment of tine angle.

2.4.4 Results

2.4.4.1 The five most abundant weed species at each trail site

Average weed densities before treatments ranged from 35 plants m^{-2} in winter wheat to 275 plants m^{-2} in spring oats both in Hirrlingen 2019, representing medium to high infestation levels in cereals (Table 2.4-3). The most abundant weed species with their dominance are listed in Table 2.4-3. *Chenopodium album* L. (lamb`s quarters), the perennial *Cirsium arvense* L. (creeping thistle) and *Polygonum aviculare* L. (common knotgrass) were most abundant in spring oats. *Galium aparine* L. (cleavers), *Veronica persica* (birdeye speedwell) and *Capsella bursa-pastoris* L. (Shepherd's purse) occurred in spring oats and winter wheat (Table 2.4-3)

Table 2.4-3: Average weed density (weeds m^{-2}) and the dominance of the five most abundant weed species (%) in the trials in Hirrlingen, KHH and Eningen in 2019 and 2020.

Location, Year	Crop	Weed density Weeds m^{-2}	Weed species
Hirrlingen, 2019	Spring oats	275	*Chenopodium album* L. (lamb's quarters) 40% *Cirsium arvense* L. (creeping thistle) 27% *Stellaria media* L. (chickweed) 21% *Galium aparine* L. (cleavers) 4% *Veronica persica* POIR. (birdeye speedwell) 3%
Hirrlingen, 2019	Winter wheat	35	*Capsella bursa-pastoris* L. (Shepherd's purse) 33% *Veronica persica* (birdeye speedwell) 12% *Galium aparine* (cleavers) 11% *Viola arvensis* Murray (field pansy) 9% *Fumaria officinalis* L. (common fumitory) 8%
KHH, 2019	Spring oats	74	*Galium aparine* (cleavers) 28% *Veronica persica* (birdeye speedwell) 23% *Chenopodium album* (lamb's quarters) 21% *Stellaria media* (chickweed) 12% *Sinapis arvensis* L. (charlock mustard) 4%

Hirrlingen, 2020	Winter wheat	70	*Galium aparine* (cleavers) 27% *Veronica persica* (birdeye speedwell) 22% *Lamium purpureum* L. (red dead-nettle) 14% *Capsella bursa-pastoris* (shepherd's purse 13% *Stellaria media* (chickweed) 7%
Eningen, 2020	Spring oats	140	*Thlaspi arvense* L. (field pennycress) 36% *Veronica persica* (birdeye speedwell) 25% *Polygonum aviculare* L. (common knotgrass) 15% *Chenopodium album* (lamb's quarters) 10% *Capsella bursa-pastoris* (shepherd's purse) 9%

2.4.4.2 WCE, crop dry mass and grain yield in Hirrlingen and KHH in 2019

The highest WCE was recorded for the herbicide treatments (98-99%). Harrowing was less efficient than chemical weed control at both sites. WCE significantly increased with higher harrowing intensity (Table 2.4-4). The lowest intensity (Man_I) resulted in 19-32% WCE, Man_II 59-66% and Man_III even 73-88% WCE, which was not significantly different from the herbicide treatments.

The highest crop dry mass was observed for Man_II with 291-482 g m^{-2} at both locations and for the herbicide treatment in Hirrlingen. The highest intensity of harrowing (Man_III) reduced crop dry biomass in spring oats at KHH and winter wheat in Hirrlingen. However, spring oats in Hirrlingen tolerated even higher harrowing intensity and produced equal amounts of dry biomass as Man_II. In the untreated controls, lowest crop dry mass was observed. Man_I ranged between the untreated controls and Man_II.

The highest grain yields with 6.0-10.6 t ha^{-1} were always recorded in the herbicide plots and in the Man_II treatments. They were significantly higher than the untreated controls (5.0-9.0 t ha^{-1}), the low intensity (Man_I) with 5.5-10.4 t $ha^{-1}$and the highest intensity (Man_III) with 5.0-10.1 t ha^{-1}. Winter wheat yielded higher than spring oats in Hirrlingen (Table 2.4-4).

Table 2.4-4: Weed control efficacy (WCE, %, ±SD), crop dry biomass (g m^{-2}, ±SD) and grain yield (t ha^{-1}, ±SD) of the experiments in Hirrlingen and KHH in 2019. Means with the same letter within a column are not significantly different according to HSD-test at $p \leq 0.05$. Levels of significance are given for each experiment separately.

Location, Year	**Crop**	**Treatment**	**WCE (%)**	**Dry biomass (g m^{-2})** ±SD	**Grain Yield (t ha^{-1})** ±SD
Hirrlingen, 2019	Winter wheat, cv. Porthus	CON	-	302 (±9) c	9.0 (±0.3) b
		HERB	98% a	389 (±12) a	10.6 (±0.1) a
		Man_I,	19% c	333 (±31) bc	10.4 (±0.5) ab
		Man_II,	59% b	378 (±24) ab	10.6 (±0.3) a
		Man_III	73% ab	352 (±14) b	10.1 (±0.9) ab
Hirrlingen, 2019	Spring oats, cv. Apollon	CON	-	269 (±11) b	6.6 (±0.5) c
		HERB	98% a	304 (±8) a	8.4 (±0.2) a
		Man_I,	32% c	269 (±14) b	6.9 (±0.4) bc
		Man_II,	66% b	291 (±21) ab	8.2 (±0.2) a
		Man_III	80% ab	290 (±18) ab	7.6 (±0.3) b
KHH, 2019	Spring oats, cv. Apollon	CON	-	384 (±12) c	5.0 (±0.3) b
		HERB	99% a	452 (±17) b	6.0 (±0.2) a
		Man_I,	25% c	401 (±31) bc	5.5 (±0.4) ab
		Man_II,	62% b	482 (±11) a	5.7 (±0.5) ab
		Man_III	88% a	402 (±42) bc	5.0 (±0.4) b

2.4.4.3 Mean CSC and standard deviation for conventional and automatic settings in Hirrlingen and Eningen in 2020

Standard deviations of CSC were generally higher for conventional harrowing than for camera-controlled harrowing. For the automatic adjustment, standard deviations varied from 3% (CSC 10%) to 9% (CSC 60%), while the standard deviations of the conventional settings varied from 12% (Man_I) to 25% (Man_III). Average CSC however, were equal for Man_I and CSC 10%, Man_II and CSC 20%, and Man_III and CSC 60% (Figure 2.4-2).

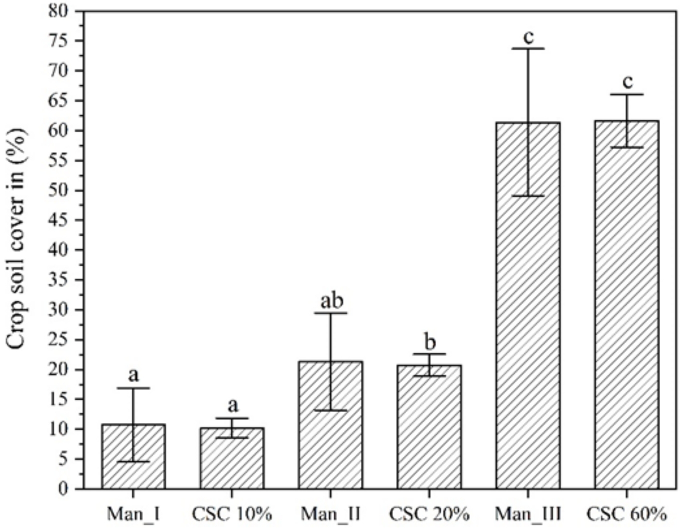

Figure 2.4-2: Mean crop soil cover (CSC) and standard deviation measured in Eningen and Hirrlingen in 2020 after harrowing in three conventional and three automatic settings, p = 0.0034. Means with the same letter were not significantly different according to the HSD-test at $\alpha \leq 0.05$. Man_I = low conventional adjustment of tine angle (10°); Man_II = medium conventional adjustment (tine angle 40°); Man_III high conventional adjustment (tine angle 70°); CSC 10% = threshold for automatic adjustment, soil burial 10%; CSC 20% = threshold for automatic adjustment, soil burial 20%; CSC 60% = threshold for automatic adjustment, soil burial 60%.

2.4.4.4 WCE in spring oats and winter wheat in Eningen and Hirrlingen in 2020

In 2020, WCE was high for chemical and mechanical treatments at both locations. Highest WCEs were recorded for the herbicide treatments with 98 and 100%, followed by CSC 60% with 98% WCE (Figure 2.4-3 a and b). WCE of Man_I was significantly lower than all other treatments. In general, camera-controlled harrowing resulted in slightly higher WCEs than conventional harrowing. For CSC 10%, WCE was 25-35% higher than for Man_I. In the medium intensity, WCE for CSC 20% was 13-25% higher than for Man_II and for CSC 60%, WCE was 9-10% higher than for Man_III (Figure 2.4-3).

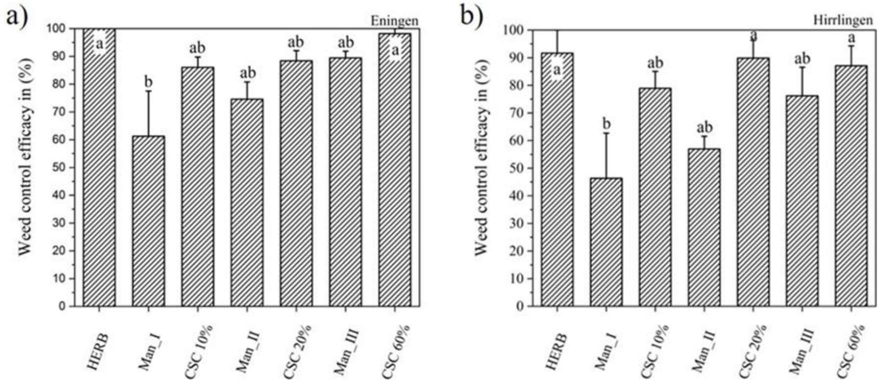

Figure 2.4-3: Percentage of weed control efficacy in spring oats in Eningen, $p = 9.489 \times 10^{-16}$ (**a**) and winter wheat in Hirrlingen $p = 2.064 \times 10^{-05}$ (**b**) in 2020. The measurement was done directly after treatment, only the herbicide treatment was measured 14 days after application. Means with the same letter were not significantly different according to the HSD-test at $\alpha \leq 0.05$. HERB = herbicide application, conventional intensity (Man_) I, II, and III = tine angle 10°, 40°, and 70°; Crop soil cover (CSC) 10, 20, and 60% = plant burial by 10, 20, and 70% soil. The error bars show the standard deviation.

2.4.4.5 Crop density after treatment and weed density at harvest time at Eningen and Hirrlingen in 2020

Crop density was reduced by conventional harrowing in both experiments and by the herbicide treatment in winter wheat in Hirrlingen compared to the untreated control and all camera-controlled harrowing treatments (Table 2.4-5). Conventional harrowing reduced crop density by up to 20% compared to the untreated plots and the camera-controlled harrowing. Weed infestation in 2020 relatively low shortly before harvest with 29-33 plants m^{-2} in the untreated control. In conventional harrowing, higher densities were found with up to 8-18 weeds m^{-2} than in the camera-controlled treatments and the herbicide plots with only 0-1 plants m^{-2}. The comparison of the lowest intensity pair (Man_I, CSC of 10%) showed significant lower weed densities for the camera-controlled plots. At higher intensities, type of harrowing showed no significant differences in both experiments (Table 2.4-5).

Table 2.4-5: Crop density (plants m^{-1}, ±SD; $p = 0.0053$ for Hirrlingen and $p = 0.0086$ for Eningen) after the treatments and weed density (weeds m^{-2}, ±SD; $p = 1.567 \times 10^{-09}$ for Hirrlingen and $p = 1.946 \times 10^{-12}$ for Eningen) at harvest time for winter wheat in Hirrlingen and spring oats in Eningen in 2020. Crop density in the herbicide treatment was measured 14-days after application. Means with the same letter within a column are not significantly different according to the HSD-test at $p \leq 0.05$.

Treatment	Crop density (Plants m^{-1})		Weed density at harvest time (Weeds m^{-2})	
	Winter wheat Hirrlingen (±SD)	Spring oats Eningen (±SD)	Winter wheat Hirrlingen (±SD)	Spring oats Eningen (±SD)
CON	52 (±1.4) a	60 (±1.4) a	29 (±1.8) a	33 (±1.2) a
HERB	45 (±3.3) b	58 (±1.4) a	0 (±0) c	0 (±0) c
Man_I	39 (±2.6) c	56 (±1.6) b	18 (±1.1) b	8 (±0.3) b
Man_II	49 (±2.3) ab	59 (±1.0) a	5 (±2.2) bc	0 (±0) c
Man_III	46 (±1.0) b	49 (±2.2) c	0 (±0) c	0 (±0) c
CSC 10%	54 (±1.2) a	61 (±1.2) a	1 (±0.8) c	0 (±0) c
CSC 20%	52 (±1.5) a	60 (±1.9) a	0 (±0) c	0 (±0) c
CSC 60%	51 (±1.2) a	61 (±0.7) a	0 (±0) c	0 (±0) c

2.4.4.6 Crop dry mass in spring oats and winter wheat at Eningen and Hirrlingen in 2020

The highest dry mass was achieved in the sensor-based treatment CSC of 10% with a value of 674 g m^{-2} for Eningen and 413 g m^{-2} for Hirrlingen compared to untreated control with 489 g m^{-2} in spring oats and 210 g m^{-2} in winter wheat (Figure 2.4-4a and b). In Eningen, the analysis showed no significant differences between chemical and mechanical treatments. In Hirrlingen the lowest intensity CSC of 10% was, with 100 g m^{-2} of dry mass more, significantly higher than the conventional Man_I. Within the medium and strongest intensity pairs, no significant differences were found in Hirrlingen. All sensor-based treatment had a significantly higher dry mass then the herbicide application in Hirrlingen.

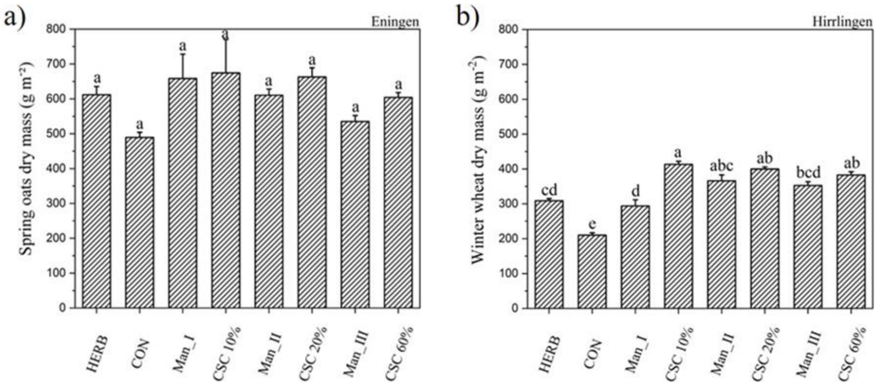

Figure 2.4-4: Dry biomass (g m^{-2}) of spring oats in Eningen, $p = 0.1445$ (**a**) and winter wheat in Hirrlingen, $p = 1.458 \times 10^{-07}$ (**b**) in 2020. Biomass was measured at BBCH 49 in Eningen and BBCH 59 in Hirrlingen. Means with the same letter were not significantly different according to the HSD-test at $\alpha \leq 0.05$. HERB = herbicide application, CON = untreated control, conventional intensity (Man_) I, II, and III = tine angle 10°, 40° and 70°; Crop soil cover (CSC) 10, 20, and 60% = plant burial by 10, 20, and 70% soil. The error bars show the standard deviation.

2.4.4.7 Grain yield in spring oats and winter wheat at Eningen and Hirrlingen in 2020

The highest grain yields were achieved in the camera-based treatment CSC 20% (7.4 t ha^{-1}) in Eningen and in the CSC 60% (8.6 t ha^{-1}) in Hirrlingen. The untreated control exhibited the lowest grain yield (5.9 t ha^{-1}) in Eningen and Man_III (6.5 t ha^{-1}) in Hirrlingen. There were no significant differences for grain yield between all camera-based and chemical treatments. Also, no significant differences were measured between all conventional and the untreated control plots. In Hirrlingen the strongest intensity (Man_III, CSC of 60%) differed significantly with up to 2 t ha^{-1} higher yield for the automatic adjustment. All other harrowing pairs did not differ significantly from each other at both locations (Figure 2.4-5).

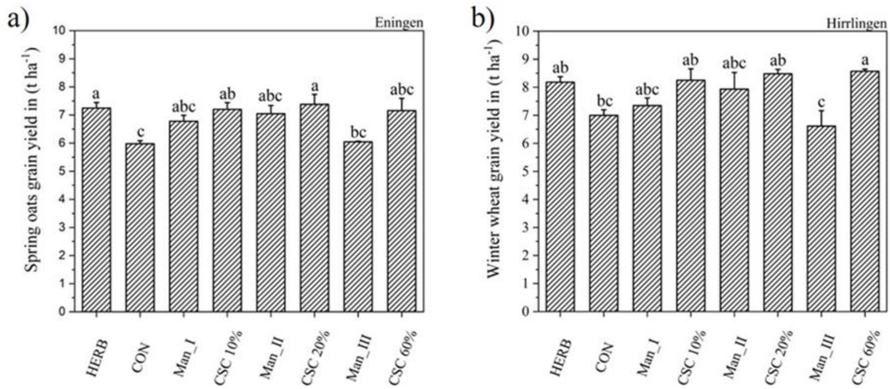

Figure 2.4-5: Grain yield (t ha^{-1}) of spring oats in Eningen, p = 0.0039 (**a**) and winter wheat in Hirrlingen, p = 0.0032 (**b**) in 2020. Means with the same letter were not significantly different according to HSD-test at $\alpha \leq 0.05$. HERB = herbicide application, CON = untreated control, conventional intensity (Man_) I, II and III = tine angle 10°, 40° and 70°, Crop soil cover (CSC) 10, 20, and 60% = plant burial by 10, 20 and 70% soil. The error bars shows the standard deviation.

2.4.5 Discussion

This study presents a pair-wise comparison of conventional harrowing with cam-era-based harrowing using a decision-support-system based on crop soil cover (CSC) (Gerhards et al., 2020). Results revealed the benefits of the new camera-based harrowing system in terms of higher WCE, crop density, crop biomass, and grain yield.

WCE in the present study was considerably high for camera-based and conventional harrowing and both for spring oats and winter wheat. Even at the lowest conventional intensity, on average, 61% WCE was achieved. It increased to 89% WCE for the strongest intensity. Conventional harrowing could achieve a high amount of WCE but only in combination within a high crop damage. High WCE in the present study can be attributed to relatively small weeds at time of harrowing, the tilled soil with a rotary hoe, a high proportion of annual broadleaved weed species in the fields, dry soil conditions before and after harrowing, and a fine seedbed. Similar results regarding WCE, soil tillage, optimal weather and field conditions, and crop damage for conventional harrowing were achieved in previous studies (Rasmussen et al., 2008; Rueda-Ayala et al., 2009; Rueda-Ayala et al., 2011; Bàrberi et al., 2000). However, the sensor-based system can achieve a more precise fine tuning, thus improving the result with minimal crop damage. In other studies, the combinations of pre- and post-emergence harrowing resulted only in a maximum 62% WCE (Brandsaeter et al., 2012). Rasmussen et al. (2008) observed similar WCE of 80% in spring cereals in Denmark. In this study, automatic adjustment of harrowing intensity could avoid excessive crop damage and simultaneously increase WCE, which is in line with (Rueda-Ayala et al., 2013). WCE by automatic intensity control for spring oats was up to 89% and for winter wheat 98% without crop damage in this study. Rasmussen et al. (2008) found a correlation between crop recovery and weather conditions. In their study, CSC of approx. 40% resulted in total crop recovery in dry years. In our case, a total crop recovery was even achieved with CSC of 60% in the automatic treatments, but not with fixed intensity under dry weather and good growth conditions. Furthermore, crop dry mass and grain yield even increased by automatic adjustment up to 10% and 6% compared to the fixed intensity, respectively. Rueda-Ayala et al. (2013) and Spaeth et al. (2020) even achieved similar results with automatic intensity control. They showed an increase in crop biomass and WCE compared to untreated- and herbicide control in spring cereals in their studies. Rasmussen et al. (2008) reported that harrowing selectivity decreased from autumn to spring cereal cultivation. With the presented automatic harrowing system, there were no differences between winter and spring cereals in these experiments regarding selectivity.

Favourable field conditions during and after harrowing could also explain the high crop recovery of spring oats and winter wheat of up to 60% CSC for the camera-based treatment in the present study without significant yield losses compared to lower intensities. In previous studies, optimum CSC for conventional harrowing were observed in the range of 2–33% (Rasmussen et al., 2008; Rydberg, 1994). Above approx. 40% CSC, significant yield losses were observed, especially under moist soil conditions (Rasmussen et al., 2008). Rydberg (1994) and Rueda-Ayala et al. (2009) reported 80% WCE was associated with CSC variation of 13–16% around an average of 15% CSC in spring barley. Camera-based harrowing resulted in lower variations of CSC and crop losses than conventional harrowing. Additionally, camera-based harrowing did not use an equally strong tine angle such as conventional harrowing to achieve a CSC of 60% under optimum soil condition. If CSC is lower than the optimum, mainly in areas with high crop coverage and heavy soils, WCE decreases with the fixed setting of the tine angle. In areas with lower weed density and light soils, the tine angle becomes flatter with camera-based settings to achieve the decrease in pre-set CSC and crop losses. Rydberg (1994); Rueda-Ayala et al. (2009); Krustjens et al. (2000); and Rueda-Ayala et al. (2011) also reported that incorrect intensities in mechanical weeding increased crop and yield losses. This explains the higher yield and lower crop losses of camera-based harrowing compared to conventional harrowing. Therefore, it is important that harrow intensity needs to be adjusted continuously to achieve high selectivity over the entire field.

However, the efficacy of mechanical weed control by harrowing is also dependent on the weed species and growth stages as well as on the soil texture (Kurstjens et al., 2000; Home et al., 2002; Hock et al., 2006). The presented automatic harrow adjustment works depending on all these factors simultaneously, because they are comprised with the CSC. If there are difficult-to-control weed species or heavy soil conditions, the system adjusts to a stronger tine angle to generate the pre-set CSC. If there are non-difficult-to-control and small weed species, the system adjusts to a lower tine angle to generate the pre-set CSC. This flexibility facilitates the practical use of the new system. In previous works from Rueda-Ayala et al. (2013); Engelke (2001); Peteinatos (2018) and Søgaard (1998), several parameters were included in the decision algorithm, which made automatic adjustment more complicated.

2.4.6 Conclusion

The present study shows that camera-based adjustment of harrowing intensity increased WCE, crop biomass, and grain yield compared to conventional harrowing with a fixed intensity. The implementation of camera-based real-time adjustment of tine angle into a commercial harrow is rather simple and does not require substantial costs, training, and maintenance for the user. The hydraulic regulation of the tine angle is based on continuous measurements of the CSC and the comparison to a pre-set threshold for tolerable CSC. This decision algorithm guarantees that the threshold for CSC is not exceeded during harrowing. Therefore, crop damage was lower for camera-based harrowing compared to conventional harrowing. Camera-based weed harrowing may help to accomplish the targets to reduce pesticide use in European Union member countries. However, further investigations are needed to determine crop and weed response to harrowing under different field conditions.

2.4.7 Acknowledgements

The authors thank Marcus Saile for setting up and conducting the experiments in Hirrlingen. The authors also acknowledge the technical support of Hatzenbichler in providing a commercial 6 m wide harrow with hydraulic adjustment of tine angle for our studies. We are also grateful to Tobias Konrad and Oliver Hübner for their technical support in the experiments in Eningen and Klein Hohenheim.

Author Contributions: All authors contributed extensively to this work. M.S. (Michael Spaeth) organized the setup of the experiment, analyzed the data, evaluated the results, and drafted the manuscript. M.S. (Matthias Schumacher) and R.G. helped in the concept of the manuscript and in drafting and revision of the paper. All authors have read and agreed to the published version of the manuscript.

2.4.8 References

Bàrberi, P.; Silvestri, N.; Peruzzi, A.; Raffaelli, M. Finger-Harrowing of Durum Wheat under Different Tillage Systems. In: Biological Agriculture & Horticulture 2000, 17 (4), 285–303. DOI: 10.1080/01448765.2000.9754850.

Brandsaeter, L.O., Mangerud, K. and Rasmussen, J. (2012) Interactions between pre- and post-emergence weed harrowing in spring cereals. *Weed Research*, 52, 338–347.

Busi, R., Vila-Aiub, M.M., Beckie, H.J. et al. (2013) Herbicide-resistant weeds: from research and knowledge to future needs. *Evolutionary applications*, 6, 1218–1221.

Engelke, B. (2001) *Entwicklung eines Steuersystems in der ganzflächig mechanischen Unkrautbekämpfung [Development of a self-adjusting system for broadcast mechanical weed control]*. Dissertation, Christian-Albrechts-Universität zu Kiel Göttingen.

Gerhards, R., Späth, M., Sökefeld, M., Peteinatos, G.G., Nabout, A. and Rueda Ayala, V. (2020) Automatic adjustment of harrowing intensity in cereals using digital image analysis. *Weed Research*, 61, 68–77.

Hillocks, R.J. (2012) Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. *Crop Protection*, 31, 85–93.

Hock, S.M., Knezevic, S.Z., Martin, A.R. and Lindquist, J.L. (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. *Weed Science*, 54, 38–46.

Home, M.C.W., Tillett, N.D., Hague, T. and Godwin, R.J., *et al.* (2002) An experimental study of lateral positional accuracy achieved during inter-row cultivation. In: *Proceedings 2002 of the 5th EWRS Workshop on Physical and Cultural Weed Control* (Ed D.C. Cloutier) (11-13 March, Pisa, Italy). 101–110 Pisa, Italy: EWRS.

Kurstjens, D.A.G. and Kropff, M.J. (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research*, 41, 211–228.

Kurstjens, D.A.G. and Perdok, U.D. (2000) The selective soil covering mechanism of weed harrows on sandy soil. *Soil and Tillage Research*, 55, 193–206.

Marshall, E.J.P. (2001) Biodiversity, herbicides and non-target plants. In: *Proceedings 2001 of Brighton Crop Protection Conference Weeds* (Ed E.J. Jones) (13-15 November, Farnham, UK). 855-862 Farnham, UK: BCPC.

Peteinatos, G., Gierer, F. and Gerhards, R. (2018) Precision harrowing using a bispectral camera and a flexible tine harrow. In: *Proceedings of the 28. Deutsche Arbeitstagung über Fragen der Unkrautbiologie und -bekämpfung* (Eds H. Nordmeyer, L. Ulber) (27-01 March, Braunschweig). 385–389. Braunschweig: JKI.

Rasmussen, J. (1991) A model for prediction of yield response in weed harrowing. *Weed Research*, 31, 401–408.

Rasmussen, J. (1992) Testing harrows for mechanical control of annual weeds in agricultural crops. *Weed Research*, 32, 267–274.

Rasmussen, J., Bibby, B.M. and Schou, A.P. (2008) Investigating the selectivity of weed harrowing with new methods. *Weed Research*, 48, 523–532.

Rasmussen, J., Nielsen, H.H. and Gundersen, H. (2009) Tolerance and Selectivity of Cereal Species and Cultivars to Postemergence Weed Harrowing. *Weed Science*, 57, 338–345.

Rasmussen, J. and Svenningsen, T. (1995) Selective Weed Harrowing in Cereals. *Biological Agriculture & Horticulture*, 12, 29–46.

Rueda-Ayala, V., Peteinatos, G., Gerhards, R. and Andújar, D. (2015) A non-chemical system for online weed control. *Sensors*, 15, 7691–7707.

Rueda-Ayala, V., Weis, M., Keller, M., Andújar, D. and Gerhards, R. (2013) Development and testing of a decision-making based method to adjust automatically the harrowing intensity. *Sensors*, 13, 6254–6271.

Rueda-Ayala, V.P. and Gerhards, R. (2009) Selectivity of Weed Harrowing with Sensor Technology in Cereals in Germany. In: *Proceedings of the 7th European Conference on Precision Agriculture (ECPA)* (Eds E.J. van Henten, D. Goense, C. Lokhorst) (6-7 July, Wageningen, Netherlands). 339-348. Wageningen, Netherlands: Wangeningen Academic.

Rueda-Ayala, V.P., Rasmussen, J., Gerhards, R. and Fournaise, N.E. (2011) The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat. *Weed Research*, 51, 478–488.

Rydberg, T. (1994) Weed Harrowing—the Influence of Driving Speed and Driving Direction on Degree of Soil Covering and the Growth of Weed and Crop Plants. *Biological Agriculture & Horticulture*, 10, 197–205.

Søgaard, H.T. (1998) Automatic Control of a Finger Weeder with Respect to the Harrowing Intensity at Varying Soil Structures. *Journal of Agricultural Engineering Research*, 70, 157–163.

Spaeth, M., Machleb, J., Peteinatos, G.G., Saile, M. and Gerhards, R. (2020) Smart Harrowing—Adjusting the Treatment Intensity Based on Machine Vision to Achieve a Uniform Weed Control Selectivity under Heterogeneous Field Conditions. *Agronomy*, 10, 1925.

Steinmann, H.-H. (2002) Impact of harrowing on the nitrogen dynamics of plants and soil. *Soil and Tillage Research*, 65, 53–59.

Van der Weide, R.Y., Bleeker, P., Molema, G.J., Lotz, L.A.P., Fogelber, F. and Melander, B. (2008) Innovation in mechanical weed control in crop rows. *Weed Research*, 48, 215–224.

3 GENERAL DISCUSSION

This thesis discusses a novel approach to enhance precision farming technology for mechanical weed control in cereals. A camera-based harrowing system, using digital image analysis, was developed and implemented during the work for this thesis. The target was to examine and compare the benefits of different sensor-based and conventional harrow adjustments on weed control efficacy, crop dry mass and grain yield characteristics in cereals. Therefore, the first research paper “Automatic adjustment of harrowing intensity in cereals using digital image analysis” provides a comprehensive description of the current developments, how they fit into agricultural sensor technology, and how agriculture can profit from the use of such a system. Additionally, a patent (second publication) emerged due to the development, which is presented as the second publication in this thesis but is not discussed further. Again, the function and theoretical construction of the sensor-based harrow are described in detail there.

The third research paper “Smart Harrowing—Adjusting the Treatment Intensity Based on Machine Vision to Achieve a Uniform Weed Control Selectivity under Heterogeneous Field Conditions” assesses the functionality and feasibility of the sensor-based harrow in winter- and spring cereals. Different crop soil cover (CSC) thresholds are examined to obtain high selectivity under heterogeneous field conditions. Selectivity is the most common method to describe the effectiveness of a harrow. For this thesis, selectivity is described as the ratio between percentage of weed control and the percentage of CSC immediately after harrowing (Rasmussen *et al.*, 2008). Therefore, both the weed control efficacy and the CSC value are fundamental parameters of this research paper.

Lastly a comparison between a conventional harrow and the current harrow development is presented and discussed in the paper “Comparing sensor-based adjustment of weed harrowing intensity with conventional harrowing under heterogeneous field conditions". The following discussion provides a general assessment of the summarized findings of the entire thesis. Each paper will be directly discussed again and finally there will be a thorough analysis of prospects for future research and developments from which modern agriculture may profit.

Artificial intelligence and sensor technology are becoming an increasingly important sector in agriculture (Bogue, 2017). The first article “Automatic adjustment of harrowing intensity in cereals using digital image analysis” addresses this innovative development by focusing on the substantial improvement of sensor technology for mechanical weed control with a harrow. An entirely new smart control system was designed, constructed and successfully tested with a harrow in the field. Prior to the development of the novel harrowing sensor, system as presented in the first paper, it was found that the uniform field treatment of a conventional harrow, even though quite effective, has to be improved in order to increase the weed control and simultaneously decrease crop damage. Harrowing is an effective control method against most annual broad-leaved weeds in cereals because it acts in as well as between the crop rows (Rasmussen, 1992). However, harrowing alone is less effective against larger weeds, annual grasses (e.g. *Alopecurus myosuroides* Huds) and perennial weeds (e.g. *Cirsium arvense* L.) (Terpstra & Kouwenhoven, 1981; Melander *et al.*, 2012). Therefore, to achieve a more uniform result, if these weed species are present, it is important to combine harrowing with other curative methods like hoeing or chemical weed control (Terpstra & Kouwenhoven, 1981; Melander *et al.*, 2012; Hillocks, 2012). The main weed control mechanism of harrowing is soil burial and uprooting of small weed seedlings (Leblanc & Cloutier; Kurstjens & Kropff, 2001). Under optimum weather conditions, harrowing can achieve up to 90% weed control efficacy (WCE) in spring cereals (Kurstjens & Kropff, 2001; Rasmussen *et al.*, 2008; Van der Weide *et al.*, 2008; Rasmussen *et al.*, 2009). Similar results were observed in the first paper, conventional harrowing resulted in an average WCE of up to 82% along with a maximum CSC (CSC 12-41%) which was compensated by the crop 14 days after harrowing. The intensity of harrowing can be regulated by adjusting the driving speed, tine angle, tine pressure, number of passes to the field conditions, and therefore minimise the risk of crop damage (Rydberg, 1994; Rasmussen & Svenningsen, 1995). Harrowing is always about finding a balance between tolerable crop damage and satisfactory weed removal. Conventional harrows usually possess a manual tine harrow system and the harrowing intensity must be adjusted manually by the farmer. This, however, is seldom done more than once per field. Thus, conventional harrows can never achieve optimal weeding results due to the heterogeneity of agricultural fields. Therefore, the challenge for future harrow developments is to achieve a high degree of weed control while keeping crop damage as low as possible (high selectivity).

The crop-weed selectivity of harrowing and crop recovery have been studied as key relationships to determine the optimal harrowing intensity (Rasmussen *et al.*, 2008). Previous studies have already attempted to achieve high selectivity using sensor-based harrowing systems by adapting intensity levels (Müter *et al.*, 2014; Peteinatos *et al.*, 2018; Søgaard, 1998; Engelke, 2001; Rueda-Ayala *et al.*, 2013; Rueda-Ayala *et al.*, 2015). This was realise by using electronic load cell sensors (Rueda-Ayala *et al.* (2013), bispectral-cameras (Rueda-Ayala *et al.* (2015) & Peteinatos *et al.* (2018), ultrasonic sensors (Rueda-Ayala *et al.* (2013), photoelectric sensors (Engelke (2001), and working depth sensors (Søgaard (1998). However, all these works have shown that it is not easy to define a standard intensity for site-specific field conditions, because it depends on the growth stage of the crop plants, the weed infestation level and the soil conditions. Not even by using acquired information of previous sensor-based harrow systems and combined expert knowledge, was sufficient to formulate simple rules and develop a system for automatic control of harrow intensity. Nevertheless, crop damage, was reduced by some of these harrowing systems through continuous adjustment of the intensity to variable field conditions, both in winter wheat and winter barley (Engelke, 2001; Rueda-Ayala *et al.*, 2013). Also, a higher WCE was achieved when the harrowing intensity was not kept constant along entire field (Rueda-Ayala *et al.*, 2013).

Jensen *et al.* (2004) showed, that the actual crop damage is mainly caused by covering the plants with an excessive amount of soil (CSC) or by tearing off pieces of plant leaves. Therefore, Rasmussen *et al.* (2008) defined the CSC as the percentage of the crop that is covered by soil immediately after harrowing This can be measured in real time based on digital image analysis (Rueda-Ayala & Gerhards, 2009; Weis *et al.*, 2008). The CSC value in the presented approach can be measured and calculated in real time using two RGB cameras. By using the Excessive Green Red Index (ExGR) according to Mink *et al.* (2018) to enhance the contrast between green vegetation and soil while creating a binary image, and by using weed removal from the binary image based on size and shape of plants according to Weis *et al.* (2008), the CSC is obtained. The actual CSC value on the field, is calculated based on the difference between the images from front and rear cameras. The developed decision algorithm in this thesis is based on the selectivity model by Rasmussen & Svenningsen (1995) and Rasmussen *et al.* (2008; 2009) with a threshold for maximum % CSC. This CSC values are set to automatically adjust the tine angle of the harrow. The proper functioning was tested, and the deviation of the achieved CSC value varied from 1.5% to 3 %. Different from previous works (Søgaard, 1998; Engelke, 2001; Müter *et al.*, 2014; Rueda-Ayala *et al.*, 2013), the automatic regulation system is less dependent on the crop growth stage, weed infestation level, driving speed and soil texture as it uses the CSC value as the only input parameter. Gerhards *et al.* (2020b) and Rasmussen *et al.* (2008; 2009; 2010) had observed that cereals could compensate up to 41% burial of crop leaves during harrowing. Taken together, the CSC value is an important variable, that needs to be adjusted, for a site-specific field treatment. Until now, there are only few companies, which presented or already sell a sensor-based harrow. Three of these companies are Einböck (Einböck GmbH, Austria), Treffler (Treffler Maschinenbau GmbH & Co. KG, Germany), and Hatzenbichler (Thomas Hatzenbichler Agro-Technik GmbH, Austria). The harrow, that Einböck presented, is called "AEROSTAR-EXACT" and was equipped with a distance sensor (SMART-CONTROL-Module) to ensure a constant working depth of the tines at a set value. A constant control of the distance between the harrow frame and the soil as well as the deformation of the tines by different counter-pressures according to the soil type are monitored by a sensor. Each separate harrow sections will be adjusted automatically, depending on the soil type. A two-stage regulator compensates the difference between the frame and the soil according to the pre-set value and adjusts all the tines to one constant working depth. The Treffler harrow, called "Precision tine harrow", which is already available on the market, is equipped with a similar depth sensor compared to Einböck. The sensors are used to determine the actual working depth. If the actual working depth is lower or higher than the pre-set threshold, the tine pressure is adjusted as required. Additionally, the ISOBUS compatible operating unit ensures an easy adjustment and monitors the required harrow parameter handling. Hatzenbichler is using the harrow "Original-Striegel" equipped with the decision algorithm, two RGB-cameras and the image-recognition-software from this thesis. This development was presented on the agricultural machinery exhibition "Agritechnica" 2019 in Northern Germany.

However, while implementation of automation and camera-guiding for whole field cultivators like harrows is progressing slowly, there are already commercially available systems for Inter- and Intra-row hoeing technology available. Machleb *et al.* (2020) provide an overview of commercially available sensor-guided hoeing systems, robots, and their manufacturers. Research conducted in the last decade showed that sensor-guided/sensor-based/machine vision hoeing is already established, and provides higher benefits (higher driving speed, better control efficacy) for plant protection than conventional systems without sensor guidance (Kunz *et al.*, 2015; 2018; Gerhards *et al.*, 2020a; Tillett *et al.*, 2002). Fennimore *et al.* (2014) used the Garford In-Row Weeder in *Brassica rapa subsp. chinensis* (L.) (bok choy), *Apium graveolens* (L.) (celery), *Lactuca sativa* (L.) (lettuce), and *Cichorium intybus var. foliosum* (radicchio) and spent 25% less time for additional hand weeding and thinning, and weed infestations were reduced up to 85%. Another advantage according to Prince *et al.* (2012) is, that a hoe equipped with automatic row guidance, can be an important tool in herbicide resistance management to control herbicide-resistant weed biotypes. Even narrow row distances in cereals can be processed with camera-guided hoes. Gerhards et al. (2020a) demonstrated this possibility by equipping a 6 m wide camera-steered hoe with a highly precise GPS reference module to track the movement of the hoe. The authors measured a maximum lateral offset from the row center of only 18.42 mm with a driving speed of up to 15 km h^{-1}. However, such a setup is expensive and not yet affordable for smaller farms until the costs for camera row-guidance systems decline. In general, sensor technology for agriculture such as row-guidance systems, are in the high-cost rage and therefore needs to be more focused on the economic view. Simultaneously, there are robust and cost-effective real-time sensor systems that are commercially available (Zhang *et al.*, 2002). Over the past decades, the challenge was to determine if sensor technology could be applied in the agricultural sector. Now, after successful testing, the aim changes to making the sensor technology commercially available. The presented development of this paper offers, due to its simplicity, a sensor-based mechanical weed control solution in the low-cost range. Only two RGB cameras, one controller, and one operating terminal are required to upgrade an existing hydraulically adjustable harrow.

The third paper “Smart Harrowing—Adjusting the Treatment Intensity Based on Machine Vision to Achieve a Uniform Weed Control Selectivity under Heterogeneous Field Conditions” deals with the application, adaption and feasibility of a sensor-based harrow under normal, heterogeneous field conditions in cereals. Generally, the spatial distribution of weeds is non-uniform across the field (Wiles *et al.*, 1992; Rew & Cousens, 2001; Gonzalez-Andujar & Saavedra, 2003). This can be well observed on this article, where this non-uniform distribution of weed species and weed densities was displayed in the experimental fields at several locations. However, taking only the mean weed density into consideration is of limited value for estimation of yield loss or description of weed population dynamics over a whole field. Additionally, taking spatial distributions into account can provide benefits such as reduced application rates for herbicides. Gerhards & Oebel (2006), reduces herbicide costs for the farmer, and thus protects the environment. Therefore, it is important to apply such strategies that take into account the spatial distribution (Cardina *et al.*, 1997). This has encouraged several weed scientists to develop and use field-specific applications based on machine vision, sensor technology, and satellite data for weed mapping (Machleb *et al.*, 2020; Fernández-Quintanilla *et al.*, 2018). Gerhards & Oebel (2006) developed a patch sprayer using geographical information systems (GIS), that contained three treatment maps and three separate tanks with herbicides to control specific weed species. Computer vision systems and weed identification software were used to classify annual grasses, annual broad-leaved weeds, and perennial weeds. Application considering site-specific weed distribution resulted in herbicide savings of 60% for annual broadleaf weeds and 90% for annual grasses. Using the presented sensor-based harrow, site-specific intensity adjustment was achieved irrespective of the weed density and weed species present in the field. A CSC threshold of 70% shows, a WCE of 91% was achieved at the trial site in Hirrlingen. Half of the average weed density of the most abundant weed species were difficult-to-control weeds such as *C. arvense* or *Polygonum aviculare* (L.). These weeds need an aggressive intensity (like CSC 70%) to be buried and considerably damaged. However, the sensor-based harrow does not take into account the species themselves, rather they are well controlled using the CSC as threshold. In order to achieve a species-specific application intensity, crop plant and weed identification is a necessary component to perform weed control. Peteinatos *et al.* (2020) could achieve up to 98% plant detection and weed species discrimination, using an Artificial Neural Network (ANN) based on ResNet–50, in maize, sunflower, and potatoes. The combined use of such an ANN in the presented harrow development or adapting it to PA in general, could allow a species-specific pre- or post-treatment and poses a new tool for IWM to further reduce herbicide use. Herbicide savings of up to 65% were reported by Kunz *et al.* (2018) when camera-steered inter-row hoeing was combined with band-spraying in comparison to broadcast spraying. Using ANN during site-specific weed control methods, could lead in such cases to even more precise treatment applications (Peteinatos *et al.*, 2020).

However, apart from the benefits of these combined methods, each system is complex, and has to operate in an even more complex and unstructured environment (Bechar & Vigneault, 2016). Therefore, the challenge is to perform treatments uniformly and robustly throughout the field. There is a large number of environmental and sensor-innate factors that limit the quality and functionality of sensors for agriculture. Optical properties such as foliage reflectance properties are related to environmental factors. Uncontrolled environmental conditions, such as variable illumination, overlapping plants, leaf deformations due to pest damage, and seasonal differences through irrigation, could affect the visual appearance of crop and weed plants. The small recording range of e.g. ultrasonic sensors, and the complex processing of the large volume of data obtained by sensors are only two of several factors that influence the suitability of certain sensor (Ali *et al.*, 2015; Andújar *et al.*, 2011; Longchamps *et al.*, 2012; Wen-Hao, 2020). Especially the variable illumination by sunlight needs to be taken into account for machine vision systems using cameras in the field (McCarthy *et al.*, 2010). Spectral reflectance of plants has a very distinctive shape with low reflectance in the visible spectrum, but with increased reflectance in the green wavelength range (550 nm). At the end of the red range, entering into the NIR region (750-901 nm), there is a high increase of plant reflectance of up to 50% and more (Steward *et al.*, 2019; Amziane *et al.*, 2020). The change between shadow and sunlight, can result in an amplification of the light irradiation. Therefore, improvements should be made in the generation of field images under these varying conditions (Riehle *et al.*, 2020; Arroyo *et al.*, 2016). The cameras used in this thesis, were also limited by changing sunlight conditions, which resulted in repeated errors in the decision support system. There was no automatic shutter regulation, therefore the exposure settings had to be adjusted manually. To avoid such errors, previous studies showed that illumination problems could compensate for outdoor conditions when using a special light ring, backlighting, spectral-reflectance based sensor, dark room or a skyward pointing spectrometer (Sujaritha *et al.*, 2017; Mathieu *et al.*, 2014; Askraba *et al.*, 2016; Pulido-Rojas *et al.*, 2016; Wendel & Underwood, 2017; Zeng *et al.*, 2017). Despite the many possibilities, no device represents a proper solution for practical agriculture. The test-light mounted on the harrow was already destroyed due to humidity even before it could used properly. Even though, it had a protection level of IP64. It might be useful to use a higher protection level for temporary submersion (IPX 7).

The fourth scientific paper “Comparing sensor-based adjustment of weed harrowing intensity with conventional harrowing under heterogeneous field conditions” deals with the comparison of a conventional harrow and the improvements provided by using a camera-based harrow. Among conventional mechanical weed control methods in cereals, harrowing is one of the few effective methods of treating in narrowly spaced cereals. Only a few studies have been conducted successfully, on the adjustment of hoeing in narrowly spaced cereals without damaging the crop plants (Machleb *et al.*, 2018; Gerhards *et al.*, 2020a). In contrast, harrowing can be used successfully in crop-rows below 15 cm in cereals without damaging crop plants and a high WCE (Brandsaeter *et al.*, 2012; Gerhards *et al.*, 2020b). However, regardless of the effectiveness of conventional weed harrowing heterogeneous field conditions, too aggressive fixed intensity, or harrowing during at the most sensitive developmental stage, i.e. 1–2 true leaves stage of the crop, usually result in a yield reduction (Lundkvist, 2009; Rasmussen, 1993). The results of this work have shown, that the use of a constantly applied fixed intensity, results in either too low WCE and too high weed compensation or in a reduction of the yield due to crop plant reduction. Due to the constantly changing field conditions, an optimal result could not be achieved by conventional harrowing. There was no WCE higher than 80% where simultaneously the corresponding yields were equal to the yield of the herbicide application. The sensor-based harrow could achieve a WCE of up to 98% while grain yield was tended to be higher compared to the herbicide application. However, this was due to minimal or non-existent crop damage with the sensor-based harrow. By comparing the fixed conventional (Man_II) harrowing application with the automatic counterpart adjustment by CSC threshold of 20%, a higher field adaptation (lower variation in CSC), and adjustment of the treatment intensity was observed. This was reflected in tends to be higher results for WCE, dry mass and grain yield and less crop damage in all field experiments. Similar results were found for the biomass and yield in cereals by Engelke (2001) and Rueda-Ayala *et al.* (2013). Through the sensor-based adjustment, there were no functional limitations of the developed harrow. The driving speed was in a typical range for harrowing (8-10 km h^{-1}) and therefore comparable to conventional harrows. Also, Rueda-Ayala *et al.* (2013) and Peteinatos *et al.* (2018) were able to perform experiments with a driving speed set up between 8-10 km h^{-1}. Machleb *et al.* (2020) provides an overview of machine-vision-guidance mechanical weed control systems, e.g. tractor-pulled hoes and full-autonomous robots, that have an average driving speed between 3-5 km h^{-1}. Normally, robots operate at a maximum speed of 1 km h^{-1}. There are a few exceptions in which camera-guided hoes performed better at higher speeds like 8 km h^{-1} (Kunz *et al.*, 2015; Gerhards *et al.*, 2020a). However, while WCE increased in these experiments at a higher hoeing speed, grain yield did not show a consistent result compared to the herbicide treatment of the experiments. The benefit of the much higher driving speeds of a harrow in combination with a site-specific application, provides our system with a clear advantage compared to other camera-based mechanical weeding systems, in cereals. The higher driving speed of the harrow is practical through the whole-field cultivation and the processing power of the controller. Precision-hoes should never get too close to the crop row and therefore require a much higher precision than harrows, especially in narrowly sown crops. This can only be achieved by a slower driving speed and using precision sensor and RTK/GNSS technology. An additional reason is that in previous developments the extensive processing power was not available, and machine vision needs to be improved with faster classification algorithms (Lee *et al.*, 1999; Fernández-Quintanilla *et al.*, 2018). This was also the limiting factor for the sensor-based harrow, development by Peteinatos *et al.* (2018). Due to a lack of processing power, the data collected by the sensor could not be processed properly, resulting in the operating software crashing frequently (Peteinatos, 2021). In our development, we could not observe such problems. Due to the constant improvement in technical performance, these problems fade. It can be concluded that sensor-supported machinery, especially for mechanical weeding, can help the farmer to facilitate the labor and increase the efficiency of weed control operations (Machleb, 2020).

There are a large number of factors that can affect the selectivity of harrowing. Machine-dependent factors such as tine pressure, single-tine adjustment, tine angle, tine type and thickness, but also field conditions such as soil texture, weed infestation, weed species, crop and weed growth stage should be taken into account (Rueda-Ayala *et al.*, 2013; Peteinatos *et al.*, 2018; Gerhards *et al.*, 2020b; Spaeth *et al.*, 2020b). Generally, all factors should be taken into account for the optimal adjustment of harrow intensity, but due to the large number of variations, this would only be possible by combining several sensors-systems. By combining the camera-based harrow from Gerhards *et al.* (2020b) with a single-tine adjustment (e.g. "Precision tine harrow" from Treffler), and using a working depth sensor, selectivity on each tine can be adjusted to the prevailing situation on the field. The camera system ensures that the field conditions are taken into account and the tine angle is adjusted. Using the single-tine adjustment, selectivity is achieved on each tine, and with the working depth sensor, each tine will be controlled individually to ensure that all tines are at a similar depth. These provides the possibility to treat also cultures like potatoes. Meanwhile, the technical possibilities are available, but the economic aspects are not taken into account in such considerations. Despite all, the presented development works relatively independent of all factors which can affect harrow intensity. The most important adjusting parameter is, that the result (image from the rear side of the harrow, after treatment) of the current treatment intensity is online taken into the decision support system. So, the next decision is always based on the previous treatment. None of the previous sensor-based harrow developments considered the result of their intensity adjustment, for the next intensity decision. But especially taken the result into account is essential for a precision, site-specific field adjustment of harrowing intensity. If the automatic adjusted treatment intensity does not achieve the desired effect, the presented system will re-adjust the intensity immediately.

Now, change is in progress and precision agriculture has become state of the art in science, and its feasibility has been proven in the last decades in Europe. Also, sensor-based machines used for mechanical weed control (e.g. "K.U.L.T. iVision" or "Precision Tine Harrow from Treffler") start to get established and commercially available on the market. In the near future, research should be focused on the fusion and integration of different approaches for site-specific weed control. Future approaches should be based, less on a one-sided consideration and much more on a holistic weed management approach where different technologies are combined. Each additional combination reduces factors of influence that are not taken into account and increases the overall efficiency of weed management. For example, with the developed automatic harrow, decisions can be made and weed species could be recorded using the same cameras (with an Artificial Neural Network (ANN)) simultaneously. The big disadvantage of this example would be that the driving speed must be reduced a lot. Peteinatos *et al.* (2020) was able to classify 11 different weed species in maize with an accuracy of 98%. After a harrowing treatment, a list of weed species would be available, which can be used to decide if a second treatment with a harrow is needed or if a weed species specific herbicide should be applied, e.g. against grass weeds. In combination with an additional sensor-based weed mapping system, like the one described by Mink *et al.* (2018), the herbicide could also be applied site-specific and therefore be reduced to a minimum. The big disadvantage of this example would be that the driving speed for the harrowing application must be reduced a lot. But also other site-specific weed control system such as the development of Gerhards & Oebel (2006) could be used. Gerhards & Oebel (2006) showed with their system herbicide savings of up to 90% for broad-leaf weeds. In combination with a mechanical site-specific pre-treatment, the application rate (L ha^{-1}) for herbicides can be reduced and WCE maximized. A sensor-based holistic weed management approach can enhance the workflow and weed control results but, also increases the costs considerably. Therefore, using combined sensor technology strategies for weed control management in the field, should be an approach for future research. Moreover, using ANNs a distinction between rare/endangered and noxious weeds could be taken into account, which might increase biodiversity in the field and preserve it in the long run. The production of agricultural goods and consumer behavior have the highest contribution to biodiversity loss, with expanding impacts due to growing populations (Dudley & Alexander, 2017). Biodiversity is essential for food, life and keeps the climate in balance (Dudley & Alexander, 2017; Ortiz *et al.*, 2021). The European Union is also promoting the increase of biodiversity until 2030 with strategies such as the "European Green Deal" or the "Farm to Fork" strategy, where the preservation and support of rare species (plants, animals) and the end consumer are taken into account in the whole food value chain (European Commission, 2020). In this context, the main focus for crop protection is to develop alternative strategies for the reduction of plant protection products and to increase productivity in organic farming. Nowadays, using ANNs for species recognition and plant-specific application can be put into practice. Also, making decisions if a certain weed should be controlled or not based on its state of endangerment, is possible. Therefore, this technique should be further developed in the near future to preserve rare weeds during herbicide applications or mechanical weed control. It is only a small step for tackling a complex problem, but it would be a start to ensure further biodiversity loss.

4 SUMMARY

Chemical weed control still plays a major role in weed management strategies and there is a strong need for alternative and integrated weed control measures. The main focus is the reduction of herbicide use because of the negative impact on the environment, possible residues in food products and the increase of herbicide-resistant weed populations. Therefore, the use of mechanical weed control methods such as hoeing, or harrowing can be an alternative for herbicide reduction. However, mechanical control methods are not always an equivalent substitute for chemical weed control, as they are highly dependent on weather, soil and weed pressure. Furthermore, alternative weed control methods must be economically feasible for the farmer. Using intelligent sensor technology for site-specific weed control can increase the efficacy of such traditional weed control implements. The advantage of using sensors for mechanical weed control is an increased precision of the tool guidance as well as the automatic adjustment of the treatment intensity, which results in a higher weed selectivity as well as working speed compared to manual steering. Several scientific studies successfully used intelligent sensors for automatic harrow control by taking many different parameters into account such as weed density, soil resistance factor, and plant growth. However, none of the systems was practically feasible because these factors made the control system too complex and unattractive for farmers. Defining only one parameter (crop soil cover) instead of many provides a new and simple approach which was investigated in this work. The following objectives were addressed within this thesis:

- Developing and testing of the new sensor-based harrow system for automatic adjustment of crop soil cover (CSC);
- Evaluation of the sensor-based harrowing system to determine the effect of CSC value on weed control efficacy (WCE) and crop corresponding parameters;
- Comparison of a conventional harrow with the automatic control system to analyse the effects of constant burial within a field with homogenous weed infestation.

The research objectives were addressed in four scientific publications, the second publication is a patent and is related to the first publication. Therefore, it will not be discussed in the summary.

The first scientific publication focuses on the development, practical implementation and testing of the automatic harrow control system. Two RGB-cameras were mounted before and after the harrow and constantly monitored crop cover. The CSC was then computed out of these resulting images. The image analysis, decision support system and automatic control of harrowing intensity by hydraulic adjustment of the tine angle were installed on a controller which was mounted on the harrow. Eight field experiments were carried out in spring cereals. Mode of harrowing intensity was changed in four experiments by speed, number of passes and tine angle. Each mode was varied in five intensities. In four experiments, only the intensity of harrowing was changed. Modes of intensity were not significantly different among each other. However, intensity had significant effects on WCE and CSC. Cereal plants recovered well from 10% CSC, and selectivity was in the constant range at 10% CSC. Therefore, 10% CSC was the threshold for the decision algorithm. If the actual CSC was below 10% CSC, intensity was increased. If the actual CSC was higher than 10%, intensity was decreased. The new system was tested in an additional field study. Threshold values for CSC were set at 10%, 30% and 60%. Automatic tine angle adjustment precisely realised the three different CSC values with variations of 1.5% to 3%.

The third publication discussed and assessed the site-specific field adaptation of the sensor-based harrow in cereals. In 2020, three field experiments were conducted in winter wheat and spring oats to investigate the response of the weed control efficacy and the crop to different harrowing intensities, in southwest Germany. In all experiments, six levels of CSC were tested. Each experiment contained an untreated control and an herbicide treatment as a comparison to the harrowing treatments. The results showed an increase in the WCE with an increasing CSC threshold. Difficult-to-control weed species such as *Cirsium arvense* (L.) and *Galium aparine* (L.) were best controlled with a CSC threshold of 70%. With a CSC threshold of 20% it was possible to control up to 98% of *Thlaspi arvense* (L.) The highest crop biomass, grain yield, and selectivity were achieved with an CSC threshold of 20–25% at all trial locations. With this harrowing intensity, grain yields were higher than in the herbicide control plots and a WCE of 68–98% was achieved. Due to the rapid adjustment of tine angle, the new sensor-based harrow allows users to apply the most selective harrowing intensity in every location of the field.

The fourth scientific article compares pairwise a conventional harrow intensity with automatic sensor-based harrowing intensity. Five field experiments in cereals were conducted at three

locations in southwestern Germany in 2019 and 2020 to investigate if camera-based harrowing resulted in a more homogenous CSC and higher WCE, biomass, and crop grain yield than a conventional harrow with a constant intensity across the whole plot. For this purpose, pairwise comparisons of three fixed harrowing intensities (10 °, 40 °, and 70 ° tine angle) and three predefined CSC thresholds (CSC of 10%, 20%, and 60%) were realized in randomized complete block designs. Camera-based adjustment of the intensity resulted in 6-16% less standard deviation variation of CSC compared to fixed settings of tine angle. Crop density, WCE, crop biomass and grain yield were significantly higher for camera-based harrowing than for conventional harrowing. WCE and yields of all automatic adjusted harrowing treatments were equal to the herbicide control plots. The optimum selectivity was achieved with 20% CSC. It was demonstrated that camera-based harrowing in combination with CSC control provides a robust technology for effective weed management with lower risk of crop damage.

In this PhD-thesis, a sensor-based harrow was developed and successfully investigated as an alternative to conventional herbicide application in cereals. A permanent, equal replacement of chemical weed control in arable farming systems can only be achieved using modern, sensor-based mechanical weed control approaches. Therefore, the efficacy of the mechanical weed control method can be improved and increased continuously. It has been shown that the precise adjustment of mechanical weed control methods to site-specific weed conditions allows similar WCE results as an herbicide application without causing yield losses. These findings contribute towards modern plant protection strategies to reduce the herbicide use and to establish the acceptance of technical progress in society.

5 ZUSAMMENFASSUNG

Herbizide nehmen nach wie vor eine dominierende Stellung in der Unkrautbekämpfung ein. Dennoch fordert die Politik und auch der Konsument den Einsatz von Herbiziden zu reduzieren und Alternativmaßnahmen zu fördern. Das Ziel ist es, die negativen Auswirkungen auf die Umwelt in Form von Herbizidrückständen in den Lebensmitteln, sowie die Zunahme herbizidresistenter Unkrautpopulationen, zu minimieren. Die Anwendung von mechanischen Unkrautbekämpfungsmaßnahmen, wie beispielsweise Hacken oder Striegeln, können hierbei eine Alternative bzw. Ergänzung zum herkömmlichen Herbizideinsatz darstellen. Ein gleichwertiger Ersatz für die chemische Unkrautbekämpfung stellen mechanische Bekämpfungsmethoden allerdings nur in den wenigsten Fällen dar, da diese stark von Wetter, Boden und Unkrautdruck abhängig sind. Aber auch auf der Ebene Effektivität und Wirtschaftlichkeit müssen alternative Unkrautbekämpfungsmethoden mit Herbiziden konkurrieren können, um einen adäquaten Ersatz darzustellen. Durch den Einsatz von Sensortechnik bei der Unkrautbekämpfung, kann die Effektivität und Auslastung der Maschinen gesteigert werden. Der Vorteil im Bereich der mechanischen Unkrautbekämpfung ist die Anpassung der Maschinen an die jeweiligen Unkraut- oder Bodensituationen auf dem zu behandelnden Feld. Hierbei wird die Präzision der Werkzeugführung wie auch die automatische Anpassung der Intensität erhöht, was eine Steigerung der Unkrautbekämpfung und ebenfalls der Arbeitsgeschwindigkeit mit sich bringt. Die automatische Anpassung der Striegelintensität durch Sensoren, wurde bereits in zahlreichen wissenschaftlichen Arbeiten untersucht, jedoch hat sich keines der Systeme auf dem Markt etablieren können. Bei diesen Striegel-Prototypen wurden verschiedenste Parameter wie beispielsweise die Unkrautdichte, der Bodenwiderstand oder das Pflanzenwachstum berücksichtigt. Allerdings konnten bisherige Systeme nur einzelne Einflussfaktoren berücksichtigen und sie eigneten sich daher nicht für den großflächigen praktischen Einsatz. Dieses Problem kann umgangen werden, wenn der Fokus auf die gezielte Verschüttung von Unkräutern und Kulturpflanze (CSC) gerichtet wird. Diese neue Vorgehensweise bei der sensorgesteuerten Striegeltechnik bietet einen einfachen und zugleich umfangreichen Ansatz, der alle Pflanzen-, Boden- und Unkrautrelevanten Parameter berücksichtigt und abdeckt. Mit diesem Prinzip einer automatischen Striegelsteuerung wurden folgende Ziele im Rahmen dieser Arbeit behandelt:

- Entwicklung und Erprobung eines kamerabasierten Striegelsystems zur automatischen Anpassung des CSC
- Untersuchung und Bewertung des entwickelten Striegelsystems, welcher CSC-Wert am besten für die Kulturpflanze geeignet ist;
- Vergleich eines kamerabasierten, automatischen Striegelsystems mit einem konventionellen Striegel mit konstanter Intensität, unter besonderer Berücksichtigung des weed control efficacy (WCE), Bestandesdichte, Selektivität und Kornertrag.

Die Forschungsziele wurden in vier wissenschaftlichen Publikationen behandelt, wobei die zweite Veröffentlichung ein Patent darstellt und mit der ersten Veröffentlichung zusammenhängt. Daher wird in der Zusammenfassung nicht weiter darauf eingegangen.
Die erste wissenschaftliche Veröffentlichung befasst sich mit der Entwicklung und einem praktischen Test der automatischen Striegelsteuerung. Hierzu wurden zwei RGB-Kameras vor und hinter dem Striegel angebracht, um den tatsächlichen CSC-Wert zu messen, berechnen und mit einem vorgegebenen CSC-Schwellenwert abgleichen zu können. Da der Zinkenwinkel den größten Einfluss auf die Verschüttung nimmt, wurde dieser als Parameter für die Ansteuerung festgelegt. Die Ansteuerung erfolgte im Anschluss hydraulisch, durch elektrische Signale an das Magnetventil. Wurde der vorgegebene CSC-Schwellenwert unterschritten, wurde die Striegelintensität erhöht. War der tatsächliche, gemessene CSC-Wert über dem vorgegebenen Schwellenwert, wurde die Intensität verringert. In einem ersten Feldexperiment wurde das neue System auf Genauigkeit getestet und mit einem manuell eingestellten Zinkenwinkel verglichen. Hierbei wurden für das automatische System CSC-Schwellenwerte von 10%, 30% und 60% und für die manuelle Ansteuerung drei äquivalente Zinkenwinkel, festgelegt. Es konnten die voreingestellten, automatischen CSC-Schwellenwerte mit einer Präzision bzw. Standardabweichung von 1,5-3% realisiert werden, während die manuell eingestellten Zinkenwinkel eine Standardabweichung zwischen 18-20% aufwiesen. Dies zeigt deutlich eine höhere Präzision des sensorbasierten Striegels, sowie eine genauere Anpassung an die jeweilige Unkrautsituation auf dem Feld.
Die dritte Veröffentlichung befasst sich mit der standortspezifischen Feldanpassung des sensorbasierten Striegels im Getreide. Drei Feldexperimente wurden durchgeführt, um die Auswirkungen der Feldanpassung sowohl im Sommer-, als auch Wintergetreide zu

untersuchen. In allen Experimenten wurden sechs verschiedene CSC-Schwellenwerte (CSC von 5, 15, 20, 25, 45 und 70%) getestet. Jedes Experiment enthielt eine unbehandelte Kontrolle und eine Herbizidbehandlung als Vergleich. Die Ergebnisse zeigten einen Anstieg des WCE mit einem steigenden CSC-Schwellenwert. Schwer zu bekämpfende Unkrautarten wie *Cirsium arvense* (L.) und *Galium aparine* (L.) wurden am besten mit einem CSC-Schwellenwert von 70% kontrolliert. Mit einem CSC-Schwellenwert von 20% war es möglich, bis zu 98% von *Thlaspi arvense* (L.) zu bekämpfen. Die höchste Kulturpflanzenbiomasse und Kornertrag konnte mit einem CSC-Schwellenwert zwischen 20-25%, an allen Standorten erzielt werden. Bei dieser Striegeleinstellung konnten sogar tendenziell höhere Kornerträge als in den Herbizidbehandlungen erzielt werden. Durch die rasche Einstellung des Zinkenwinkels ermöglicht der neue sensorgestützte Striegel dem Anwender, an jeder Stelle des Feldes die höchstmögliche Anpassungsgenauigkeit, in Abhängigkeit der aktuellen Feldsituation (Unkrautart, Bodentyp) zu erreichen.

Der vierte wissenschaftliche Artikel vergleicht paarweise eine konventionelle Striegelintensität mit einer automatischen, sensorbasierten Striegelsteuerung. In den Jahren 2019 und 2020 wurden dafür fünf Feldversuche in Getreide an drei Standorten in Südwestdeutschland durchgeführt. Hierbei wurde untersucht, ob sensorbasiertes Striegeln im Vergleich zu konventionellem Striegeln mit konstanter Intensität über die gesamte Parzelle zu homogenerem CSC und höherem WCE, Biomasse und Kornertrag führt. Zu diesem Zweck wurden paarweise Vergleiche von drei festen Striegelintensitäten (10 °, 40 ° und 70 ° Zinkenwinkel) und drei vordefinierten CSC-Schwellenwerten (CSC von 10%, 20% und 60%) durchgeführt. Die automatische Anpassung der Intensität führte zu einer 6-16% geringeren Standardabweichung des CSC im Vergleich zu den festen Einstellungen des Zinkenwinkels. Pflanzendichte, WCE, Pflanzenbiomasse und Kornertrag waren beim kamerabasierten Striegeln signifikant höher als beim konventionellen Striegeln. WCE und Erträge aller automatisch eingestellten Striegelbehandlungen waren vergleichbar mit den Herbizid-Kontrollparzellen. Die optimale Selektivität wurde mit einer automatischen Intensitätsanpassung von 20% CSC erreicht. Das kameragestützte Striegeln bietet eine robuste Technologie für eine effektive Unkrautbekämpfung mit geringerem Risiko von Ernteschäden.

In dieser Dissertation wurde ein sensorbasiertes Striegelsystem entwickelt und als erfolgreiche Alternative zur konventionellen Herbizidanwendung und zur

Effektivitätssteigerung herkömmlicher Striegel, im Getreide aufgezeigt. Durch eine präzise Anpassung an standortspezifische Unkraut- und Bodensituationen waren nicht nur die Bekämpfungserfolge vergleichbar mit denen einer Herbizidanwendung, sondern es entstanden auch nur geringfügige Pflanzen- bzw. Ertragsverluste. Die Ergebnisse dieser Arbeit haben das Potential Einfluss auf zukünftige Pflanzenschutzstrategien zu nehmen, da sie die Möglichkeiten der mechanischen Unkrautbekämpfung erweitern, den Herbizideinsatz reduzieren und die Akzeptanz des technischen Fortschritts in der Gesellschaft fördern.

6 GENERAL REFERENCES

Ali, A., Streibig, J.C., Christensen, S. and Andreasen, C. (2015) Image-based thresholds for weeds in maize fields. *Weed Research*, 55, 26–33.

Amziane, A., Losson, O., Mathon, B., Dumenil, A. and Macaire, L., *et al.* (2020) Frame-based reflectance estimation from multispectral images for weed identification in varying illumination conditions. In: *Proceedings 2020* I*nstitute of Electrical and Electronics Engineers, IEEE* (9-12 Nov., Paris, France).

Andújar, D., Escoà, A., Dorado, J. and Fernández-Quintanilla, C. (2011) Weed discrimination using ultrasonic sensors. *Weed Research*, 51, 543–547.

Arroyo, J., Guijarro, M. and Pajares, G. (2016) An instance-based learning approach for thresholding in crop images under different outdoor conditions. *Computers and Electronics in Agriculture*, 127, 669–679.

Askraba, S., Paap, A., Alameh, K., Rowe, J. and Miller, C. (2016) Laser-Stabilized Real-Time Plant Discrimination Sensor for Precision Agriculture. *IEEE Sensors Journal*, 16, 6680–6686.

Bàrberi, P.; Silvestri, N.; Peruzzi, A.; Raffaelli, M. Finger-Harrowing of Durum Wheat under Different Tillage Systems. In: Biological Agriculture & Horticulture 2000, 17 (4), 285–303. DOI: 10.1080/01448765.2000.9754850.

Bechar, A. and Vigneault, C. (2016) Agricultural robots for field operations: Concepts and components. *Biosystems Engineering*, 149, 94–111.

Bhaskar, A. and Vyas, K. (1988) Studies on competition between wheat and Chenopodium album L. *Weed Research*, 28, 53–58.

Blackmore, S. (1994) Precision Farming An Introduction. *Outlook on Agriculture*, 275–280.

Bogue, R. (2017) Sensors key to advances in precision agriculture. *Sensor Review*, 37, 1–6.

Brandsaeter, L.O., Mangerud, K. and Rasmussen, J. (2012) Interactions between pre- and post-emergence weed harrowing in spring cereals. *Weed Research*, 52, 338–347.

Bucci, G., Bentivoglio, D. and Finco, A. (2018) Precision agriculture as a driver for sustainable farming systems: State of art in literature and research. *Quality - Access to Success*, 19, 114–121.

Busi, R., Vila-Aiub, M.M., Beckie, H.J. et al. (2013) Herbicide-resistant weeds: from research and knowledge to future needs. *Evolutionary applications*, 6, 1218–1221.

Cardina, J., Johnson, G.A. and Sparrow, D.H. (1997) The nature and consequence of weed spatial distribution. *Weed Science*, 45, 364–373.

Charalampopoulos, D., Wang, R., Pandiella, S.S. and Webb, C. (2002) Application of cereals and cereal components in functional foods: a review. *International Journal of Food Microbiology*, 79, 131–141.

Dudley, N. and Alexander, S. (2017) Agriculture and biodiversity: a review. *Biodiversity*, 18, 45–49.

Engelke, B. (2001) *Entwicklung eines Steuersystems in der ganzflächig mechanischen Unkrautbekämpfung [Development of a self-adjusting system for broadcast mechanical weed control]*. PhD thesis, Christian-Albrechts-Universität zu Kiel Göttingen, Germany.

European Commission (2020) Communication from the commission to the european parlament, the council, the european economic and social committee and the committee of the regions EU. In: *Biodiversity Strategy for 2030 Bringing nature back into our lives*. COM/2020/380 final Bruessel.

Fennimore, S.T., Smith, R.F., Tourte, L., LeStrange, M. and Rachuy, J.S. (2014) Evaluation and Economics of a Rotating Cultivator in Bok Choy, Celery, Lettuce, and Radicchio. *Weed Technology*, 28, 176–188.

Fernández-Quintanilla, C., Peña, J.M., Andújar, D., Dorado, J., Ribeiro, A. and López-Granados, F. (2018) Is the current state of the art of weed monitoring suitable for site-specific weed management in arable crops? *Weed Research*, 58, 259–272.

Gerhards, R., Kollenda, B., Machleb, J. et al. (2020a) Camera-guided Weed Hoeing in Winter Cereals with Narrow Row Distance. *Gesunde Pflanzen*, 72, 403–411.

Gerhards, R. and Oebel, H. (2006) Practical experiences with a system for site-specific weed control in arable crops using real-time image analysis and GPS-controlled patch spraying. *Weed Research*, 46, 185–193.

Gerhards, R., Späth, M., Sökefeld, M., Peteinatos, G.G., Nabout, A. and Rueda Ayala, V. (2020b) Automatic adjustment of harrowing intensity in cereals using digital image analysis. *Weed Research*, 61, 68–77.

Gerowitt, B. (2003) Development and control of weeds in arable farming systems. *Agriculture, Ecosystems & Environment*, 98, 247–254.

Gonzalez-Andujar, J.L. and Saavedra, M. (2003) Spatial distribution of annual grass weed populations in winter cereals. *Crop Protection*, 22, 629–633.

Hettwer, U. and Gerowitt, B. (2004) An investigation of genetic variation in Cirsium arvense field patches. *Weed Research*, 44, 289–297.

Hillocks, R.J. (2012) Farming with fewer pesticides: EU pesticide review and resulting challenges for UK agriculture. *Crop Protection*, 31, 85–93.

Hock, S.M., Knezevic, S.Z., Martin, A.R. and Lindquist, J.L. (2006) Soybean row spacing and weed emergence time influence weed competitiveness and competitive indices. *Weed Science*, 54, 38–46.

Home, M.C.W., Tillett, N.D., Hague, T. and Godwin, R.J., *et al.* (2002) An experimental study of lateral positional accuracy achieved during inter-row cultivation. In: *Proceedings 2002 of the 5th EWRS Workshop on Physical and Cultural Weed Control* (Ed D.C. Cloutier) (11-13 March, Pisa, Italy). 101–110 Pisa, Italy: EWRS.

Jensen, R.K., Rasmussen, J. and Melander, B. (2004) Selectivity of weed harrowing in lupin. *Weed Research*, 44, 245–253.

Kumar, S. and Anand, R. (2021) Effect of Germination and Temperature on Phytic Acid Content of Cereals. *International Journal of Research in Agricultural Sciences,* 24–36.

Kunz, C., Weber, J. and Gerhards, R. (2015) Benefits of Precision Farming Technologies for Mechanical Weed Control in Soybean and Sugar Beet—Comparison of Precision Hoeing with Conventional Mechanical Weed Control. *Agronomy,* 5, 130–142.

Kunz, C., Weber, J.F., Peteinatos, G.G., Sökefeld, M. and Gerhards, R. (2018) Camera steered mechanical weed control in sugar beet, maize and soybean. *Precision Agriculture,* 19, 708–720.

Kurstjens, D.A.G. and Kropff, M.J. (2001) The impact of uprooting and soil-covering on the effectiveness of weed harrowing. *Weed Research*, 41, 211–228.

Kurstjens, D.A.G. and Perdok, U.D. (2000) The selective soil covering mechanism of weed harrows on sandy soil. *Soil and Tillage Research*, 55, 193–206.

Leblanc, M.L. and Cloutier, D.C. Mechanical weed control in cereal crops in Eastern Canada. *Canadian Weed Science*, 6, 35–42.

Lee, W.S., Slaughter, D.C. and Giles, D.K. (1999) Robotic Weed Control System for Tomatoes. *Precision Agriculture*, 1, 95–113.

Longchamps, L., Panneton, B., Simard, M.J. and Leroux, G.D. (2012) Could Weed Sensing in Corn Interrows Result in Efficient Weed Control? *Weed Technology*, 26, 649–656.

Lundkvist, A. (2009) Effects of pre- and post-emergence weed harrowing on annual weeds in peas and spring cereals. *Weed Research*, 49, 409–416.

Machleb, J. (2020) *Evaluation of Sensor-based Precision Methods for Mechanical Weed Control in Arable Crops*. PhD thesis, University of Hohenheim Stuttgart, Germany.

Machleb, J., Kollenda, B., Peteinatos, G.G. and Gerhards, R. (2018) Adjustment of Weed Hoeing to Narrowly Spaced Cereals. *Agriculture*, 8, 54.

Machleb, J., Peteinatos, G.G., Kollenda, B.L., Andújar, D. and Gerhards, R. (2020) Sensor-based mechanical weed control: Present state and prospects. *Computers and Electronics in Agriculture*, 176, 105638.

Marshall, E.J.P. (2001) Biodiversity, herbicides and non-target plants. In: *Proceedings 2001 of Brighton Crop Protection Conference Weeds* (Ed E.J. Jones) (13-15 November, Farnham, UK). 855-862 Farnham, UK: BCPC.

Mathieu, M., Hassina, B. and Frédéric, L. (2014) The effect of surface orientation on spray retention. *Precision Agriculture*, 15, 241–254.

McCarthy, C.L., Hancock, N.H. and Raine, S.R. (2010) Applied machine vision of plants: a review with implications for field deployment in automated farming operations. *Intelligent Service Robotics*, 3, 209–217.

Melander, B., Holst, N., Rasmussen, I.A. and Hansen, P.K. (2012) Direct control of perennial weeds between crops – Implications for organic farming. *Crop Protection*, 40, 36–42.

Mink, R., Dutta, A., Peteinatos, G. et al. (2018) Multi-Temporal Site-Specific Weed Control of Cirsium arvense (L.) Scop. and Rumex crispus L. in Maize and Sugar Beet Using Unmanned Aerial Vehicle Based Mapping. *Agriculture*, 8, 65.

Monteiro, A.L., Freitas Souza, M. de, Lins, H.A. et al. (2021) A new alternative to determine weed control in agricultural systems based on artificial neural networks (ANNs). *Field Crops Research*, 263, 108075.

Müter, M., Damerow, L. and Schulze Lammers, P. (2014) Kameragesteuerte mechanische Unkrautbekämpfung in Pflanzenreihen. *Landtechnik*, 69, 3.

Oerke, E.C. (2006) Crop losses to pests. *Journal of Agricultural Science.*, 144, 31–43.

Oerke, E.-C. and Dehne, H.-W. (2004) Safeguarding production—losses in major crops and the role of crop protection. *Crop Protection*, 23, 275–285.

Ortiz, A.M.D., Outhwaite, C.L., Dalin, C. and Newbold, T. (2021) A review of the interactions between biodiversity, agriculture, climate change, and international trade: research and policy priorities. *One Earth*, 4, 88–101.

Peteinatos, G., Gierer, F. and Gerhards, R. (2018) Precision harrowing using a bispectral camera and a flexible tine harrow. In: *Proceedings 2018 of the 28. Deutsche Arbeitstagung über Fragen der Unkrautbiologie und -bekämpfung* (Eds H. Nordmeyer, L. Ulber) (27-01 March, Braunschweig). 385–389. Braunschweig: JKI.

Peteinatos, G.G., Reichel, P., Karouta, J., Andújar, D. and Gerhards, R. (2020) Weed Identification in Maize, Sunflower, and Potatoes with the Aid of Convolutional Neural Networks. *Remote Sensing*, 12, 4185.

Peteinatos, G.G. (2021) Discussion about his Paper: Precision harrowing using a bispectral camera and a flexible tine harrow. Personal conversation University of Hohenheim.

Prince, J.M., Shaw, D.R., Givens, W.A. et al. (2012) Benchmark Study: III. Survey on Changing Herbicide Use Patterns in Glyphosate-Resistant Cropping Systems. *Weed Technology*, 26, 536–542.

Pulido-Rojas, C.A., Molina-Villa, M.A. and Solaque-Guzmán, L.E. (2016) Machine vision system for weed detection using image filtering in vegetables crops. *Revista Facultad de Ingeniería Universidad de Antioquia*, 80, 124–130.
Rasmussen, J. (1991) A model for prediction of yield response in weed harrowing. *Weed Research*, 31, 401–408.
Rasmussen, J. (1992) Testing harrows for mechanical control of annual weeds in agricultural crops. *Weed Research*, 32, 267–274.
Rasmussen, J. (1993) Yield response models for mechanical weed control by harrowing at early crop growth stages in peas (Pisum sativum L.). *Weed Research*, 33, 231–240.
Rasmussen, J., Bibby, B.M. and Schou, A.P. (2008) Investigating the selectivity of weed harrowing with new methods. *Weed Research*, 48, 523–532.
Rasmussen, J., Mathiasen, H. and Bibby, B.M. (2010) Timing of post-emergence weed harrowing. *Weed Research*, 50, 436–446.
Rasmussen, J., Nielsen, H.H. and Gundersen, H. (2009) Tolerance and Selectivity of Cereal Species and Cultivars to Postemergence Weed Harrowing. *Weed Science*, 57, 338–345.
Rasmussen, J. and Svenningsen, T. (1995) Selective Weed Harrowing in Cereals. *Biological Agriculture & Horticulture*, 12, 29–46.
Rew, L.J. and Cousens, R.D. (2001) Spatial distribution of weeds in arable crops: are current sampling and analytical methods appropriate? *Weed Research*, 41, 1–18.
Riehle, D., Reiser, D. and Griepentrog, H.W. (2020) Robust index-based semantic plant/background segmentation for RGB- images. *Computers and Electronics in Agriculture*, 169, 105201.
Riemens, M.M., Van der Weide, R.Y. and Bleeker, P.O. & Lotz, L.A.P. (2007) Effect of stale seedbed preparations and subsequent weed control in lettuce (cv. Iceboll) on weed densities. *Weed Research*, 47, 149–156.
Rueda-Ayala, V., Peteinatos, G., Gerhards, R. and Andújar, D. (2015) A non-chemical system for online weed control. *Sensors*, 15, 7691–7707.
Rueda-Ayala, V., Weis, M., Keller, M., Andújar, D. and Gerhards, R. (2013) Development and testing of a decision-making based method to adjust automatically the harrowing intensity. *Sensors*, 13, 6254–6271.
Rueda-Ayala, V. and Gerhards, R. (2009) Selectivity of Weed Harrowing with Sensor Technology in Cereals in Germany. In: *Proceedings 2009 of the 7th European Conference on Precision Agriculture (ECPA)* (Eds E.J. van Henten, D. Goense, C. Lokhorst) (6-7 July, Wageningen, Netherlands). 339-348. Wageningen, Netherlands: Wangeningen Academic.
Rueda-Ayala, V., Rasmussen, J., Gerhards, R. and Fournaise, N.E. (2011) The influence of post-emergence weed harrowing on selectivity, crop recovery and crop yield in different growth stages of winter wheat. *Weed Research*, 51, 478–488.
Rydberg, T. (1994) Weed Harrowing—the Influence of Driving Speed and Driving Direction on Degree of Soil Covering and the Growth of Weed and Crop Plants. *Biological Agriculture & Horticulture*, 10, 197–205.
Sardana, V., Mahajan, G., Jabran, K. and Chauhan, B.S. (2017) Role of competition in managing weeds: An introduction to the special issue. *Crop Protection*, 95, 1–7.
Shaner, D.L. (2014) Lessons Learned From the History of Herbicide Resistance. *Weed Science*, 62, 427–431.
Shewry, P.R. (2009) Wheat. *Journal of experimental botany*, 60, 1537–1553.

Søgaard, H.T. (1998) Automatic Control of a Finger Weeder with Respect to the Harrowing Intensity at Varying Soil Structures. *Journal of Agricultural Engineering Research*, 70, 157–163.

Spaeth, M., Machleb, J., Peteinatos, G.G., Saile, M. and Gerhards, R. (2020) Smart harrowing – adjusting the treatment intensity based on machine vision to achieve a uniform weed control selectivity under heterogeneous field conditions. *Agronomy*.

Steinmann, H.-H. (2002) Impact of harrowing on the nitrogen dynamics of plants and soil. *Soil and Tillage Research*, 65, 53–59.

Steward, B., Gai, J. and Tang, L. (2019) The use of agricultural robots in weed management and control. *Agriculture and Biosystems Engineering*, 161–186.

Sujaritha, M., Annadurai, S., Satheeshkumar, J., Kowshik Sharan, S. and Mahesh, L. (2017) Weed detecting robot in sugarcane fields using fuzzy real time classifier. *Computers and Electronics in Agriculture*, 134, 160–171.

Swanton, C.J., Nkoa, R. and Blackshaw, R.E. (2015) Experimental Methods for Crop–Weed Competition Studies. *Weed Science*, 63, 2–11.

Swanton, C.J. and Weise, S.F. (1991) Integrated Weed Management: The Rationale and Approach. *Weed Technology*, 5, 657–663.

Terpstra, R. and Kouwenhoven, J.K. (1981) Inter-row and intra-row weed control with a hoe-ridger. *Journal of Agricultural Engineering Research*, 26, 127–134.

Tillett, N.D., Hague, T. and Miles, S.J. (2002) Inter-row vision guidance for mechanical weed control in sugar beet. *Computers and Electronics in Agriculture*, 33, 163–177.

Van der Weide, R.Y., Bleeker, P., Molema, G.J., Lotz, L.A.P., Fogelber, F. and Melander, B. (2008) Innovation in mechanical weed control in crop rows. *Weed Research*, 48, 215–224.

Weis, M., Gutjahr, C., Rueda Ayala, V., Gerhards, R., Ritter, C. and Schölderle, F. (2008) Precision farming for weed management: techniques. *Gesunde Pflanzen*, 60, 171–181.

Wendel, A. and Underwood, J. (2017) Illumination compensation in ground based hyperspectral imaging. *Journal of Photogrammetry and Remote Sensing*, 129, 162–178.

Wen-Hao, S. (2020) Advanced Machine Learning in Point Spectroscopy, RGB- and Hyperspectral-Imaging for Automatic Discriminations of Crops and Weeds: A Review. *Smart Cities*, 3, 767–792.

Weston, L.A. and Duke, S.O. (2003) Weed and Crop Allelopathy. *Plant Sciences*, 22, 367–389.

Wiles, L.J., Oliver, G.W., York, A.C., Gold, H.J. and Wilkerson, G.G. (1992) Spatial Distribution of Broadleaf Weeds in North Carolina Soybean (Glycine max) Fields. *Weed Science*, 40, 554–557.

Wiltshire, J.J.J., Tillett, N.D. and Hague, T. (2003) Agronomic evaluation of precise mechanical hoeing and chemical weed control in sugar beet. *Weed Research*, 43, 236–244.

Zeng, C., King, D.J., Richardson, M. and Shan, B. (2017) Fusion of Multispectral Imagery and Spectrometer Data in UAV Remote Sensing. *Remote Sensing*, 9, 696.

Zhang, N., Wang, M. and Wang, N. (2002) Precision agriculture—a worldwide overview. *Computers and Electronics in Agriculture*, 36, 113–132.

7 DECLARATION IN LIEU OF AN OATH ON INDEPENDENT WORK

according to Sec. 18(3) sentence 5 of the University of Hohenheim's Doctoral Regulations for the Faculties of Agricultural Sciences, Natural Sciences, and Business, Economics and Social Sciences

1. The dissertation submitted on the topic

"Development of a sensor-based harrowing system, using digital image analysis to achieve a uniform weed control selectivity in cereals"

is work done independently by me.

2. I only used the sources and aids listed and did not make use of any impermissible assistance from third parties. In particular, I marked all content taken word-for-word or paraphrased from other works.

3. I did not use the assistance of a commercial doctoral placement or advising agency.

4. I am aware of the importance of the declaration in lieu of oath and the criminal consequences of false or incomplete declarations in lieu of oath. I confirm that the declaration above is correct. I declare in lieu of oath that I have declared only the truth to the best of my knowledge and have not omitted anything.

Stuttgart-Hohenheim, 14.10.2021

Place, date

Signature (Michael Spaeth)

8 ACKNOWLEDGEMENT

I especially like to thank Prof. Dr. Roland Gerhards for being my Doctorfather and supervisor during the PhD-Thesis. Furthermore, I thank Dr. Gerassimos Peteinatos who was always available for any technical problems since the very first time. Additionally, I also thank Dr. Adnang Nabout who has programmed the image-analysis-software for the harrow "naGITML" and for improving it constantly.

I would also thank Prof. Dr. Dionisio Andujar Sánchez for being my co-expert, and Prof. Dr. Hans W. Griepentrog for being the third auditor from my PhD.

A special thanks to my parents Elfriede und Ferdinand Spaeth for encouraging and supporting me during the hard times in the study and the PhD. Furthermore, I would like to thank my girlfriend Miriam Messelhäuser for beeing my discussion partner always and in all cases during the PhD.

I would also thanks Marcus Saile, for setting up and conducting experimental fields in Hirrlingen in 2018 – 2020, and for providing the machines of his research farm. Additionally, I am grateful to Tobias Konrad for setting up the experimental fields in Eningen.

I also like to thank Jannis Machleb and Matthias Schumacher for supporting me and for sharing experiences and ideas.

I am grateful to Hatzenbichler for providing me a commercial 6 m wide harrow with hydraulic adjustment of tine angle for my PhD.

9 CURRICULUM VITAE

Personal Data	
Name	Michael Spaeth
Date and Place of Birth	15.04.1994, Reutlingen, Germany
University Education	
12/2018 – 11/2021	Doctorate candidate of the department of Weed Science, Institute of Phytomedicine, University of Hohenheim
10/2016 – 12/2018	Studies in Agriculture Engineering, University of Hohenheim Master of Science (M.Sc.)
10/2013 – 10/2016	Studies in Agriculture Sciences, University of Hohenheim Bachelor of Science (B.Sc.)
School Education	
09/2010 – 08/2013	Technical-High-School, Reutlingen, Germany
09/2009 – 08/2010	Secondary-School, Orschel-Hagen, Germany
09/2000 – 08/2009	Primary-School, Eningen u.A., Germany

Stuttgart-Hohenheim, 14.10.2021

Place, date

Signature (Michael Spaeth)