Integrated weed management in a pesticide free area

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1 GENERAL INTRODUCTION

The European agricultural landscape is dominated by a few high-yielding crops such as winter wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and soybeans (*Glycine max* (L) MERR.). The stability of crop yield and food supply to national and international markets can only be guaranteed in a highly industrialized cultivation system. At the same time, the number of people affected by hunger, increased dramatically from 150 to 828 million since 2019 (World Health Organization 2022). To counteract the increasing rate of hunger and ensure food security, it is necessary to increase crop productivity with efficient utilization of available water and land resources (Carvalho 2006).

Crop yield is often influenced by abiotic factors, such as temperature, water and nutrients. Without crop protection practices, biotic factors, like weed infestation, diseases and animal pests further impact crop yield negatively (Oerke 2006). The application of chemical pesticides has helped to reduce such biotic yield losses globally (Oerke and Dehne 2004). Of all the biotic stresses, weed are the most severe, causing up to 34 % yield losses (Oerke and Dehne 2004). In the last decades, weed control with herbicide application achieved up to 95 % weed control efficacy (Messelhäuser et al. 2022), however, since the first weed became resistant against herbicides in 1970 in the USA, weed control strategies getting divers including alternatives to herbicides (Ryan 1970). Currently, the number of resistant weeds has increased. About 267 known different weed species are identified to be resistant against 21 out of 31 existing modes of action (Heap 2022). Herbicide resistant weeds like *Alopecurus myosuroides* HUDS. cause yield losses up to 60 % (Messelhäuser et al. 2021). In addition, herbicides and other pesticides have had a negative impact on the environment with potential risks of residues in food, soil and water (E. Demjanová et al. 2009). To counteract the risks to the environment caused by agricultural production, the European Union declared the EU Green Deal targets. These state a reduction of fertilizers by 30 % and a reduction of chemical pesticides by 50 % until 2030 to increase biodiversity (European Commission 2020).

Pesticide reduction requires a integrated weed management (IWM) strategy for agriculture, that secures yield and allows the waiver of herbicides. A integrated approach that not only provides direct control of weeds in the crop but also combines preventive cultural methods like soil tillage, cover cropping, delayed autumn sowing, competitive crops, and crop rotation is needed while maintaining weed control efficacy (WCE) (Chauvel et al. 2001; Moss and Clarke 1994). IWM methods provide benefits to a cropping system: Conventional tillage uproots and buried weeds, stimulates the weed seed bank in the soil to germinate, which can be safely controlled by re-tilling the soil (Gruber and Claupein 2009; Schappert et al. 2018; Weber et al. 2017). Selective tillage reduces weed infestation immediately in the following crop. Riemens et al. (2007) were able to show that the establishment of a false seedbed reduced weed infestation by 43-83 %, depending on location and year. The cultivation of cover crops can suppress weed germination between 40 and 95 %, depending on the species. Annual weeds like *Chenopodium album* L. were better suppressed compared to perennial weeds like *Cirsium arvense* (L.) SCOP. and *Convolvulus arvensis* L. Cover crops also show positive side effects; nutrients are protected from leaching and soil erosion is reduced (Schappert et al. 2019; Kunz et al. 2016; Schappert et al. 2018; Hartwig and Ammon 2002; Brust et al. 2011).

For direct weed control, mechanical weeding can be used in a cropping system as pre-and post-emergence weed control. Mechanical weed control can be used as a stand-alone or in combination with herbicides, e.g., in a flat or band application. Under optimal field and weather conditions, mechanical weed control can be as effective as a single herbicide application (Spaeth et al. 2020). Studies have shown similarity in mechanical weed control efficacy and herbicide application in cereals (Saile et al. 2022; Spaeth et al. 2020). For hoeing and harrowing, the knowledge of the farmer is important to carry out this weed control method effectively. Furthermore, weed control success with mechanical weeding mainly depends on soil and weather conditions, as well as crop growth (Rasmussen 1993; Gerhards et al. 2021). Conventional mechanical weed control can achieve WCE of approximately 47-61 % (Brandsteader et al. 2012). Using automatic sensor-guided systems for precise inter-row hoeing and automatic adjustment of harrowing intensity can increase WCE up to 80 % (Gerhards et al. 2020; Saile et al. 2022; Spaeth et al. 2020; Machleb et al. 2018; Kunz et al. 2018).

To reduce pesticides by 50 % until 2030 and create a pesticide-free agricultural landscape all approaches of weed control must be included. Therefore, an integrated weed management (IWM) strategy comprising direct and indirect (preventive) weed control methods must be developed. Creating a pesticide-free area remains a big challenge. Hence, future research projects must directly address the question on the combination of preventive and direct weed control measures, not only in organic farming, but also in conventional farming.

1.1 Objectives

The objectives of the thesis were:

- to determine the effect of integrated cropping practices for IWM, using different soil tillage, cover cropping and straw fertilization on weed suppression
- to evaluate different mechanical, biological and chemical weed control practices for the suppression on *Alopecurus myosuroides* HUDS.
- to test different weed control methods including herbicide application and different sensor based mechanical weed control practices to reduce herbicide use
- to investigate a pesticide-free cropping system using mineral fertilizers and the impact of mineral fertilization on weed control in this system.

1.2 Structure of the Thesis

This dissertation focuses on integrated weed management. The first chapter (chapter 1) is a general introduction that focuses on the current political situation, which targets a reduction of pesticide usage up to 50 % until 2030, and integrated weed management approaches. The following chapter (chapter 2) includes five scientific research articles, which represent the main topic of the dissertation. Four of them were published in peer-reviewed journals and one is submitted.

The first study is titled **“Weed Suppressive Ability of Cover Crop Mixtures Compared to Repeated Stubble Tillage and Glyphosate Treatments”** and was published in the journal *Agriculture*. Weed control efficacy was examined in the period after harvest until spring cropping. Different sowing practices of cover crop mixtures, using mulch and no-till systems, were compared to diverse stubble tillage treatments and glyphosate applications during the crop-free period in autumn and winter.

The second article is titled “**Effect of cinmethylin against *Alopecurus myosuroides* Huds. in winter cereals”** and was published in *Plant, Soil and Environment.* It describes three field experiments over a period of three years dealing with pre- and post-emergence herbicide application and different sowing dates of winter cereals. The effects of those factors on *A. myosuroides* control efficacy and cereal grain yield were measured.

The third article is titled “**Exploring the effects of different stubble tillage practices and glyphosate application combined with the new soil residual herbicide Cinmethylin against *Alopecurus myosuroides* Huds. in winter wheat**” and was published in the journal *Agronomy*. The effects of various stubble tillage, glyphosate, and preemergence herbicide treatments in four field trials on *A. myosuroides* HUDS. and winter wheat density and crop yield effects are presented.

The fourth article is titled **“Evaluating Sensor-based Mechanical Weeding Combined with Pre- and Post-Emergence Herbicides for Integrated Weed Management in Cereals”** and was published in *Agronomy*. Different integrated approaches for weed control were used in field experiments in summer and winter crops. The combination of sensor based-hoeing and -harrowing and herbicide application were evaluated for their impact on crop yield and weed control.

The fifth article is titled “**Weed control in a pesticide-free farming system with mineral fertilizers”** and was submitted to the journal *Weed Research*. The article shows weed control approaches in a cropping system without pesticides but using mineral fertilizers. Crop yield and the effects of weed control were measured.

The next chapter is a general discussion (chapter 3) where all research articles are discussed generally and which gives an overview on IWM. The thesis closes with the summary (chapter 4).

Apart from the peer-reviewed journal articles, one more contribution to an international scientific conference as an oral presentation was made. This work was supplementary to the included articles, and therefore not included in the current thesis.

Marcus Saile and Roland Gerhards (2022). “**Weed control in a mineral–ecological cropping system (MECSs) including wider crop rotations and stubble tillage compared to organic- and conventional cropping**

systems”. In: 19th European Weed Research Society Symposium 20-23 June 2022 in Athens.

2 PUBLICATIONS

2.1 Weed Suppressive Ability of Cover Crop Mixtures Compared to Repeated Stubble Tillage and Glyphosate Treatments

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www.mdpi.com/journal/agriculture, doi:10.3390/agriculture8090144

2.1.1 ABSTRACT

The utilization of an effective stubble management practice can reduce weed infestation before and in the following main crop. Different strategies can be used, incorporating mechanical, biological, and chemical measures. This study aims at estimating the effects of cover crop (CC) mixtures, various stubble tillage methods, and glyphosate treatments on black-grass, volunteer wheat and total weed infestation. Two experimental trials were conducted in Southwestern Germany including seven weed management treatments: flat soil tillage, deep soil tillage, ploughing, single glyphosate application, dual glyphosate application, and a CC mixture sown in a mulch-till and no-till system. An untreated control treatment without any processing was also included. Weed species were identified and counted once per month from October until December. The CC mixtures achieved a black-grass control efficacy of up to 100 %, whereas stubble tillage and the single glyphosate treatment did not reduce the black-grass population, on the contrary it induced an increase of black-grass plants. The dual glyphosate application showed, similar to the CC treatments, best results for total weed and volunteer wheat reduction. The results demonstrated, that well-developed CCs have a great ability for weed control and highlight that soil conservation systems do not have to rely on chemical weed control practices.

KEYWORDS

Biological; black-grass (*Alopecurus myosuroides* HUDS.); chemical; mechanical; mulch-till; no-till systems; stubble tillage; weed management

2.2 Effect of Cinmethylin against *Alopecurus myosuroides* Huds. in Winter Cereals

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2.2.1 ABSTRACT

Cinmethylin is a potential new selective pre-emergence herbicide in inhibiting the fatty acid thioesterases (FAT). It is effective against *Alopecurus myosuroides* HUDS. and other grass-weeds in winter cereals and oil-seed rape. Five field experiments were conducted in Southwestern Germany from 2018 until 2020 to assess the control efficacy of cinmethylin and other common pre-emergence herbicides and combinations of herbicides against *A. myosuroides* and the yield response of winter wheat and winter triticale. In four experiments, the effect of early and late sowing of winter cereals was included as second factor in the experiment to investigate if late sowing can reduce *A. myosuroides* density and increase weed control efficacy. All fields were heavily infested with *A. myosuroides* with average densities of 105-730 plants m^{-2} in the early sown controls. Late sowing reduced weed densities in three out of four experiments. Herbicides controlled 42 – 100 % of the *A. myosuroides* plants. However, none of the treatments was consistently better than the other treatments. In three out of five experiments, grain yields were significantly increased by the herbicide treatments. The results demonstrate that cinmethylin is a new option for controlling *A. myosuroides* in winter cereals. However, it needs to be combined with other weed control tactics.

KEYWORDS

Black-grass; ALS inhibitors; ACCase inhibitors; very long chained fatty acid inhibitors; IWM; seeding time

2.3 Exploring the Effects of Different Stubble Tillage Practices and Glyphosate Application Combined with the New Soil Residual Herbicide Cinmethylin against *Alopecurus myosuroides* Huds. in Winter Wheat

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2.3.1 ABSTRACT

An effective control of *Alopecurus myosuroides* HUDS. solely by a chemical treatment is not guaranteed anymore because populations exhibit resistance to almost all herbicide modes of action. Integrated weed management against black-grass is necessary to maintain high weed control efficacies in winter cereals. Four field experiments were conducted in Southwest Germany from 2018 until 2020 to control *A. myosuroides* with a combination of cultural and chemical methods. Stubble treatments including flat-, deep-, inversion soil tillage, false seedbed preparation and glyphosate use were combined with the application of the new pre-emergence herbicide cinmethylin in two rates in winter wheat. Average densities of *A. myosuroides* in the untreated control plots were up to 505 plants m^{-2}. The combination out of different stubble management strategies and the pre-emergence herbicide cinmethylin controlled 86-97 % at the low rate and 95-100 % of *A. myosuroides* plants at the high rate until 120 days after sowing. The different stubble tillage practices varied in their efficacy between trials and years. Most effective and consistent were pre-sowing glyphosate application on the stubble and stale seedbed preparation with a disc harrow. Stubble treatments increased winter wheat density in the first year but had no effect on crop density in the second year. Pre-emergence applications of cinmethylin did not reduce winter wheat densities. Multiple tactics of weed control including stubble treatments and pre-emergence application of cinmethylin provided higher and more consistent control of *A. myosuroides.* Integration of cultural weed management could prevent the herbicide resistance development.

KEYWORDS

Black-grass; soil tillage; herbicide resistance; integrated weed management; glyphosate; mode of action

2.4 Evaluating Sensor-based Mechanical Weeding Combined with Pre- and Post-Emergence Herbicides for Integrated Weed Management in Cereals

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2.4.1 ABSTRACT

Due to the increasing number of herbicide-resistant weed populations and the resulting yield losses, weed control must be given high priority to ensure food security. Integrated weed management (IWM) strategies, including reduced herbicide application, sensor-guided mechanical weed control and combinations thereof are indispensable to achieve this goal. Therefore, this study examined combinations of pre- and post-emergence herbicide applications with sensor-based harrowing and hoeing in cereals by conducting five field experiments at two locations in Southwestern Germany from 2019 to 2021. Each experiment contained an untreated control and a single post-emergence herbicide treatment as a comparison to these IWM treatments. The effects of the different IWM approaches on weed control efficacy (WCE), crop density, and grain yield were recorded. All experiments were set up in a randomized complete block design with four repetitions. Pre-emergence herbicide application combined with one-time harrowing and subsequent hoeing (Pre-Herb + Harr + Hoe) achieved the highest WCE (100 %), followed by an approach of WCE (95 %) for two-times hoeing. In contrast, a single pre-emergence herbicide application achieved the worst result with an average WCE of 25%. Grain yield was equal between all treatments in between 6 t ha^{-1} and 10 t ha^{-1}, except for a single pre-emergence herbicide application, which achieved a 2.5 t ha^{-1} higher grain yield in winter wheat in 2021 that averaged 11 t ha^{-1}, compared to the combination of Pre-Herb + Harr + Hoe that averaged 8.5 t ha^{-1}. The results showed that it is possible to reduce and replace herbicides while achieving equivalent yield and WCE.

KEYWORDS

Precision farming; digital farming; site-specific; camera-guided; herbicide reduction; integrated weed management

2.5 Weed Control in a Pesticide-Free Farming System with Mineral Fertilizers

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2.5.1 ABSTRACT

Negative impacts of pesticides on the environment and human health, the risk of pesticide residues in the food chain, and the problems with herbicide-resistant weed biotypes support the need for alternative cropping systems. The objective of this study was to investigate weed populations, weed management and crop yield in a pesticide-free cropping system with the use of mineral fertilizers.

Conventional-, organic- and mineral-ecological farming (MECS) with 6-year crop rotations including winter wheat, maize, winter triticale or winter rye, soybean or spring pea, and spring barley were established in a randomized complete strip plot design with four repetitions. Experiments were conducted at four locations in Germany. Preventive and sensor-guided mechanical weed management strategies were applied in all crops in the organic system and in MECS. Herbicide were applied in the conventional farming system. Weed densities, weed species composition, weed control efficacy and crop yield were analysed over two years in 2020 and 2021.

Conventional farming had the highest weed control efficacy and 1-7 weeds m^{-2} (2.7 % weed coverage) after herbicide application. In the organic cropping system and MECS, up to 27 weeds m^{-2} were counted after camera-guided weed hoeing. Weed coverage in MECS (9.7 %) was higher than in the organic cropping system with 7.7 %. Crop yield in MECS were equal to the conventional farming system and 20 % higher yield than in the organic farming system. MECS represents a promising new and productive cropping practice if an effective integrated weed management strategy is applied.

KEYWORDS

Integrated weed management; herbicide reduction; precision mechanical weed control; mineral fertilization; diverse farming systems

3 GENERAL DISCUSSION

Integrated weed management (IWM) is composed of a combination of multiple weed control techniques for a sustainable plant protection. This approach considers the use of cultural, physical, biological and chemical weed control methods. The target of IWM is to reduce the amount of herbicides, protect the environment and increase biodiversity (Chauvel et al. 2001; E. Demjanová et al. 2009; Gerhards et al. 2022). In this thesis five articles give an overview about different IWM strategies for arable crops.

This chapter is structured and will be discussed in the following order:

- *Alopecurus myosuroides* HUDS. control with a new mode of action
- preventive weed control methods combined with pre- and post-emergence herbicides
- precision mechanical weed control
- impact of mineral fertilization on weed control

Nowadays, *A. myosuroides* populations are resistant against several mode of action of herbicides. The common resistant classes are pre-emergence herbicides which are inhibiting the fatty acid synthesis (K1) and post-emergence herbicides which are inhibiting the photosystem II- (PS2), acetyl CoA carboxylase (ACCase)- and acetolactate synthase (ALS) (Heap 2014; Délye et al. 2013; Bailly et al. 2012; Dücker et al. 2019). Therefore, IWM strategies needs the integration of a new mode of action to reduce the risk for new resistant weed species (Lutman et al. 2013).

In the secound publications, the new pre-emergence herbicide LUXINUM® with the active ingredient cinmethylin, was used to evaluate the effectiveness of cinmethylin compared to common pre- and post-emergence herbicides against *A. myosuroides*. In the presented studies, results shown, using cinmethylin results in a control efficacy of 100 % against *A. myosuroides* in winter wheat without crop and grain yield losses. Gerhards et al (2022) obtain an *A. myosuroides* control efficacy of 91 % and an increase of grain yield using cinmethylin in combination with delayed sowing. But, Messelhäuser et al. 2021a already showed that two out of 17 *A. myosuroides* populations were slightly tolerant to recommended field rates (395 g a.i.) of cinmethylin. To obtain a more effective and sustainable *A. myosuroides* control with cinmethylin, it must be integrated in a combined IWM approach that involves preventive or mechanical control methods (Messelhäuser et al. 2021b; Menegat and Nilsson 2019; Lutman et al. 2013; Schappert et al. 2018).

Preventive weed control practices are cultural methods like crop rotation, stubble tillage, cover cropping or delayed sowing. All cultural methods contributing to decrease the weed density in the field. Therefore, combining preventive methods with herbicide application, safes the efficacy of the active ingredients over a longer period without the risk that weeds getting resistance. In the presented study, different stubble tillage methods (straw harrow, disc harrow, rotary harrow, cultivar and mouldboard plough) combined with different common and the new pre-emergence herbicides (LUXINUM®) were investigated to maximize the efficacy of *A. myosuroides* control in winter and summer cereals. The combination of different stubble treatments and cinmethylin controlled 95-100 % of *A. myosuroides* plants until 120 days after sowing. All stubble tillage practices varied in their efficacy between years and trials. Stubble treatments increased winter wheat density in the first year but had no effect on crop density in the second year. Cinmethylin did not reduce winter wheat densities. In period from 2017 -2019 field studies showed that soil tillage practices reducing *A. myosuroides* density of 100 % (Schappert et al. 2018; Messelhäuser et al. 2021). Further effects of stubble tillage were shown by Zeller et al. (2021), using a disc harrow, inversion tillage and false seedbed preparation weed infestations was reduced by 70 %. The establishment of a false seedbed is a proven method Riemens et al. (2007) showed weed reduction between 43-83 %.

A further cultural method especially for winter crops is delayed sowing. Winter cereals sowing after mid-october can reduce *A. myosuroides* by 50 % while early sowing (end of september) can increase *A. myosuroides* density (Melander 1995; Rasmussen 2004; Lutman et al. 2013). In the presented study *A. myosuroides* germination rates were reduced by 40 % within a sowing date end of october. Several different researchers shown an interaction between an early sowing date of winter cereals within an increased weed infestation (Moss and Clarke 1994; Lutman et al. 2013; Moss 2017). Riemens et al. (2007) showed that the weed potential in the field can be reduced by 80 % within delayed sowing. However, climatic changes and milder conditions can expand the sowing period of winter cereals (Gerhards et al. 2022). Winter cereal varieties in Southwestern Germany are adapted climate conditions for delayed sowing dates without decrease of grain yield (Gerhards et al. 2022).

Cover crops included in the crop rotation, is characterised by a high weed suppression for arable crops. In the presented study direct cover crop sowing and flat tillage plus cover crop sowing after harvest could obtain a WCE of 100 %. Kunz et al. (2015) could show that the weed suppression of cover crops ranged up to 80 % in annual weeds and only up to 40 % for perennial weeds. The effect of cover crops on weed suppression depends mainly on the soil moisture and therefore for the germination of the cover crops. The combination of species and the mixture of cover crops has a direct impact on the germination. Using mixtures with fast and slow growing species is essential to achieve long term success.

Mechanical weed control is usually performed by harrowing and hoeing. The selectivity and efficacy of mechanical weed control depends on the environmental conditions, weed species and their growth stage relative to the crop (Gerhards et al. 2021; Spaeth et al. 2021; Melander et al. 2012; Rasmussen 1992). In the presented studies, sensor-based harrowing and hoeing achieved 100 % WCE in winter wheat and spring oats without crop and yield losses. However, the weed density was relatively low with only 5-10 weeds m^{-2}. Spaeth et al. (2021) found similar WCE (95-100 %) of sensor-based weed harrowing at higher weed density of up to 100 weeds m^{-2}. Sensor-guidance and automatic adjustment of harrowing intensity resulted in higher WCE and less crop damage compared to conventional mechanical weeding. Gerhards et al. (2020) observed a lateral offset from the row centre of 23 mm for the 3 m wide hoe and 18 mm for the 6 m wide hoe for sensor guidance of the hoe. Furthermore, camera-guided hoeing resulted in 72-96 % inter-row and 21-91 % intra-row WCE (Gerhards et al. 2020). Better in-row weed control was associated to weed burial at higher driving speed. The results of this thesis show that it was possible to replace chemical weed control by sensor-based mechanical weed control without loss of WCE and yield. But, mechanical weeding requires optimal weather and soil conditions.

The new cropping system is characterized by a complete reduction of pesticides while still using mineral fertilizers. The positive effect of mineral fertilizer is an enhanced crop growth and a continuously increase of the yield (Bertic et al. 2007). However, nutrients are also taken up by weeds and thus produce more biomass. Consequently, weeds increase their competitiveness against crops and leading to higher yield losses. The present study could not answer if weed competition is increased in the MECS. Results from two-year field experiment in arable crops showed no positive effect of mineral fertilization on weed infestation. The weed infestation was significant higher (8-30 weeds m^{-2}) in MECS compared to conventional cropping systems (1-5 weeds m^{-2}) and equal compared to organic cropping systems (5-25 weeds m^{-2}) without mineral fertilization. Håkansson (2003) also showed negative effects of mineral fertilization on the weed infestation. Weed dry matter was 800 % higher with mineral fertilizers while crop dry matter only increased by 10-40 %. Based on weed population dynamics, there is a high potential of an increasing weed infestation. Weed soil seedbank will expand and therefore, additional cost for weed control in the following years arise (Håkansson 2003; Cousens and Mortimer 1995). Gantoli et al. (2013) and Brozović et al. (2021) showed opposite results. Due to a 75 % reduced dose of nitrogen fertilization, the critical period for weed control extended from six to ten leaf stage in maize. Precision application technologies can help that crops profits more from mineral fertilization than weeds by application at the right time, rate, and location (Håkansson 2003; Brozović et al. 2021). In contrast to previous studies, Brozović et al. (2021) shows a positive effect on the crop growth, while mineral fertilization inhibited the weed infestation. achieved positive effects of higher doses of nitrogen fertilization, increased crop growing and shorted critical periods of weed infestation.

The results of this work clearly show that IWM practices, consisting of mechanical weed control and preventive measures, can significantly reduce the use of pesticides in a cropping system and be an alternative for conventional farming. A sustainable cropping system in which crop rotation is varied, soil management is balanced, and nutrient supply is sustainable and gets more stable, to diseases and insect pest, so European Union goal reducing amount of pesticides by 50 % can reached. For the new cropping system MECS there are excellent perspectives to achieve very high weed suppression effects in a dynamic IWM and to become a sustainable cultivation system that will be accepted by the broad mass of lime farmers.

4 SUMMARY

Weed control is a challenging task for farmers in highly specialized crop production systems. The competition of weeds for light, nutrients and water causes significant yield losses. Chemical weed control is still the standard method in European cropping systems. Due to their high selectivity and efficacy against a wide range of weed species, herbicides provide the most efficient weed control in most crops. However, negative impact of herbicides on the environment, loss of biodiversity, possible risks to consumers due to residues in food chain and the increase and spread of herbicide-resistant species force farmers to reduce herbicide use and call for alternative weed control methods. Mechanical weed control methods including hoeing and harrowing represent the most promising alternative direct weed control methods. Weed control costs for mechanical methods are still higher than for herbicides and weed control efficacy is often lower with less than 80 % compared to around 95 % for herbicides. The efficacy of mechanical weed control is dependent on external factors such as soil water content, soil texture, and weed species diversity in the particular field. Herbicides can therefore not be replaced by a single mechanical weed control method. It needs an Integrated Weed Management (IWM) strategy including preventive and direct methods of weed suppression. In this study, IWM were investigated for typical arable farming systems in Southwestern Germany. Studies for this thesis were conducted from 2017 to 2022. The objectives of the thesis were to combine preventive and curative methods of weed control in diverse cropping systems and to improve mechanical weed control methods by precision farming technologies. The results of the thesis have been published in five papers.

The first article addressed the effects of preventive weed control by stubble tillage, cover cropping, and the use of glyphosate treatments against *Alopecurus myosuroides* and volunteer cereals. In two field trials at two sites, cover crop mixtures achieved equal weed control efficacy of up to 100 % as the dual glyphosate treatment. Stubble tillage practices resulted in lower control but caused the highest energy consumption.

The second article focused on the effect of two seeding dates (early-, delayed-sowing) and different herbicide strategies on *A. myosuroides* control on winter cereals. This study was conducted over three years at three locations. Delayed sowing reduced weed emergence by 30-40 %. Delayed sowing in combination with the pre-emergence herbicide cinmethylin provided equal weed control efficacy as a combination of pre-emergence and post-emergence herbicides.

The third article focused on the control of *A. myosuroides* including the combination of integrated stubble management and various application rates of the pre-emergence herbicide cinmethylin. In four field trials over a two-year period, the pre-emergence herbicide cinmethylin was applied at two application rates at two sites. Control success of up to 100 % was achieved through the combination of inversion tillage, false-seedbed preparation and the reduced rate of cinmethylin. The results also showed a high variation of the effect of preventive measures.

The fourth article deals with IWM in spring oats and winter wheat. Field experiments were conducted at two locations over two years in five field trials. Chemical weed control was combined with sensor-based mechanical weed control. Data showed that sensor-based mechanical weed control (hoeing and harrowing) in the field trials achieved equal weed control efficacy of up to 100 %. However, highest grain yields were recorded for the combination of pre-emergence herbicide and post-emergence mechanical weed control.

The last article dealt with a new cultivation system without chemical synthetic pesticides but with mineral fertilizers (MECS). The hypothesis was that MECS would increase the competitiveness of the crop on the weeds and generate higher yield benefit compared to the organic cultivation system. Field trials were conducted at four sites over two years. Three different cropping systems, an organic cropping system managed according to organic farming guidelines, a conventional cropping system and a MECS, were compared in a 5-year crop rotation. After two years of studies, no clear conclusion can be made how MECS affects the interaction of crops and weeds. Weed control efficacy in MECS was lower than organic farming. The increase in weed pressure in MECS will cause problems in the subsequent crops. Yields were significantly higher in MECS compared to the organic system and only slightly lower than in the conventional system.

It can be concluded from these studies that IWM in combinations with precision farming technologies for mechanical weeding can replace herbicides. However, weed control costs were higher with non-chemical weed control methods.

5 ZUSAMMENFASSUNG

Die Unkrautbekämpfung ist eine herausfordernde Aufgabe für Landwirte in hochspezialisierten Anbausystemen. Die Konkurrenzkraft der Unkräuter um Licht, Nährstoffe und Wasser führt zu erheblichen Ertragseinbußen. Die chemische Unkrautbekämpfung ist in europäischen Anbausystemen immer noch die Standardmethode. Aufgrund ihrer hohen Selektivität und Wirksamkeit gegen eine breite Palette von Unkrautarten bieten Herbizide in den meisten Kulturen die effizienteste Unkrautbekämpfung. Die negativen Auswirkungen von Herbiziden auf die Umwelt, der Verlust der Artenvielfalt, mögliche Risiken für die Verbraucher aufgrund von Rückständen in der Nahrungskette und die Zunahme und Verbreitung herbizidresistenter Arten zwingen die Landwirte jedoch, den Herbizideinsatz zu reduzieren und alternative Unkrautbekämpfungsmethoden zu suchen. Mechanische Unkrautbekämpfungsmethoden wie Hacken und Striegeln sind die vielversprechendsten alternativen Methoden der direkten Unkrautbekämpfung.

Die Kosten für mechanische Unkrautbekämpfungsmethoden sind immer noch höher als die für Herbizide, und die Wirksamkeit der Unkrautbekämpfung ist oft geringer (weniger als 80 % im Vergleich zu etwa 95 % bei Herbiziden). Die Wirksamkeit der mechanischen Unkrautbekämpfung hängt von externen Faktoren wie dem Wassergehalt des Bodens, der Bodenbeschaffenheit und der Vielfalt der Unkrautarten auf dem jeweiligen Feld ab. Herbizide können daher nicht durch eine einzige mechanische Unkrautbekämpfungsmethode ersetzt werden. Es bedarf einer Strategie des integrierten Unkrautmanagements (IWM), die präventive und direkte Methoden der Unkrautunterdrückung umfasst. In dieser Studie wurden IWMs für typische Ackerbausysteme im Südwesten

Deutschlands untersucht. Die Untersuchungen für diese Arbeit wurden von 2017 bis 2022 durchgeführt. Ziel der Arbeit war es, präventive und kurative Methoden der Unkrautbekämpfung in verschiedenen Anbausystemen zu kombinieren und mechanische Unkrautbekämpfungsmethoden durch Precision Farming Technologien zu verbessern. Die Ergebnisse der Arbeit wurden in fünf wissenschaftlichen Artikeln veröffentlicht.

Der erste Artikel befasste sich mit den Auswirkungen der präventiven Unkrautbekämpfung durch Stoppelbearbeitung, Zwischenfruchtanbau sowie Glyphosatbehandlungen gegen *Alopecurus myosuroides* und Ausfallgetreide. In zwei Feldversuchen an zwei Standorten erzielten Deckfruchtmischungen die gleiche Wirksamkeit bei der Unkrautbekämpfung von bis zu 100 % wie die duale Glyphosatbehandlung. Die Stoppelbearbeitung führte zu einer geringeren Kontrolle, verursachte aber den höchsten Energieverbrauch.

Der zweite Artikel befasste sich mit den Auswirkungen von zwei Aussaatterminen (Früh- und Spätsaat) und verschiedenen Herbizidstrategien auf die Bekämpfung von *A. myosuroides* in Wintergetreide. Diese Studie wurde über drei Jahre an drei Standorten durchgeführt. Die späte Aussaat reduzierte das Aufkommen von Unkraut um 30 bis 40 %. Spätsaat in Kombination mit dem Vorauflaufherbizid Cinmethylin bot die gleiche Wirksamkeit bei der Unkrautbekämpfung wie eine Kombination aus Vorauflauf- und Nachauflaufherbiziden.

Der dritte Artikel befasste sich mit der Bekämpfung von *A. myosuroides* in Kombination mit einer integrierten Stoppelbearbeitung und verschiedenen Aufwandmengen des Herbizids Cinmethylin vor Pflanzenaufgang. In vier Feldversuchen über einen Zeitraum von zwei Jahren wurde das

Vorauflaufherbizid Cinmethylin in zwei Aufwandmengen an zwei Standorten eingesetzt. Durch die Kombination von inverser Bodenbearbeitung, falscher Saatbettbereitung und der reduzierten Cinmethylin-Dosierung wurde ein Bekämpfungserfolg von bis zu 100 % erzielt. Die Ergebnisse zeigten eine hohe Schwankungsbreite in der Wirkung der vorbeugenden Maßnahmen.

Der vierte Artikel befasste sich mit IWM in Sommerhafer und Winterweizen. An zwei Standorten wurden in fünf Feldversuchen über zwei Jahre hinweg Feldversuche durchgeführt. Die chemische Unkrautbekämpfung wurde mit der sensorgestützten mechanischen Unkrautbekämpfung kombiniert. Die Daten zeigten, dass die sensorgestützte mechanische Unkrautbekämpfung (Hacken und Striegeln) in den Feldversuchen eine gleichwertige Unkrautbekämpfungseffizienz von bis zu 100 % erzielte. Die höchsten Kornerträge wurden jedoch bei der Kombination aus Herbizid vor Pflanzenaufgang und mechanischer Unkrautbekämpfung nach Pflanzenaufgang erzielt.

Der fünfte Artikel befasste sich mit einem neuen Anbausystem ohne chemisch-synthetische Pestizide, aber mit Mineraldünger (MECS). Die Hypothese lautete, dass MECS die Konkurrenzfähigkeit der Pflanzen gegenüber Unkräutern erhöht und im Vergleich zum ökologischen Anbausystem einen höheren Ertragsvorteil bringt. Die Feldversuche wurden über zwei Jahre an vier Standorten durchgeführt. Drei verschiedene Anbausysteme, ein ökologisches Anbausystem nach den Richtlinien des ökologischen Landbaus, ein konventionelles Anbausystem und ein MECS, wurden in einer fünfjährigen Fruchtfolge verglichen. Nach zwei Jahren konnte keine eindeutige Schlussfolgerung darüber gezogen werden, wie sich das MECS auf die Interaktion von Pflanzen und Unkraut auswirkt.

Die Wirksamkeit der Unkrautbekämpfung war in MECS geringer als im ökologischen Landbau. Der erhöhte Unkrautdruck in MECS wird in den Folgekulturen Probleme verursachen. Die Erträge waren in MECS deutlich höher als im ökologischen System und nur geringfügig niedriger als im konventionellen System.

Diese Studien lassen den Schluss zu, dass IWM in Kombination mit Technologien der Präzisionslandwirtschaft zur mechanischen Unkrautbekämpfung Herbizide ersetzen kann. Allerdings waren die Kosten für die Unkrautbekämpfung bei nicht-chemischen Methoden höher.

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8 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
"Integrated weed management in a pesticide free area"
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.

Hohenheim,12.10.2023 M. Saidi

Place,Date Signature

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