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Cover cropping in integrated weed management

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Für meine Eltern

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Chapter I

General Introduction

1 General Introduction

The integrated weed management implements the careful selection of appropriate crop protection methods to counteract the emergence and spread of weed populations within the field [1]. This management system aims to provide healthy, high-yielding crops by combining biological, mechanical and chemical approaches with minimal disturbance of the agricultural ecosystem [2]. The integration of cover crops and living mulches into crop rotation can be useful for the ecologic and economic production of food, while providing various ecological services [3]. Cover cropping between two main crops contributes to the agricultural production by reducing soil erosion [4] and nitrate leaching [5,6], improving soil fertility and structure [7,8], enhancing the microbial activity [9] and biological weed suppression [4,10–13]. Studies reported weed suppression by more than 90% for winter annual weeds and 40% for perennial weeds during autumn and winter after cover crop cultivation [12,14–19]. Cover crop and living mulch inclusion in the crop rotation provides three opportunities to interfere with the lifecycle of weeds [20].

The first result of cover crop inclusion is the inhibition of weed germination, growth and seed production in autumn as a result of the competition of cover crops and weeds for limited resources as light, water, space and nutrients and allelopathic effects [19]. Allelopathy is described as any process involving secondary metabolites, produced by plants, which were released in the environment and influence the development and growth of adjacent plants in agricultural systems [21]. These substances can be introduced actively during the cover crop germination and growth via various pathways as root exudation, volatilization or by the leaching from plant biomass [22,23]. Allelochemicals are diverse in their chemical structure and were identified and isolated in many cover crops [23–25]. For example, members of the family of Poaceae, like *Avena* sp. and *Secale* sp., were reported to exude phytochemicals with high allelopathic effects on weeds [26–29]. Schulz et al. identified 16 allelochemicals in rye (*Secale cereale* L.), including the benzoxazinones, and emphasized their high allelopathic contribution to the overall weed suppression [28]. The complete pathway and dynamics from the exudates of the donor plant, the transformation, and

degradation processes to the uptake by the target plant is extremely complex and requires intensive research [27].
The allelopathy phenomenon was investigated in terms of inducibility by biotic and abiotic factors [29]. Pathogen or insect attacks were studied as elicitor for biotic-induced and -enhanced allelopathy in conjunction with forced release rates of allelochemicals or higher gene expression that regulates the biosynthesis of the phytotoxic compounds [27,29–31]. Beside the biotic factors, changes in the environment as temperature, humidity, nutrients, mechanical damage or irradiation can also increase the accumulation and expression of allelochemicals [20,29,32,33]. Among other weed suppressing effects, the clear understanding of the proportions of allelopathic effects on the overall weed suppression under natural conditions is lacking [34]. The knowledge about the contribution of allelopathic and competitive effects of different cover crops could enable farmers to suppress specific weed species or communities with appropriate cover crop mixtures in autumn and winter. Additionally, a mixture of different cover crop species is more flexible to unpredicted biotic and abiotic stressors due to a higher elasticity and ability to recovery compared to a mono cultivation. From this might also follow a more effective weed suppression [35]. Furthermore, cropping methods, like an optimum cover crop sowing date and fertilization, may enhance the beneficial effects in agricultural systems.

In spring, the cover crops froze or were sprayed with non-selective herbicides to induce the formation of mulch which provides the second opportunity for interference in the weeds lifecycle. The cover crop residues on the soil surface offer ecological benefits like reducing the soil evaporation and erosion [36–39], decreasing daily soil temperature excursion [40–42] and suppressing weeds [42–45]. Cover crop mulch alters physically the weed seeds environment by changes in light availability, humidity, nutrient mobilization, soil temperature, soil moisture and can also offer additional allelopathic effects [17]. Especially cover crops with high allelopathic properties seem to be well-suited for suppression of weed germination and growth [46]. Moreover, the incorporation and the associated mechanical wounding of these cover crops could enhance the biochemical weed suppression in spring [20]. Therefore, a combination of diverse cover crops with optimum physical and allelopathic traits could provide higher weed control efficacy due to a combination of different inhibitory mechanisms prior to the main crop sowing.

The biological interference with weed development by cover crops from autumn to spring can be continued by the integration of living mulches in the main crop in summer, which provides the third opportunity. Living mulches are cover crops, which are sown simultaneously with or shortly after sowing the main crop [4,47]. The level of competition for natural resources between the undersown cover crop and the main crop depends on the cover crop species and must be carefully selected to avoid quantitative and qualitative yield losses [48]. Especially in main crops with wide row distances, as sugar beets, living mulches provide similar ecological benefits compared to summer or autumn sown cover crops including the inhibition of weed germination and development [4,47–52]. Furthermore, the substantial weed suppression during the growth of the main crop could reduce herbicide input which contributes to environmentally sustainable agriculture.

1.1 Objectives

In the presented thesis, the main objectives were

- to investigate the weed suppressing effects of different cover crops under mono and mixture cultivation in autumn and winter
- to optimize cover crop weed control by different cover crop sowing dates and fertilization
- to explore the impact of diverse cover crop mulches on sugar beet development and the germination and growth of specific weed species
- to test the feasibility of the cultivation of living mulches in sugar beet for weed suppression with respect to sugar beet quality and quantity parameters
- to evaluate the contribution of competitive and biochemical effects on the overall weed suppression by cover crops
- to identify susceptibilities of different weed species to specific cover crops

1.2 Structure of the dissertation

The current thesis consists of ten chapters contributing to the optimization and exploration of approaches for integrated weed management with cover crops. The thesis begins with the general introduction (Chapter I) presenting the field of research and emphasizing the objectives of this work. The following chapters (Chapters II-VII) are six research articles composing the main work of this thesis.

The scientific articles were arranged along an agricultural vegetation period from late summer over spring to the following summer and present the opportunities and strategies for interference in the lifecycle of weeds. In Chapter II and III, cover crops were investigated on their weed suppressive ability in autumn and winter concerning the cultivation in mono and mixture cultivation as well as the impact of cover crop sowing date and fertilization. Chapter IV and V deal with the role of competitive and biochemical effects on the overall weed suppression and demonstrates the sensitivity of specific weeds to biochemical stresses. Chapter VI presents the potential of different cover crop mulches to suppress weeds in the early development of sugar beet crops. In Chapter VII, the possibility of living mulch cultivation in sugar beet crops was tested with respect to weed suppression and quantity and quality parameters of the main crop. The general discussion (Chapter VIII) gives a critical overview of the research articles. The whole thesis is summarized in Chapter IX.

Apart from the peer-reviewed journal articles, three more contributions to national and international scientific conferences were presented as an oral presentation during the course of this thesis. This work was supplementary to the included articles and therefore not included in the current thesis.

- Sturm, D.J. & Gerhards, R. (2016). Comparison of different cover crop mulches and extracts on inhibition of crop and weed growth. In: *Proceedings of the 27^th German Conference of Weed Biology and Weed Contro*l, 452, 424-430.

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

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

Chapter II

Do cover crop sowing date and fertilization affect field weed suppression?

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2 Do cover crop sowing date and fertilization affect field weed suppression?

Summary

The weed suppressive ability of oilseed radish (*Raphanus sativus* var. *oleiformis* Pers.) cover crop is attributed to high competitiveness for resources and allelopathic effects on weeds. The oilseed radish cover crop was sown in five treatments plus an untreated control over a period of five weeks before and three weeks after winter wheat harvest. Additionally, fertilization effects on oilseed radish biomass and weed suppression were measured. The highest biomass of the cover crop was observed 12 weeks after harvest (WAH) when the oilseed radish was sown one week after harvest (1 WAH) (2015) and five weeks before harvest (5 WBH) (2016). No differences of fertilization were observed concerning oilseed radish and weed biomass in 2015, whereby increased biomass was found after fertilization in 2016. The highest weed control efficacy of up to 83% and 90% was achieved in treatments 1 WAH (2015) and 5 WBH (2016) at 12 WAH. The early sowing of oilseed radish in winter wheat resulted in low germination and biomass yield within the field, due to low precipitation in 2015. Nevertheless, there is a high potential of early sown oilseed radish for higher weed control efficacy, which was demonstrated in 2016.

Keywords: allelopathy, Brassicaceae, intercropping, cropping system, competition, weed density

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Chapter III

Allelopathic effects and weed suppressive ability of cover crops

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3 Allelopathic effects and weed suppressive ability of cover crops

Summary

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

Keywords: allelopathy, erosion, root growth, competition, intercropping

Chapter IV

Contribution of competitive and biochemical effects by different cover crops to weed suppression

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4 Contribution of competitive and biochemical effects by different cover crops to weed suppression

Summary

Cover crops can suppress weeds within agricultural fields due to competitive and biochemical effects. Greenhouse experiments were conducted to evaluate the relative proportions of both effects to the total weed inhibition. Six different cover crop species were combined with three weed species in the presence or absence of active carbon over a period of four weeks. Active carbon was used as an adsorbent for biochemical substances in the soil. Our study reveals that the balance of competition between cover crops and weeds shifted when biochemical effects in the soil were minimized by active carbon. We assume that the degree of cover crops biochemical effects on weeds is species-specific, both on the side of cover crops, as well as on the weed side. The knowledge about the contribution of competitive and biochemical effects by cover crops would enable us to create cover crop mixtures to suppress specific weed species and communities.

Keywords: Allelopathy, *Alopecurus myosuroides*, Intercropping, *Stellaria media*, *Triticum aestivum*, Weed control

4.2 Introduction

Cover cropping provides ecological and economic benefits in agricultural fields, including nutrient recycling, reduction of soil erosion and effective weed suppression with a potential contribution to Integrated Weed Management [4]. The weed suppressive ability of cover crops is characterized by a high competition for light, water, space and nutrients attributed to a combination of competitive and biochemical effects [11]. Several studies have shown that allelopathy can play an important role in the overall weed suppression and the competition for limited plant resources [11]. Allelopathy is the chemically mediated interference between co-occurring plants and includes a growth stimulation or inhibition of the target-plant, mostly following a hormesis [53]. Callaway & Ashehoug reported stronger allelopathic effects of the invasive plant *Centaurea diffusa* Lam. on different grass species in North America compared to grass species to which *C. diffusa* is native [54]. Based on that concept, cover crops are non-coevolved competitors to weeds, therefore weeds lack a natural adaption to their novel phytochemicals. Therefore, greater allelopathic interference can be expected when an allelopathic plant occurs in a non-native range [55]. Some cover crop species were investigated for the active release of allelopathic compounds as the family of Poaceae [28], *Fagopyrum* sp. [56] or *Helianthus annuus* L. [57]. The general effects of competition within the field are partly well understood as isolated mechanisms, but there is a lack of information about the relative proportions on the total weed suppressive effects [58].

The aim of this study was to estimate the relative proportions of biochemical and competitive effects of six different cover crops on the overall weed suppression of two weed species (*Stellaria media* (L.) Vill. and *Alopecurus myosuroides* Huds.) and volunteer wheat (*Triticum aestivum* L.) in greenhouse trials. In order to determine the allelopathic capability of the selected cover crops, the weeds were grown in the presence and absence of the potential allelopathic competitor (with and without cover crops) in the presence or absence of active carbon, as an adsorbent for biochemical compounds, in the soil. The knowledge about the proportions of biochemical and competitive effects could enable us to create cover crop mixtures with optimum traits for more effective specific weed suppression within the field.

4.3 Material and Methods

4.3.1 Experimental set-up

The greenhouse experiments were carried out at the University of Hohenheim from 2015-2016 to estimate the relative contribution of competitive effects and biochemical traits to the overall weed suppression on different weed species (*S. media* and *A. myosuroides*) and volunteer wheat (*T. aestivum*). A soil with 60% sand and 40% turf (v/v) was prepared (Soil-N). Pulverized active carbon (Carl Roth GmbH + Co. KG, Karlsruhe, Germany), with a particle size of < 0.8 mm, was mixed with half of the Soil-N to reach a concentration of 6% (v/v) (Soil-AC). The addition of active carbon was performed to reduce potential biochemical interference in the soil between cover crops and weeds [54]. Active carbon is used as adsorbent due to the high porosity and adsorptive capacity for many organic compounds. An enhanced weed growth after soil implementation with active carbon indicates the presence of allelopathic compounds released by the cover crops [55]. Both soils were filled in 2-L pots separately and one gram of a slow release fertilizer (16:9:12 N:P:K, Osmocote®, Scotts Celaflor GmbH, Mainz, Germany) was added to each pot. This was performed to reduce possible effects of the active carbon on the nutrient availability in the soil [59]. The different cover crops (Tab. 7) were sown separately in pots, using recommended sowing rates, together with 40 seeds of *A. myosuroides* or 30 seeds of *S. media* (Herbiseed, Reading, UK) or 7 seeds of winter wheat (*T. aestivum* cv. 'Pamier').
Shortly after germination, weeds were thinned out to ten and the winter wheat to five plants per pot. Two controls with Soil-N (Control-N) and Soil-AC (Control-AC), plus weeds and no cover crops were prepared to determine confounding effects of the active carbon on weed growth. The greenhouse setup was 12 h / 12 h (day/night) with the temperatures being respectively 20/15 °C. All pots were irrigated daily with tap water to field capacity. The pots were arranged in a randomized complete block design with four replicates and the experiment was

repeated in time. Cover crop and weed biomass were harvested after four weeks and were dried at 80°C for 48 h before being weighed.

Table 1 Different cover crop treatments and sowing rates in the greenhouse experiments.

Cover crop	**Scientific name**	**Plant Family**	**Sowing rate [kg ha^{-1}]**
Oilseed radish	*Raphanus sativus* var. *oleiformis* Pers.	Brassicaceae	20
Buckwheat	*Fagopyrum esculentum* Moench	Polygonaceae	45
Black Oat	*Avena strigosa* Schreb.	Poaceae	100
Common flax	*Linum usitatissimum* L.	Linaceae	100
Ramtil	*Guizotia abyssinica* (L.f.) Cass.	Asteraceae	8
Sunflower	*Helianthus annuus* L.	Asteraceae	25

4.3.2 Statistical Analysis

The data of the greenhouse experiments were analyzed with the statistical language R version 3.1.1 [60] with a linear mixed effects model taking soil type and cover crop as different factors. The homogeneity of variance and the normal distribution were checked visually and transformations of data were performed, if necessary. An analysis of variance (ANOVA) was carried out to test the effects of active carbon, cover crop species and their interaction. Years and replications were considered random effects. Further, separate analyses were performed for each weed species. Means were separated via a Tukey's *HSD* test at $P \leq 0.05$.

The proportions of competitive and biochemical effects in the greenhouse experiments were calculated as following:

$$\textbf{Overall weed suppression [\%]} = 1 - \frac{\text{Weed biomass with cover crop}}{\text{Weed biomass without cover crop}} * 100$$

Biochemical weed suppression [%] =

Overall weed suppression in Soil-N [%] - Overall weed suppression in Soil-AC [%]

Biochemical effects are considered significant, if significant differences between weed biomass in Soil-N and Soil-AC and no statistical differences between Control-N and Control-AC were observed.

4.4 Results

4.4.1 Weed suppressive effects of the different cover crops

The utilization of active carbon as an adsorbent for organic compounds to minimize biochemical effects in the soil represents a suitable approach for the evaluation of biochemical effects on the overall weed suppression.

The weed suppressive abilities of the selected cover crops were tested in the prepared soil (Soil-N) and the soil supplemented with 6% of active carbon (Soil-AC). The three weeds *A. myosuroides*, *S. media* and *T. aestivum* were suppressed by the different cover crops (Fig. 6). In all cases, Control-N showed no differences to Control-AC. The biomass of all weeds was significantly reduced in all cover crop treatments compared to the controls.

S. media biomass was reduced by 21 to 80% with the most effective growth suppression caused by *H. annuus* (80%), *F. esculentum* (77%) and *R. sativus* (59%) across both soil treatments. Suppression of *S. media* by the cover crops *R. sativus*, *F. esculentum*, *A. strigosa* and *H. annuus* was significantly lower in Soil-AC. No suppression was found for *L. usitatissimum* and *G. abyssinica*. The biomass of the weed *A. myosuroides* was significantly reduced among all cover crops with up to 89% by treatment *R. sativus*. Significant differences between both different soils were observed for treatment *F. esculentum*, only. The average weed control efficacy of *T. aestivum* was 54 and 48% in Soil-N and Soil-AC across all cover crop treatments. No statistical differences between Soil-N and Soil-AC were observed, except for *A. strigosa* which reduced the growth of *T. aestivum* by 67 (Soil-N) and 48% (Soil-AC).

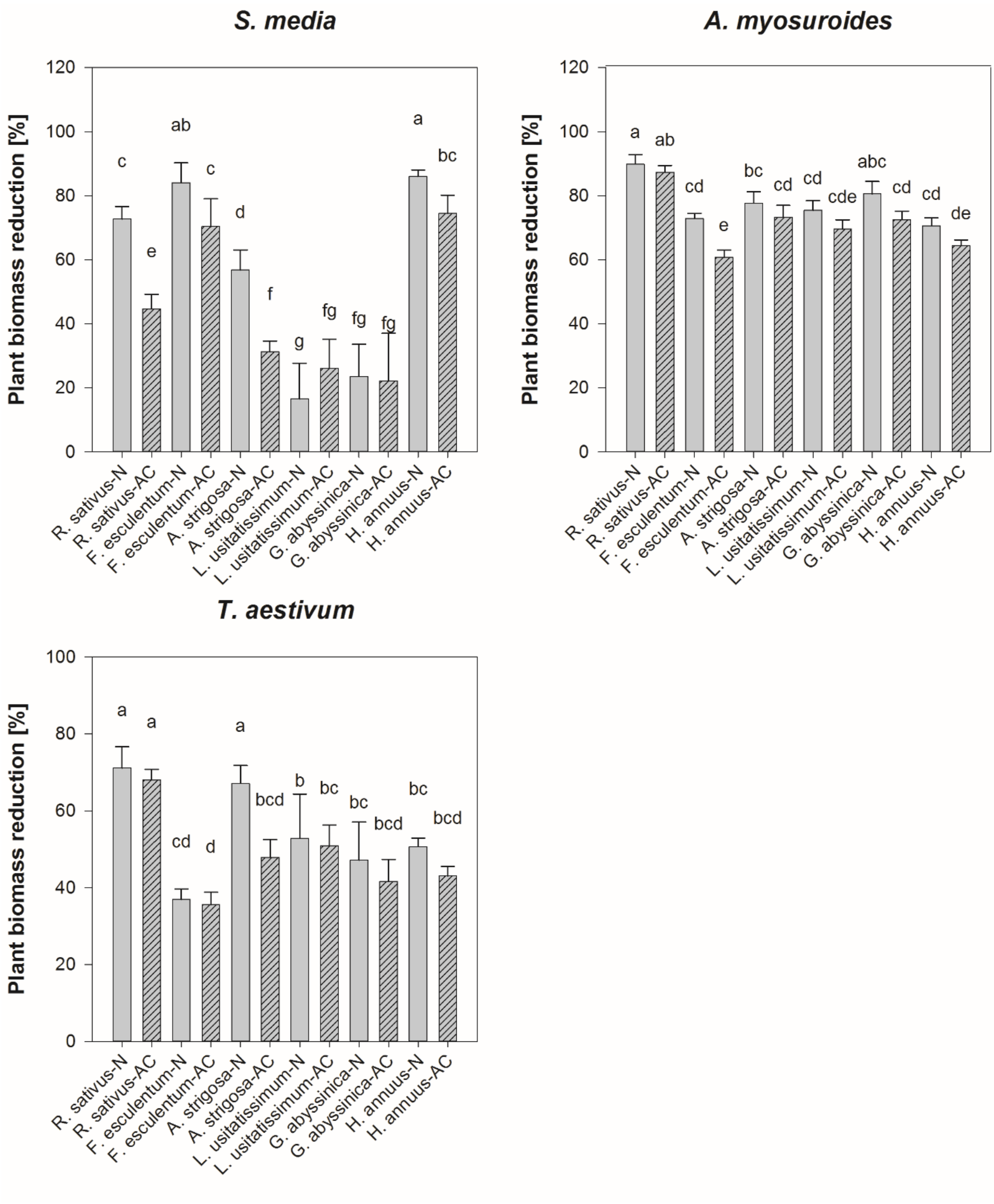

Figure 1 Overall plant biomass reduction [%] of the weeds *S. media*, *A. myosuroides* and *T. aestivum* cultivated in untreated soil (Soil-N) and soil containing 6% active carbon (Soil-AC) with different cover crops after a period of four weeks in greenhouse trials. Means with identical letters within the graph do not differ significantly based on the Tukey HSD test ($p < 0.05$).

The biomass of all cover crops growing in the presence of the weeds was not affected by both soils (Fig. 7). The highest biomass was achieved by *H. annuus* and *F. esculentum* with meanly 4.0 and 3.5 g pot^{-1} across all weeds.

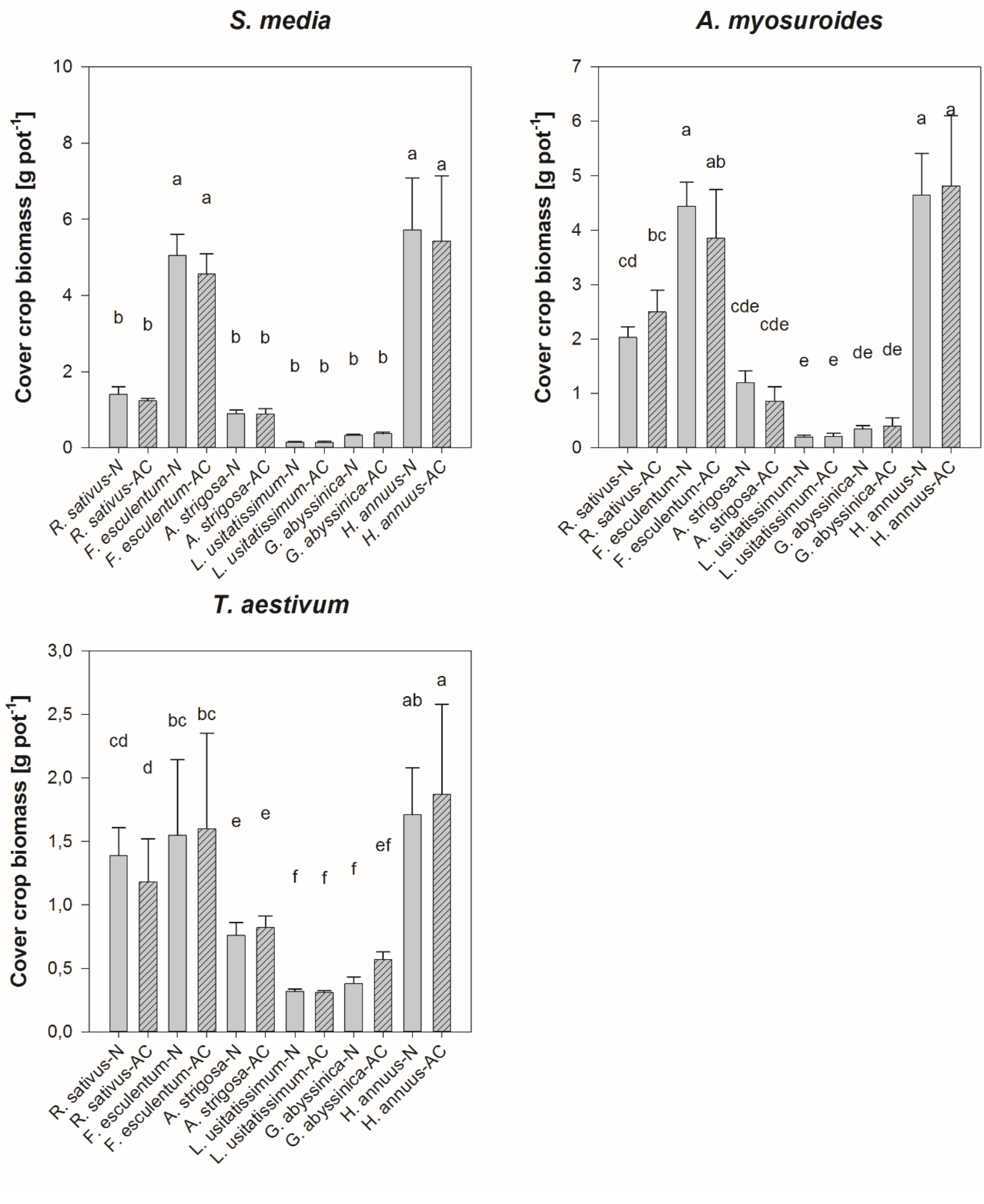

Figure 2 Biomass [g pot^{-1}] of the different cover crops cultivated in untreated soil (Soil-N) and soil containing 6% active carbon (Soil-AC) with different weeds after a period of four weeks in greenhouse trials. Means with identical letters within the graph do not differ significantly based on the Tukey HSD test ($p < 0.05$).

4.4.2 Proportions of biochemical effects on the overall weed suppression

The differences between the overall weed suppression (Soil-N) and the competitive weed suppression (Soil-AC) provides an estimation of the proportion of biochemical effects on the total interference between specific cover crop and weed species (Tab. 8).

Table 2 Proportions of biochemical effects [%] on the overall weed suppression by different cover crops in greenhouse trials (experiment 2). The calculated biochemical effects were only significant [*] if significant differences between the weed biomass in both soils (Soil-N and Soil-AC) and no differences between both controls were detected.

Cover crop	**Biochemical weed suppression [%]**		
	S. media	***A. myosuroides***	***T. aestivum***
R. sativus* var. *oleiformis	28.1 *	2.5	1.1
F. esculentum	13.7 *	12.2 *	1.3
A. strigosa	25.5 *	4.4	19.2 *
L. usitatissimum	0	5.5	2.0
G. abyssinica	1.4	8.1	5.5
H. annuus	11.5 *	6.2	7.6

Significant biochemical effects by 11.5, 13.0, 22.4 and 28.1% were calculated for *H. annuus*, *F. esculentum*, *A. strigosa* and *R. sativus* cover crops, respectively. The weed *S. media* was found to represent the most sensitive weed species to biochemical stress. The cover crops *F. esculentum* and *A. strigosa* showed significant proportions of biochemical effects on the overall weed suppression of *A. myosuroides* and *T. aestivum,* only. The two cover crops *L. usitatissimum* and *G. abyssinica* showed no significant biochemical effects on the weeds in this experiment.

4.5 Discussion

In this study, the biomass of some weeds growing with different cover crop treatments was significantly increased when active carbon was present in the soil. Correspondingly, the active carbon gave some cover crops a competitive disadvantage against the weeds. The observed effects of active carbon on the cover crops weed suppression can be interpreted as an evidence for allelopathy [54]. However, weed growth influencing effects by soil microbiota due to the addition of active carbon may be possible [54].

Some of the tested cover crops showed were known for the active release of allelochemicals during growth. Studies about the weed suppressive ability of *F. esculentum* within the field reported of reduced weed biomass with differences between various weed species [56]. A common explanation for the weed inhibiting effects is the competition for light and nutrients [61,62]. However, no experiments could prove this hypothesis, so far [56] and a significant competition for nutrients, as a factor for observed weed suppression, can be neglected in this experiment due to fertilization. This was shown in field experiments with high soil nutrient supplies resulted in an effective weed control by *F. esculentum* [62]. Kalinova *et al*. demonstrated that the high weed suppressive ability of *F. esculentum* from germination to early development originates from the root exudation of several phytotoxic substances [63]. Falquet *et al*. showed that light competition and root interaction between *F. esculentum* and the weed (*Amaranthus retroflexus* L.) led to significant weed biomass reductions, while excluding other suppressive factors as the competition for nutrients and water [64]. Further, the authors concluded the major role of the root interaction of *F. esculentum*, including the release of allelopathic root exudates, on the overall weed suppression compared to the light competition.

The family of Poaceae, including *A. strigosa*, has been documented to release allelopathic substances in the rhizosphere [28]. Substances of the chemical groups of benzoxazinones and several phenolic acids were actively exudated via the roots during growth and were tested for inhibitory effects on weed growth [28]. *H. annuus* has been investigated extensively for inherent allelopathic substances in various plant parts which might be able to influence the germination and growth of weeds [57]. Glucosinolates and their degradation products are the main sources for allelopathic effects on weeds by *R. sativus.* Several studies reported of high amounts of glucosinolate degradation products after tissue damage or the incorporation of *R. sativus* residues in the soil [65]. Alternatively, the active exudation of inhibitory substances via the roots or leachates from the leaves could be possible, as shown by the exudation of 2-phenylethyl isothiocyanate and allyl isothiocyanate by *Brassica napus* L. roots [65]. The cover crops *L. usitatissimum* and *G. abyssinica* showed a strong weed suppressive ability with no significant differences in the weed suppression in Soil-N and Soil-AC. This can be attributed to the absence of root or shoot exudation of inhibitory compounds in the soil. Moreover, there is a lack of information about potential allelochemicals and their exudation by *L. usitatissimum* and *G. abyssinica*, so far. Therefore, these two cover crop species exert weed suppression mainly by physical competition. However, there is no evidence for the volatilization of allelopathic compounds during growth induced by all investigated cover crops. Therefore, the mentioned release pathway can be neglected in this experiment.

In this experiment, *A. strigosa* showed significant substantial biochemical effects on the weeds *S. media* and *T. aestivum*. The absence of these effects on *A. myosuroides* may be attributed to a higher detoxification activity of this weed against growth suppressing allelochemicals like benzoxazolin-2(3H)-one (BOA) released by *A. strigosa* [28]. The accumulation of multi drug resistance transporters as verapamil, nifedipine and ethacrynic acid with glutathione transferases in a donor plant may enhance the extrusion of phytotoxic compounds, as BOA, out of the protoplasts [28]. In general, allelopathic effects were species-specific [11,28,66]. In this experiment, the weed *S. media* showed the greatest sensitivity to biochemical effects. Earlier studies confirm the increased biochemical susceptibility of *S. media* compared to other weeds [66]. This is also in line with other studies, which demonstrated a higher sensitivity of dicotyledonous weeds against the presence of *F. esculentum* seedlings and its released allelochemicals [63].

The proportions of competitive and biochemical effects on the overall weed suppression indicates an important role of the biochemical effects. Nevertheless, the competitive effects showed a higher contribution to the overall effects. Therefore, a rapid cover crop germination and development combined with a dense canopy and high soil coverage is a prerequisite for an effective weed suppression within the field.

Future research should investigate if competitive and biochemical effects provide additive or synergistic effects on the overall weed suppression. Moreover, further cover crop species and cultivars should be investigated with strong biochemical effects on different weeds.

Chapter V

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

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

Summary

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

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

Chapter VI

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

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

Summary

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

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

Chapter VII

Weed Suppression of Living Mulch in Sugar Beets

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7 Weed Suppression of Living Mulch in Sugar Beets

Summary

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

Keywords Biomass, *Beta vulgaris*, Cover crop, *Festuca*, *Lolium*, *Trifolium*, Intercropping, Sugar content, Sugar yield, Weed density

Chapter VIII

General Discussion

8 General Discussion

The integration of cover crops and living mulches in the crop rotation can provide a substantial biological inhibition of weed germination and growth. The aim of this work was the optimization and exploration of integrated weed control strategies with cover crops. For this purpose, three laboratory, two greenhouse and five field experiments were performed from 2014-2017 at the University of Hohenheim, Germany.

We examined the interference in the weed lifecycles by the cultivation of different cover crops from autumn to the following summer. Furthermore, attention is directed to the contribution of altering the cropping system, including sowing date and fertilization. Laboratory and greenhouse experiments provided a closer examination of the proportions of biochemical effects of cover crops on the overall weed suppression which will be discussed with regard to possible benefits for farmers.

8.1 Weed suppression by cover crops in autumn and winter

In the experiments, cover crops were able to suppress weed density and biomass by up to 91 and 89% in autumn and winter due to a combination of competitive and biochemical effects. In chapters 2 and 3, the investigated cover crops showed varying inhibitory effects on weed density and biomass depending on mono or mixture cultivation, cover crop species and sowing date. The mono cultivation of the cover crops *S. alba*, *R. sativus* var. *niger* and *V. sativa* resulted in a weed density reduction of 60%, while a weed suppression of 66% was observed for the mixtures. The mixture cultivation of cover crops compensates the disadvantages of a single species [35]. The commonly cultivated cover crops and mixtures provide a large variability concerning the genera, physiology, morphology and the resulting weed suppressive ability for each species. Every single species in a mixture has individual properties to suppress weeds (with a broad target weed spectrum) and to adapt to varying biotic and abiotic field conditions. This can be followed by a higher flexibility and adaptability against stresses with an increased dry matter production and weed suppression compared to monocultures [28,35,67]. Beside higher biomass production, cover crop mixtures provide many ecological services compared to mono cultivated cover crops, e.g. higher biodiversity and erosion control [3,4]. For example, the cultivation of rye (*S. cereale*) and a legume, as summer vetch (*V. sativa*), in a mixture is able to produce higher amounts of biomass and N accumulation compared to a mono cultivation. This effect is based on ecological interaction, which allows an earlier germination and growth of rye and the ability of the vetch to climb on rye plants combined with atmospheric nitrogen accumulation [41,68–70]. The combination of these specific plant species properties provide a more rapid canopy closure with early weed suppressive effects [35,71,72]. Moreover, the low C:N ratio of this specific mixture prevents nitrogen immobilization with improved decomposition and nitrogen release rate for the following crop [35,70,73]. However, the influence of cover crop cultivation on the weed seed bank in autumn needs to be investigated. An increased biodiversity can promote the impact of seed predators, while their efficacy needs to be tested compared to herbicide application and mechanical approaches as stubble cultivation or false seed bed preparation.

No correlation was found between cover crop biomass and weed density which could be explained by the important role of biochemical effects on the overall weed suppression. Additionally, the large heterogeneity in the occurrence of weeds within the field may lead to insignificant correlations between these parameters [74].

The sowing date of the cover crops determines their germination, development speed, biomass accumulation and weed suppression during autumn and winter. In general, a cover crop should be sown shortly after the main crop harvest to avoid soil water losses due to evaporation and to confer a competition advantage to the cover crops against the weeds. The light interception by cover crops is negatively correlated with weed biomass which can be improved by an early and high light interception over short time compared to the whole season [75]. Therefore, a cover crop could be established as living mulch, sown shortly before the main crop harvest, to pass the seedling stage quickly and to generate a growth advantage against the weeds. After the main crop harvest, the increased amount of light promotes a rapid canopy closure with early, strong light interception to suppress weeds efficiently. In chapter 2, the experimental years showed contrary results, which was probably because of soil water deficiencies. Further experiments should aim at the impact of available soil water and temperature at different cover crop sowing dates to induce optimum cover crop germination and development. A screening of different cover crops on drought tolerance could be performed to identify cover crops which were more suitable to unfavorable growth conditions. Based on this, specific cover crops could be selected for consistent germination and biomass production under varying field conditions in different years at early sowing dates. A further advantage of the early sowing would be the reduction of high workload peaks during and after main crop harvest while reducing the risk of delayed cover crop sowing with insufficient biomass production and weed control.

8.2 Inhibitory effects of cover crop mulches on weeds

Cover crops can produce high amounts of plant residues on the soil surface which can influence weed germination and growth in spring by reducing light transmittance, changing the microclimate, releasing allelochemicals and by building a physical barrier [3,35,44,71]. In chapter 5 and 6, the weed density was decreased by up to 83-97% across all locations and compared to the untreated control due to cover crop mulch. Furthermore, cover crop mulch originating from cover crop mixtures (-56%) tended to suppress weeds more effectively compared to monocultures (-31%). Significant weed reductions prior to sowing the main crop can lead to lower herbicide input accompanied by decreased environmental risks [4]. Nevertheless, the weed control is incomplete in many cases. The emerged weeds, which were not suppressed by cover crop mulch, were often sufficient to compete with the main crop and to generate significant yield reductions if no herbicides were applied [10]. While investigating the overall weed suppression by cover crop mulches, little information was available in literature regarding the changes in weed composition variation under different mulches [3]. In particular, large-seeded weeds, as *Abutilon theophrasti* Medicus, seemed to be less affected in germination by mulches compared to small-seed weeds as *Chenopodium album* [10,76]. The high impact of biochemical effects and physical parameters, e.g. bulk density, of cover crop mulch may be reasons for the observed insignificant correlation between cover crop mulch biomass and weed density. Therefore, the mulch biomass cannot be seen as the only indicator for weed control efficacy. Further parameters as the release of biochemical compounds, the mulch bulk density or the C:N ratio of the mulch should be implemented in future investigations on the weed suppressive ability of cover crop mulch. The release of allelochemicals by cover crop mulch can reduce weed germination and growth, whereby the suppressing effects are non-selective. Therefore, further experiments should aim on the release rate and persistence of allelochemicals in the soil to evaluate possible inhibitory effects on the following main crop.

8.3 Weed control with living mulches

Living mulches were shown to provide many benefits for an agricultural system by recycling nutrients, improving soil structure and suppressing weeds and pests [4,77,78]. They were used in many crops as vegetables, maize, cereals and oilseed rape [48–50,52,79–82]. The integration of living mulches in sugar beet crops is hardly performed due to the low competitiveness and slow development of sugar beet plants [51,83]. Interspecific competition for natural resources with quantitative and qualitative yield losses can limit this system [81]. In chapter 7, living mulches suppressed weeds by up to 71% and led to herbicide reductions of 65% in combination with prior hoeing and band-spraying compared to overall boom spraying. The cultivation of the living mulches 30 days after sugar beet sowing resulted in insignificant changes of white sugar yield and qualitative parameters compared to the overall boom spraying. An optimum sowing date, adequate living mulch species and cultivars, growth regulation and fertilization strategies in sugar beet crops need to be researched in future to enhance the acceptance of this cultivation method for farmers and to substantially reduce herbicide inputs in the long term.

8.4 Separation of biochemical and competitive effects by cover crops on specific weed species

Laboratory and greenhouse experiments were conducted to investigate the contribution of biochemical interaction between cover crops and weeds. During the last decades, several cover crop species were investigated for the active release of allelopathic compounds. Potential allelochemicals in the cover crops were isolated and identified as inhibitory compounds on several weed species [11,22–24,29]. Allelochemicals are naturally produced herbicides by plants with a relatively low phytotoxic activity compared to herbicides. The high efficacy of these compounds is obtained through the constant release into the environment with varying concentrations over long periods [84].

Beside other interference effects, allelopathy is an attractive explanation for observed weed suppression in many cover crop experiments, but the differentiation between all plant growth-influencing effects is difficult and diminishes the acceptance of this phenomenon in the agricultural science [59,85,86]. In plant research, nearly no other research field caused as much controversy as the studies on allelopathy [87,88].

8.4.1 Germinations tests with aqueous cover crop extracts

In chapters 3 and 5, different aqueous cover crop extracts were tested in germination tests to evaluate the biochemical inhibition by phytotoxic substances on germination, mean germination time and root length of specific weeds. Weeds are wild species and are genetically more heterogeneous compared to our crops and are characterized by a non-uniform germination [89]. Based on that, we selected representative weed species, which are naturally occurring in Germany with germination rates between 60 and 80%. This allows the detection of inhibitory and stimulatory effects combined with a low statistical variability. Monocotyledonous weeds were omitted due to possible autotoxic effects, which could affect germination [89,90].

The cover crop extracts inhibited weed germination and root growth significantly. Further, weed density within the field was correlated with the germination rate and root length of specific weeds from germination tests. This elucidates the important role of biochemical effects on the overall weed suppression within the field.

While using this experimental approach, the differentiation between allelopathic or phytotoxic effects on specific weeds constitutes a major challenge. In principle, phytotoxins which were isolated from a plant cannot be considered as allelochemicals *per se* without the knowledge about their role in plant communication or the environment [91]. Regardless of the initial purpose in the plant many substances were phytotoxic [23]. Based on that, germination tests with cover crop extracts were an important component in preliminary allelopathy studies to differentiate cover crops in their biochemical, suppressive activity on weeds [92].

Nevertheless, while testing cover crop extracts under laboratory conditions, a broad range of effects is eliminated due to the strong isolation of environmental factors. On the other hand, a field experiment would present a wide variability in response to the treatments, which necessitates the preliminary evaluation under isolated mechanisms with diverse model weeds [89]. However, chemical and biotic soil factors, the bioavailability and stability of allelochemicals in the soil as well as their uptake and response of the target plant are some of many factors which cannot be taken into account [93]. Moreover, preexisting compounds in the soil as methionine, glucose or nitrate and microbial communities were able to inhibit or promote the effects of allelochemicals in the soil [94,95].

Due to the complexity of the allelopathy phenomena, results from laboratory experiments are difficult to be transferred directly into natural field conditions [96]. However, we aimed to separate the biochemical weed suppressive effects of the cover crops from the overall weed suppression. Therefore, the relationship between the toxicity of cover crop extracts in germination tests and the weed density within the field was investigated. We observed a strong correlation between the mentioned parameters which allowed us to conclude, that biochemical effects are significantly involved on the overall weed suppression by cover crops in autumn and spring.

The inhibitory effects of the cover crop extracts varied along the different cover crops and between the investigated weeds. The highest weed suppressive effects were observed by *L. usitatissimum, H. annuus* and *T. subterraneum* which could be explained by the possible release of biochemical substances during extraction of the cover crops. The cover crop *F. esculentum* showed a higher inhibition of weed growth in experiments with cover crop mulch incorporated in soil compared to the effects in germination tests. This indicates that some biochemical substances in the cover crop need to be transformed by microorganisms in the soil to become more active phytotoxic substances [27]. The comparison of the weed suppressive ability of *L. usitatissimum* in chapters 4 and 5 reveals that this specific cover crop shows no active release of allelochemicals during growth because no significant biochemical effects were measured in chapter 4. However, high weed suppressive effects were observed in experiments with cover crop extracts and mulch.

The experiments emphasized the species-specific activity of biochemical substances induced by cover crops. This could be due to differences in seed morphology and physiology or the ability of some weeds to detoxificate allelochemicals [28,65,97]. These observations may be used to achieve selective effects by allelochemicals to avoid inhibitory effects on the main crop.

8.4.2 Active carbon as adsorbent for allelochemicals

In chapter 4, active carbon in the soil was used as adsorbent for phytotoxic biochemical compounds released by different cover crops. The use of active carbon to reduce biochemical effects in the soil represents a suitable approach to evaluate the contribution of biochemical effects in the overall weed suppression [54,85,98–100]. Only a few experimental approaches have been conducted to exclude competitive effects as light, space, water and nutrients of crops and cover crops on weeds from biochemical interactions [64,101,102].

The active carbon in the soil bound chemical compounds like potential allelochemicals which provided a competitive disadvantage for the cover crops. Consequently, the biomass of some weeds was significantly increased under particular cover crops.

A correlation was calculated for the parameters cover crop and weed biomass for treatments *F. esculentum*, *A. strigosa*, *L. usitatissimum* and *H. annuus* cultivated in soil without active carbon (Soil-N) and for treatments *R. sativus*, *F. esculentum*, *L. usitatissimum* in soil amended with active carbon (Soil-AC). In average, the correlation between cover crop and weed biomass was higher in Soil-N compared to Soil-AC. Under favorable growing conditions, an increasing amount of above-ground biomass of plants can be seen as an indicator for increasing amounts of root biomass and allelochemicals per plant [103–105]. Based on this, cover crops with a higher above-ground biomass will be more competitive against weeds due to higher competitive and biochemical effects, which could be shown in this experiment. If one factor for the competitive advantage of allelopathic cover crops is excluded, as biochemical effects due to the addition of active carbon in the soil, the influence of the cover crop biomass on weed biomass will decrease. If a specific cover crop lacks the ability to exert biochemical effects on the overall weed suppression, there will be no shift of competition between cover crop and weed. Consequently, the correlation between cover crop and weed biomass will not change, which was the case for cover crops *L. usitatissimum* and *G. abyssinica* in this study. Further studies, based on the results in chapter 4 and 5, should aim on the composition of cover crop mixtures with optimum morphological und physiological traits to suppress specific weed species or communities. Beside the weed suppression during cover crop growth, attention needs to be paid in cover crop selection regarding the weed suppressive ability of the mulch in spring due to different release ways of biochemical substances as observed for *L. usitatissimum* and *F. esuclentum* in chapters 4 and 5.

Moreover, the allelopathic effects can be species-specific and can affect the weed coexistence and the weed community composition [55,85,106]. This could be shown for the weed *S. media* as the most sensitive species to biochemical stress, which could also be observed in chapters 4 and 5.

However, active carbon can give inherent problems concerning the meaningfulness of the results. Lau et al. suggested, that the addition of active carbon in the potting soil may influence plant growth [59]. They found an increased nitrogen mineralization, if active carbon is present in the soil, which could explain a higher weed biomass in Soil-AC [59]. Furthermore, organic matter in the potting soil with allelopathic properties or changes in the soil microbial communities may affect the growth of the test plants [59,107]. Results in other publications dealing with minimizing allelopathic effects by the incorporation of active carbon reveal that the growth effects can be inconsistent and can vary across the experimental conditions. For example, active carbon stimulated the growth of *Centaurea stoebe* (L.) ssp. *micranthos* in one study [59], but showed strong negative effects on *C. strobe micranthos* in another study [108]. Therefore, the disparity in the results in allelopathy studies highlights the importance of highly detailed methodological investigations in this research area to create standardized test systems in the future.

8.4.3 Further bioassays to test on allelopathy

The future research in allelopathy should aim at simple and standardized preliminary experiments to support or to refute, if a specific plant species is allelopathic or not [84]. The establishment of conditions in which plant growth, exudation and movement of the allelochemicals are as realistic as possible demonstrates a major challenge [85]. With this knowledge, different cover crop species and cultivars can be selected and might inhibit weed germination and growth more sustained which could generate noteworthy herbicide reductions before and in the following crop in spring and summer. To prove allelopathy, the allelopathic substances must be identified and characterized and could be further investigated as potential herbicidal compounds with new modes of action. In this section, continued studies in alleopathy with bioassays in the future were suggested.

1. A simple method to support allelopathy of a cover crop would be the cultivation of the donor (cover crop) and receiver plant (weed) side by side on agar. The exudated allelochemicals by the donor will diffundate through the medium and gradient effects on the root length of the receiver could be observed as indicator for the presence of allelopathic compounds [84,109,110].
2. An advanced approach of the first mentioned method can be the side by side cultivation of donor and receiver plant with a semipermeable root barrier. Consequently, this system would avoid direct root contact, while allelochemicals are able to move through the barrier [111,112]. On the other hand, a non-permeable membrane can be used to eliminate resource competition and the

movement of the allelochemicals between the plants [99]. Moreover, an opaque above-ground barrier would additionally exclude light competition [84,113].

3. The cultivation of the receiver plant in soil in which the donor plant was grown previously would exclude the resource competition. If potential allelochemicals were released into the soil during the growth of the donor, germination and/or growth reductions should be visible. In this experiment, a control treatment with a non-allelopathic cultivar of the same donor plant species should be created, as shown with rice cultivars in the study of Rimano and Duke [84,114]. Attention needs to be payed on the receiver plant density due to density-dependent effects of the allelochemicals [115]. This approach would enable us to identify biochemical inhibition levels along different cover crop cultivars. Moreover, the allelochemicals in the soil should be identified.

4. A further option is to cultivate the receiver plant in soil amended or irrigated with plant or soil leachates of the donor plant [116–118]. Due to the low half-life period of many allelochemicals, the draining water from donor plant pots could be transported directly to the donor plant pots [84]. Consequently, the leachates and root exudates would reach the receiver plant promptly.

5. The inhibitory effects on weeds occurring after the incorporation of cover crop mulch in soil in greenhouse experiments can differ strongly from observed effects within the field. The addition of active carbon in the pot medium, as adsorbent for secondary metabolites originating from the mulch, crossed with the exposure to allelopathic plant material, e.g. mulch, followed by enhanced weed growth can be interpreted as an indication for the presence of allelochemicals in the soil [58,99,109,119].

6. To include the preexisting environmental effects within the field, active carbon can be added in the field soil. After the incorporation, cover crops should be sown together with defined amounts of natural occurring weeds, while the preexisting weed flora should be eliminated to form a uniform weed infestation and to avoid a high variability in the results.

All of these methods would support the indication of allelopathic effects induced by the donor on the receiver plant. Nevertheless, many parameters as sampling time of plant biomass or compounds, climatic and soil conditions, irradiation, plant cultivar, fertilization or the type of charcoal can alter the allelopathic effects, which complicates the comparability of the experiments and results. However, the following identification, characterization and exploration of the mode-of-action of the released allelochemicals is needed to understand their physiological and ecological functions [85].

Chapter IX

Summary

Zusammenfassung

9 Summary

Weed control constitutes a major challenge in the worldwide crop production. Beside chemical and mechanical weed control strategies, cover cropping provides an effective way of biological weed suppression. Five different field experiments were conducted at six locations from 2014-2016 to evaluate the weed control efficacy of different cover crops in mono and mixed cultivation combined with different fertilization strategies and sowing dates. Furthermore weed suppressing effects of cover crop mulches in spring and of living mulches in summer were investigated. Potential effects on sugar beet emergence, quality and quantity were also assessed. In three laboratory and two greenhouse experiments from 2015-2017, the proportional contribution of competitive and biochemical effects on the overall weed suppression and the identification of varying susceptibilities of different weeds against biochemical stresses were at the center of research.

In field experiments, the weed suppressive effects of cover crops and living mulches in mono and mixed cultivation were tested. The experiments emphasized the importance of cover crop and living mulch mixtures compared to mono cropping due to a higher flexibility to biotic and abiotic stresses. This was followed by a more constant biomass production and more effective weed suppression. Moreover, the observed weed control was a result of competitive and biochemical effects, induced by cover crops. These were later on analyzed for active weed growth suppressing compounds.

Altering cover crop sowing date and fertilization to optimize the weed control resulted in significant changes of cover crop and weed biomass. Early cover crop sowing five or three weeks before winter wheat harvest increased the weed control efficacy in one year, significantly. Due to contrary results over the two experimental years, we suggest that the cover crop biomass and consequently the weed suppressive ability depends on sufficient soil water for rapid cover crop germination and growth.

The use of cover crop mulch in sugar beet crops provided a weed suppression of up to 83%. Especially mulch derived from cover crop mixtures reduced the weed

density (56%) more effectively compared to mono cultivated cover crops (31%). The inclusion of cover crops, mulches and living mulches can lead to significant herbicide reductions in the main crop. However supplementary mechanical or chemical weed control strategies are still necessary, especially in crops with a low competitive ability like sugar beets. Nevertheless, novel mechanical weed control approaches and adequate herbicide application techniques, as band-spraying, can reduce the herbicide input in the long-term.

Germination tests with aqueous cover crop extracts were conducted on weed seeds to evaluate differences in the inhibition of germination and root growth. Furthermore, different sensitivities of the weeds against the different cover crop extracts were revealed. Some cover crops as *S. alba*, *F. esculentum*, *H. annuus*, *T. subterraneum* and *L. usitatissimum* showed the most effective weed suppression. Moreover, the weed *M. chamomilla* showed the highest susceptibility against biochemical stresses in the germination tests.

A strong positive correlation between the weed suppressive effects by the extracts and the field weed suppression was found. This indicated that biochemical effects play also an important role on the overall weed suppression in the field. To estimate the proportions of competitive and biochemical effects on the overall weed suppression by cover crops, greenhouse experiments with active carbon supplemented soil were conducted. These experiments revealed that biochemical effects, by the presence of active carbon in the soil, shifted the balance of competition between cover crops and weeds. In the course of the experiments, we also found species-specific effects on the donor as well as on the receiver side.

The results of this thesis demonstrate the diverse use of cover crops, their mulches and living mulches in agricultural systems. This work aims on the optimization of biological weed control strategies and indicates approaches for future research. It is for example not yet clear how cover crops suppress specific weeds and if it is possible to design combinations of specific cover crops for the suppression of individual weed communities. Additionally, these results help to reduce long-term herbicide inputs in agricultural systems.

9.1 Zusammenfassung

Die Unkrautkontrolle stellt eine der größten Herausforderungen in der heutigen Pflanzenproduktion dar. Eine Eingliederung von Zwischenfrüchten und Untersaaten in die Fruchtfolge ist, neben chemischen und mechanischen Maßnahmen, eine effektive Möglichkeit zur biologischen Bekämpfung von Unkräutern.

In fünf verschiedenen Feldversuchen von 2014-2016 wurde die unkrautunterdrückende Wirkung von Zwischenfruchtreinsaaten und -mischungen in Kombination mit verschiedenen Anbauverfahren an sechs Standorten erforscht. Zudem wurden unkrautreduzierende Effekte durch den Einsatz von Zwischenfruchtmulch im Frühjahr und Untersaaten im Sommer im Hinblick auf Keimung, Wachstum, Qualität und Ertrag von Zuckerrüben untersucht. In drei Labor- und zwei Gewächshausversuchen von 2015-2017 sollte die Frage von den Anteilen von kompetitiven und biochemischen Effekten an der gesamten Unkrautunterdrückung beantwortet werden. Gleichzeitig sollten so auch Unterschiede im Wachstum einzelner Unkrautspezies aufgrund biochemischer Effekte von Zwischenfrüchten identifiziert werden.

Die Ergebnisse der Feldversuche deckten eine höhere Effektivität von Zwischenfruchtmischungen hinsichtlich der Unkrautkontrolle im Vergleich zu Zwischenfruchtreinsaaten auf. Diese beruhten auf der höheren Flexibilität der Zwischenfruchtmischungen gegenüber biotischen und abiotischen Stressoren, gefolgt von einer konstanteren und höheren Biomasse, die in diesen Versuchen zu einer effektiveren Unkrautunterdrückung führten. Darüber hinaus konnten diverse allelopathische Substanzen in den Zwischenfrüchten nachgewiesen werden, was auf eine Unkrautunterdrückung durch sowohl kompetitive als auch biochemische Effekte hinwies. Eine Veränderung des Aussaattermins und der Düngung der Zwischenfrüchte zur Optimierung der Unkrautkontrolle zeigte signifikante Effekte auf die Biomasse von Unkräutern und Zwischenfrüchten. Eine frühe Aussaat der Zwischenfrucht fünf und drei Wochen vor der Winterweizenernte erhöhte die Unkrautkontrolle signifikant in einem Jahr. Vermutlich hängen die Biomasseproduktion der Zwischenfrüchte und die darauf basierende

Unkrautunterdrückung von ausreichend pflanzenverfügbarem Bodenwasser für eine zügige Keimung und schnelles Wachstum ab.

Zwischenfruchtmulch auf der Bodenoberfläche im Frühjahr unterdrückte bis zu 83% der Unkräuter. Insbesondere der Mulch aus Zwischenfruchtmischungen konnte die Unkrautdichte durchschnittlich effektiver (56%) als Mulch aus Zwischenfruchtreinsaaten unterdrücken (31%). Weiterhin konnten durch den Einsatz von Zwischenfrüchten, Zwischenfruchtmulch und Untersaaten signifikante Herbizideinsparungen in der Hauptkultur erzielt werden. Durch biologische Verfahren zur Unkrautbekämpfung wird meist nur eine unvollständige Unkrautunterdrückung erreicht. Daher sind chemische oder mechanische Verfahren weiterhin notwendig, insbesondere bei konkurrenzschwachen Kulturen wie der Zuckerrübe.

In Laborversuchen wurden Keimtests mit wässrigen Zwischenfruchtextrakten an einzelnen Unkrautspezies durchgeführt. Anhand der Hemmung von Keimung und Wurzellänge wurden Unterschiede zwischen verschiedenen Zwischenfruchtextrakten identifiziert. Die Extrakte der Zwischenfrüchte *S. alba*, *F. esculentum*, *H. annuus*, *T. subterraneum* und *L. usitatissimum* zeigten die effektivste wachstumshemmende Wirkung. Das Unkraut *M. chamomilla* wies eine erhöhte Empfindlichkeit gegenüber den biochemischen Effekten dieser Zwischenfrüchte im Vergleich zu den anderen getesteten Unkräutern auf. Die wachstumshemmenden Effekte durch die Zwischenfruchtextrakte wurden mit der Unkrautunterdrückung aus Feldversuchen korreliert, wobei sich ein starker positiver Zusammenhang zeigte. Dies deutete auf einen großen Anteil an biochemischen Effekten an der gesamten Unkrautunterdrückung im Feld hin. Um die Anteile an kompetitiven und biochemischen Effekten von Zwischenfrüchten auf Unkräuter zu evaluieren, wurden Gewächshausversuche mit Aktivkohle versetztem Substrat durchgeführt. Diese Versuche zeigten, dass sich die unkrautunterdrückende Wirkung aufgrund von Konkurrenz durch die Zwischenfrucht in der Anwesenheit von Aktivkohle veränderte. Zudem konnten spezifische Effekte einzelner Zwischenfrüchte auf einzelne Unkrautspezies beobachtet werden.

Die Ergebnisse dieser Arbeit zeigen die diversen Vorteile von Untersaaten und Zwischenfrüchten sowie deren Mulch in landwirtschaftlichen Systemen. Diese Arbeit zielt auf eine Optimierung von biologischen Unkrautbekämpfungsmaßnahmen ab und zeigt neue Ansätze für zukünftige Forschung im Bereich der Zwischenfrucht-Unkraut Interaktion. Zudem tragen diese Ergebnisse dazu bei, einen weiteren Schritt zur langfristigen Reduzierung von Herbizideinträgen in der Landwirtschaft zu machen.

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Weil der Gesetzgeber der Eidesstattlichen Versicherung eine besondere Bedeutung beimisst und sie erhebliche Folgen haben kann, hat der Gesetzgeber die Abgabe einer falschen eidesstattlichen Versicherung unter Strafe gestellt. Bei vorsätzlicher (also wissentlicher) Abgabe einer falschen Erklärung droht eine Freiheitsstrafe bis zu drei Jahren oder eine Geldstrafe.
Eine fahrlässige Abgabe (also Abgabe, obwohl Sie hätten erkennen müssen, dass die Erklärung nicht den Tatsachen entspricht) kann eine Freiheitsstrafe bis zu einem Jahr oder eine Geldstrafe nach sich ziehen.
Die entsprechenden Strafvorschriften sind in § 156 StGB (falsche Versicherung an Eides Statt) und in § 161 StGB (Fahrlässiger Falscheid, fahrlässige falsche Versicherung an Eides Statt) wiedergegeben.
§ 156 StGB: Falsche Versicherung an Eides Statt
Wer vor einer zur Abnahme einer Versicherung an Eides Statt zuständigen Behörde eine solche Versicherung falsch abgibt oder unter Berufung auf eine solche Versicherung falsch aussagt, wird mit Freiheitsstrafe bis zu drei Jahren oder mit Geldstrafe bestraft.
§ 161 StGB: Fahrlässiger Falscheid, fahrlässige falsche Versicherung an Eides Statt:
Abs. 1: Wenn eine der in den §§ 154 und 156 bezeichneten Handlungen aus Fahrlässigkeit begangen worden ist, so tritt Freiheitsstrafe bis zu einem Jahr oder Geldstrafe ein.
Abs. 2: Straflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des § 158 Absätze 2 und 3 gelten entsprechend.
Ich habe die Belehrung zur Eidesstattlichen Versicherung zur Kenntnis genommen.

Stuttgart, 06.03.2018

Ort und Datum	Unterschrift