University of Hohenheim

Institute of Phytomedicine, Department of Weed Science

Prof. Dr. Roland Gerhards

Evaluating different Management Strategies to Increase the Effectiveness of Winter Cover Crops as an Integrated Weed Management Measure

Dissertation to obtain the doctoral degree

of Agricultural Sciences (Dr. sc. agr.)

Faculty of Agricultural Sciences

submitted by

Alexandra Schappert

from Meisenheim

Stuttgart-Hohenheim

2020

Date of Oral Examination: 13.02.2020

Dean of the Faculty of Agricultural Sciences: Prof. Dr. Ralf T. Vögele

Examination Committee

Head of Committee: Prof. Dr. Andrea Knierim
Supervisor and Reviewer: Prof. Dr. Roland Gerhards
Co-Reviewer: Prof. Dr. Jan Petersen
Additional Examiner: Prof. Dr. Folkard Asch

This thesis was accepted as a doctoral dissertation in fulfillment of the requirements for the degree ‘Doktor der Agrarwissenschafte’ (Dr. sc. agr. / Ph.D. in Agricultural Sciences) by the Faculty of Agricultural Sciences at the University of Hohenheim on 14.12.2019.

Contents

List of figures

List of tables

List of abbreviations

ACE	*Alopecurus myosuroides* Huds. control efficacy
ai	Active ingredient
CC	Cover crop
CCs	Cover crops
°C	Degree Celsius
cm	Centimeter
DAH	Days after harvest
DAS	Days after sowing
DM	Dry matter
ET	Evapotranspiration
g	Gram
h	Hours
ha	Hectare
kg	Kilogram
L	Liter
N	Nitrogen
m	Meter
m^2	Squaremeter
mg	Milligram
t	Ton
VCE	Volunteer wheat control efficacy
WAS	Weeks after sowing
WCE	Weed control efficacy

Chapter 1

General introduction

1 General introduction

1.1 Integrated cropping systems profit from cover cropping

In the 1960s and 1970s the concept of integrated pest management in agricultural production systems was introduced (Liebman et al., 2001). Preventive weed control tools should thereby substitute or reduce the use of herbicides. This targets the raising concerns about herbicides causing environmental and health risks and the development of herbicide resistances. Also, cover crops are respected within this concept, as they may achieve a weed control of more than 90% during cultivation and afterwards (Boydston and Hang, 1995; Brust, Claupein et al., 2014; Dorn et al., 2015). Although cover crops as a biological weed control measure have been a standard practice in integrated cropping systems, they are currently receiving increased attention in Germany, caused by several reasons as mentioned in the following.

Wheat yield increase by agricultural intensification reached a certain plateauing in Northwestern-Europe (Cassman et al., 2010; van Wart et al., 2013). However, neither resources for chemical pest management nor technical know-how and energy for tillage are limited. In order to exploit the full crop potential, high inputs are necessary which reduce the economic gain (van Wart et al., 2013). The final gain, on the contrary, may increase by keeping the yield level and simultaneously reducing labor and costs. Remembering and implementing nature-based services, as provided for example by cover crops, improve soil characteristics and weed control naturally (inspired by Probst and Probst, 1982).
The herbicide input should be reduced in particular, as their consequent implementation and the repeated usage of herbicides with the same modes of actions (Evans et al., 2016) cause an increasing number of herbicide-resistant weed species (Heap, 2017). Consequently, as a decreasing number of efficient herbicides is available, additional or substitutional weed control measures as mechanical, cultural and biological methods are requested, in order to stabilize crop yields. Cover crops are thereby suitable as a preventive, as well as a curative herbicide resistance management tool (Zhou et al., 2016).

The one-sided herbicide management and the spread of problematic weeds, such as *Alopecurus myosuroides* Huds., are ascribed for narrow crop rotations which developed in Western-Europe. *A. myosuroides* infests and spreads rapidly in cropping systems with the intensive growing of winter cereals (Lutman et al., 2013). Thereby, *A. myosuroides* which has already developed multiple resistances, became one of the most challenging grass weeds in Europe (Heap, 2017;

Moss et al., 2007). Using spring crops in the crop rotation would counteract this problem (Chauvel et al., 2001; Lutman et al., 2013) in order to break the reproduction dynamics and life cycle of weeds in general (Cousens and Mortimer, 1995) and *A. myosuroides* in particular (Moss and Hull, 2012).

Implementing annual spring-sown crops, unfortunately, creates a crop-free period, lasting from fall to spring which favors the emergence of weeds, and soil erosion. As extreme weather events with heavy rainfall will occur more often in the future (IPCC, 2014), the soil implicitly needs to be protected. Intense rainfall, especially during a fallow period, also causes nutrient leaching. Nutrients leached from agricultural production systems are attributed causing environmental risks such as eutrophication (Isermann, 1990). Using cover crops, after early maturing cash crops as cereals or oilseed rape, contributes to counteracting soil and nutrient loss (Langdale et al., 1991; Thorup-Kristensen, 1994) and additionally suppresses weeds during this crop-free period (see Chapter 1.2).

The ‘greening’ strategy, which is implemented by the European Union (EU), refers to these benefits and thereby encourages, among other measures, cover cropping for soil and water improvements (Regulation (EU) No 1307/2013 of the European Parliament of the Council of 17 December 2013). Also, biodiversity is respected within this concept, as agricultural intensification is being highlighted as having considerable impact on the species loss (Potts et al., 2010). Cover crops may also contribute to this target by providing food and habitat for beneficials (Dunbar et al., 2017; Ellis and Barbercheck, 2015). Agricultural production systems additionally benefit from naturally provided weed control by the promotion of seed predation within cover crops (Gallandt et al., 2005).

1.2 Weed control by cover crops

During cultivation, cover crops are affecting weeds by the principles of ‘removal’ and ‘addition’ (Gliessman, 1986; Liebman et al., 1997). Cover crops are competing (‘removal’) with weeds for resources like light, space, nutrients, and water. Biochemicals are induced (‘addition’) into the environment by some cover crops causing allelopathic effects. Especially species belonging to the Brassicaceae and Poaceae families are attributed with allelopathic potential (Belz, 2007; Haramoto and Gallandt, 2005; Sánchez-Moreiras et al., 2003; Schulz et al., 2013). Though the impact of biochemical effects to an overall weed suppression is difficult to assess at the field scale (Belz, 2007; Rueda-Ayala et al., 2015), the contribution of allelopathy to weed control should not be neglected (Gfeller et al., 2018; Sturm et al., 2018).

Cover crops also suppress weeds after winter kill or termination. Weed seed germination is reduced by cover crop residues remaining at the soil surface. This physical barrier inhibits light quantity and quality and affects soil moisture and temperature (Teasdale, 1996). Additionally, if allelochemicals are contained in cover crop residues, biochemical compounds are emitted from decomposing plant material (Sturm et al., 2016; Tabaglio et al., 2013). General changes in the environment, such as by competition or the release of chemical compounds, during cover crop cultivation and afterwards reduce weed seed germination and growth rate, causing a decrease in weed density (Cousens and Mortimer, 1995).

To ensure that the weed suppression mechanisms induce efficient weed control during their cultivation and afterwards, it is necessary that cover crops germinate and establish quickly (Brennan and Smith, 2005; Dorn et al., 2015). The biomass production of cover crops is a relevant factor (Finney et al., 2016), however, soil coverage (Brennan and Smith, 2005) and allelopathy (Gfeller et al., 2018; Kunz et al., 2016) also contribute to efficient weed control, especially during the fall-to-winter season. Weed control in spring and during the early season of the main crop is highly dependent on the amount of cover crop residues (Teasdale and Mohler, 1993) and the concentration of allelochemicals (Mohler et al., 2001; Petersen et al., 2001) contained in the plant material.

To ensure that cover crops establish well and build up high biomass yields, they need to be able to survive and thrive under severe circumstances. Therefore, the selection of cover crops needs particular consideration. Assuming that sowing management, i.e. depth and timing, is well implemented, the lack of precipitation is the main factor determining cover crop germination and establishment. Usually, the suitability of cover crop plant species to specific regions is derived from their origin. For example, *Guizotia abyssinica* (L.f.) Cass. and *Sorghum bicolor* L. Moench originate from warm, dry regions, and they are therefore promoted by seed producers (Deutsche Saatveredelung AG, 2018) as being suitable for cover cropping in warm, dry regions of Germany. Water requirements of cover crops commonly used in Germany, such as *Sinapis alba* L., *Phacelia tanacetifolia* Benth. and *Avena strigosa* Schreb., have not been sufficiently evaluated.

The demands for water, temperature, and nutrients are species-specific. Species mixtures increase biomass stability and productivity (Tilman et al., 2001; Tilman et al., 2006) because species combinations improve the resilience against abiotic stresses and unfavorable growing conditions if composed reasonably (Dukes, 2001). Productivity also increases in mixtures by improved resource allocation compared to monocultures, because plant architecture and resource acquisition among species differ (Wacker et al., 2009). It has been determined that the leaf area index, for example, increases within mixtures compared to monocultures, causing less light transmittance through the canopy (Wacker et al., 2009). Ideally, species within cover crop mixtures show ‘niche differentiation’ in resource allocation and complementary (Wacker et al., 2009; Zuppinger-Dingley et al., 2014) instead of similar strategies, to increase the competition for resources with weeds rather than competition among mixing partners. In conclusion, the diversity among cover crop mixtures should contribute to efficient weed control compared to pure cover crop stands by increased resource competition between cover crop and weed and the opportunity to combine species with physical and chemical weed suppression mechanisms.

However, it has been evaluated by several studies that weed suppression by cover crop mixtures was not more effective than by well-performing pure cover crop stands (Baraibar et al., 2018; Brust, Weber et al., 2014; Finney et al., 2016). But as mentioned above, the contribution of crop mixtures being ascribed is to be more stable. This leads to the assumption that cover crop mixtures haven’t shown their full potential as species composition and mixing ratios are not sufficiently understood and require more research.

1.3 Objectives

The following objectives have been considered within this thesis:

- to assess if cover crops are as effective to control weeds and volunteer crops during the fall-to-winter season as chemical and mechanical weed control measures;
- to test if cover crops are an adequate weed control measure within *A. myosuroides* infested fields;
- to explore the effects of cover crops on weed control and yield during the cash crop season and to identify if the tillage system and the mulching date can, thereby, expand the weed suppressive effects of cover crop residues;
- to evaluate how species selection and species diversity are stabilizing productivity and therefore the weed suppression efficacy of cover crop mixtures compared to pure cover crop stands;
- to identify if the water requirements during cover crop establishment and water limitations are determining the weed control success of selected cover crops.

1.4 Structure and general information of the dissertation

The dissertation starts with an introduction (Chapter 1) about the benefits of cover crops within integrated cropping systems. Thereby, the general capability of cover crops on weed suppression and cover crop contribution to current challenges within the weed management were evaluated. How cover crops interfere with weeds is described within Chapter 1.2, followed by the objectives of this study (Chapter 1.3). The scientific publications which are relevant within this work are shown as followed within Chapters 2-5:

- Weed suppressive ability of cover crop mixtures compared to repeated stubble tillage and glyphosate treatments (peer-reviewed)
- A critical study of cover crop weed suppression during and after cover crop growth (submitted)
- Weed control ability of single sown cover crops compared to species mixtures (peer-reviewed)
- Weed suppressive ability of cover crops under water-limited conditions (peer-reviewed)

This order was chosen to show the weed suppression ability of cover crops following the crop rotation from cover crop sowing in fall until spring crop harvest. Later, the focus is on the cover crop species selection in order to improve the weed suppressive effect during cover cropping.

The first publication (Chapter 2) deals with the weed suppression ability of a cover crop mixture sown within differing tillage systems compared to a selected number of mechanical and chemical weed control measures during the fall-to-winter season. In the following Chapter 3, the focus in on how different cover crop species and a mixture perform in terms of weed control from fall-to-winter. Additionally, it is discussed if the weed suppressive effects of cover crop residues can be prolonged within non-inversion tillage systems in addition to an adjusted mulching date of cover crops. The impact of tillage and cover cropping on the spring crop yield was also measured. As the weed suppression ability of cover crops is highly dependent on the cover crop performance during the fall-to-winter season, further investigation was done to evaluate how species mixtures may stabilize the weed control by cover crops under unfavorable conditions in comparison to pure cover crop stands (Chapter 4). Cover crops need a certain resilience to water deficit to establishment quickly and subsequently compete with weeds. Therefore, the tolerance to water limitation of a selected number of commonly used cover crops was investigated within Chapter 5.

In addition to the peer-reviewed and the submitted journal articles, the following topics have been contributed to international conferences as oral and poster presentations. These conference contributions are not included in this thesis.

- Schappert A., Gerhards R. (2018) Weed reduction potential of cover crop mixtures. In: *18th European Weed Research Society Symposium*. New approaches for smarter weed management. 17-21 June 2018. European Weed Research Society. Ljubljana, Slovenia.
- Messelhäuser M. H., Schappert A., Saile M., Peteinatos G. G., Gerhards R. (2019) Black-grass control efficacy and yield response in spring barley after cover cropping, repeated stubble tillage and glyphosate treatments. In: *20th Conference of the Hellenic Weed Science Society*. Weed Research: Problems, trends and current challenges. 4-6 April 2019. Hellenic Weed Science Society. Agrinio, Greece.

Conclusions were drawn about the scientific articles in the discussion part in Chapter 6. Chapter 7 is summarizing the thesis.

For notification: Fall sown cover crops, which are winter killed and substitute a weedy fallow before a spring crop will be solely tackled within this study. For the sake of simplification, these winter cover crops are just named as cover crops in the previous and in the following.

Chapter 2

Weed suppressive ability of cover crop mixtures compared to repeated stubble tillage and glyphosate treatments

Alexandra Schappert[1], Miriam H. Messelhäuser[1], Marcus Saile[1], Gerassimos G. Peteinatos[1]
and Roland Gerhards[1]

[1] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany

Published in: *Agriculture* (2018), 8 (9), 144

The original publication is available at:
www.mdpi.com/journal/agriculture, doi:10.3390/agriculture8090144

2 Weed suppressive ability of cover crop mixtures compared to repeated stubble tillage and glyphosate treatments

Alexandra Schappert[1], Miriam H. Messelhäuser[1], Marcus Saile[1], Gerassimos G. Peteinatos[1], and Roland Gerhards[1]

[1] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany

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

2.1 Introduction

A crop rotation, including spring crops, requires an effective weed management strategy during the crop-free period. This might include biological, mechanical, and chemical (also repeated and in combination) weed control tools on the fallow ground not in production in autumn. These tools have the aim to encourage the germination of volunteer crops, remove emerged weeds, reduce available sources, especially for perennial weeds, and to avoid a new weed seed production. The success of a weed management technique during the crop-free period may have a major impact on the weed seed bank, and weed infestation on the subsequent crops. Weeds compete for resources with the main crops and may also act as a host for pests and diseases (Norris and Kogan, 2000). The ergot fungus (*Claviceps purpurea* (Fr.) Tul.) for example uses *Alopecurus myosuroides* Huds. (*A. myosuroides*) as an alternate host (Mantle and Shaw, 1976). An effective weed control strategy therefore improves plant health and provides yield stability. The application of synthetic herbicides is a common weed control practice in conventional farming systems. The use of non-selective herbicides (e.g., glyphosate) is a non-time-intense and efficient weed management practice particularly in conservation agriculture systems. *A. myosuroides*, an annual grassy-weed (Poaceae), became a major problem in autumn sown crops in Western Europe (Moss, 2017). The increasing impact of *A. myosuroides* in agricultural cropping systems can be attributed to the modifications on the current agricultural strategies, like increasing numbers of autumn sown crops, the alteration of cropping and tillage systems and the consequent usage of herbicides with the same mode of action (Moss, 2017). Several weed species have developed resistance to herbicides including glyphosate (Powles and Yu, 2010). Since *A. myosuroides* has already evolved field resistance to multiple herbicide modes of action (Heap, 2017), increasing the reliance on glyphosate can lead to a resistance to it (Davies and Neve, 2017). The current public concern raised, regarding the use of glyphosate in agriculture and the restrictions enforced in different countries, increases the necessity to search for alternative measures and different weed management tools. Biological and mechanical control methods might be an option to compete with resistant populations as well as to mitigate the development of herbicide resistant weeds.

Mechanical weed control practices, including tillage, might differ regarding the implementation, timing, and frequency (Pekrun and Claupein, 2006). This might include flat tillage (<5 cm) and as well a deep stubble tillage (>5 cm) (Melander et al., 2017). Ploughing buries the weed seeds and mostly prevents them to emerge from deeper soil layers. Systems with a lower or superficial soil disturbance, compared to ploughing, usually result in a greater weed infestation (Wrucke and Arnold, 1985) and weed seed accumulation near the soil surface (Colbach et al., 2006). However, reduced tillage systems have the advantage of decreasing run-off, increasing aggregate stability (Hernanz et al., 2002) and preserving a higher soil moisture (Vita et al., 2007). Repeated flat or medium deep tillage may combine the benefits of reduced tillage systems for soil conservation with a sufficient weed control, yet with a possible negative impact concerning nutrient losses, soil compaction, or carbon gas emissions.

Winter cover crops (CCs), used as a biological weed control measure (Snapp et al., 2005), may demonstrate several advantages, including nutrient recycling efficiency (Snapp et al., 2005) and reduced soil erosion (Langdale et al., 1991). The success of CCs as an integrated weed management practice, is related to a fast emergence and high soil cover, which depends on the chosen species, soil properties, and the weather conditions at the field location. Using different cover crop (CC) species within a mixture increases the resilience for management failures, bad weather conditions, and combines species-specific benefits (Wortman et al., 2012). Seed predation, which may also act as a biological weed control measure (Hartwig and Ammon, 2002), is enhanced in cover-cropping (Blubaugh et al., 2016) and no-till systems (Petit et al., 2017) and decreases the amount of weed seeds at the soil surface.

The straw management, also in combination with the different weed management practices as mentioned above, has an impact on weed infestation. Generally, straw disposal can for example reduce the number of *A. myosuroides* plants, due to weed seed removal from the field (Moss, 1979). In no-till systems the straw surface coverage, which generates a physical barrier, is reducing the weed density (Bilalis et al., 2003). Otherwise, the herbicide efficacy could be reduced by crop residues (Dao, 1991). On the other hand, the presence of straw in CC systems might lead to an immobilization of nitrogen, which will then narrow the CC development and their subsequent success for weed suppression (Kahnt, 1983).

There is little information available about the potential of repeated flat and deep stubble tillage in comparison to ploughing and cover-cropping to substitute herbicide applications in autumn. In a non-inversion tillage system grass weeds, like *A. myosuroides*, might be encouraged (Froud-Williams et al., 1984). Furthermore, CCs are a suitable tool for broad-leave weed control (Teasdale, 1996). Within cover-cropping systems grass weeds may also become a severe challenge (Clements et al., 2000) which might require the use of herbicides (Teasdale, 1996). The presence and absence of straw will additionally deliver information about the impact of straw management in combination with different weed management treatments on weed infestation.

This study aims at estimating the ability of selected biological, mechanical, and chemical weed control practices on weed suppression before spring cropping. The following hypotheses were investigated: (i) stubble tillage and CCs have similar success in reducing weeds as glyphosate applications; (ii) repeated stubble tillage is a more effective weed suppression measure in comparison to a single deep, turning soil tillage; (iii) the sowing method of CCs (mulch-tillage and no-tillage) has an impact on the success of weed suppression; (iv) the removal of straw after harvest is influencing the weed infestation.

The study was implemented at field sites with an increased population of *A. myosuroides*. The results may clarify if tillage, herbicide application, or cover-cropping can reduce the number of *A. myosuroides* plants. CCs were sown within a mulch-till and no-till systems to evaluate if no-till systems lead to an increasing number of weeds in comparison to stubble tillage systems as shown by Gruber et al. (2012).

2.2 Materials and methods

Experimental Sites

Two field experiments (Binsen: 48°25´22.0´´ N 8°53´15.4´´ E and Risp: 48°25´06.3´´ N 8°53´48.0´´ E) were conducted in Southwestern Germany from August until December 2017. The weather data are shown in Table 1.

Table 1. Monthly minimum (Min.), maximum (Max.), average temperature (T) and precipitation in Southwestern Germany from July until December 2017.

	Min. T (°C)	**Max. T (°C)**	**Average T (°C)**	**Precipitation (mm)**
July	12.6	24.9	18.5	119.5
August	12.2	24.6	18.3	88.2
September	7.0	17.9	12.0	35.3
October	4.7	15.8	9.7	40.1
November	0.7	6.8	3.6	76.0
December	-1.3	3.6	1.2	55.9

The soil type at both trials was characterized as a loamy silt with pH values of 6.9 (field Binsen) and 5.9 (field Risp). The fields had a different crop rotation history with the same previous crop at the beginning of the experiment. Crop rotation at the field Binsen was winter wheat (2013), triticale (2014), spring barley (2015), peas (2016), and winter wheat (2017). The trial at the field Risp had a crop rotation of peas (2013), winter wheat (2014), red clover (2015), flowering mixture (2016), followed by winter wheat (2017). The winter wheat was harvested at the 1st of August at both trials. The experimental trials were set up as a randomized strip-plot design. The two factorial experiments included seven weed management practices with regard to mechanical, chemical, and biological treatments (1st factor). The untreated control plots were left without any weed control treatment. The details according to the weed management treatments are shown in Table 2. The 2nd factor (which was implemented as the strip) combined the same weed management treatments as mentioned before including the presence and absence of straw. The straw from the plots with the straw removal was baled and taken from the plots at the same day as the harvest. In total, 16 treatments with 3 repetitions were included at both field trials.

The plots had a size of 16.5 x 5 m (field Binsen) and 21.5 x 5 m (field Risp). The CC mixture sown at both trials for treatments 7 and 8 was provided by DSV-Saaten (Deutsche Saatveredelung AG, 2018) and included the following CC species (their ratios within the mixture are shown in brackets): *Avena strigosa* Schreb. (45%), *Fagopyrum esculentum* Moench (18%), *Linum usitatissimum* L. (12%), *Phacelia tanacetifolia* Benth. (6%), *Raphanus sativus* var. *oleiformis* (6%), *Sinapis alba* L. (6%), *Brassica carinata* A.Braun (4%), *Helianthus annuus* L. (2%), *Camelina sativa* Crantz (1%). The plots with the CC treatments sown with mulch-till (treatment 7) were prepared with a cultivator and a rotary harrow. A Cambridge roller was used after sowing to increase the soil contact of the seeds and to improve the CC seed germination.

Table 2. Weed management treatments, weed control type and treatment dates for the experimental field sites at Binsen and Risp. Weed management dates include dates for tillage, herbicide applications, and sowing dates for the cover crop mixtures. (DAH = Days after harvest).

Treatment[1]		**Weed Management Practices (depth in cm/dose in L ha^{-1}/ seed density kg ha^{-1})**	**Weed Control Type**	**Weed Management (Date)**	**Weed Management (DAH)**
1	Control	Weed fallow without weed management	-	-	-
2	FST	Flat soil tillage with rotary harrow (5 cm)	mechanical	8 August 6 September 14 October	8 37 75
3	DST	Deep soil tillage with wing share cultivator (15-16 cm)	mechanical	8 August 6 September 15 October	8 37 76
4	PL	Turning soil tillage with a plough (25 cm)	mechanical	14 August	14
5	GLY	Single glyphosate treatment (4 L ha^{-1})	chemical	6 September	37
6	GLY+GLY	Dual glyphosate treatment (4 L ha^{-1})	chemical	6 September 4 October	37 75
7	CC+MT	Cover crop mixture + mulch-till (1-1.5 cm, 25 kg ha^{-1})	biological	19 August	19
8	CC+NT	Cover crop mixture + no-till (1-1.5 cm, 25 kg ha^{-1})	biological	7 August	7

[1] Fat soil tillage (FST), deep soil tillage (DST), ploughing (PL), single glyphosate application (GLY), dual glyphosate application (GLY+GLY), cover crop mixture + mulch-till (CC+MT) and cover crop mixture + no-till (CC+NT).

Data Collection

Individual weed species as well as the total amount of plants were identified and counted at three dates: 12th of October (73 DAH), 17th of November (109 DAH) and 13th of December (135 DAH). This was performed with a circular 0.33 m^2 frame at four randomly chosen spots per plot. CC biomass was cut at both mulch-till sown and no-till treatments once at the 14th of October. The CC biomass was measured to determine which sowing technique results in a greater CC development. The biomass of 0.33 m^2 was cut and fresh weed and CC biomass measured at four randomly chosen locations per plot.

Data Analysis

RStudio software (Version 1.1.453, RStudio Team, Boston, MA, USA) was used for analyzing the data. Prior to analysis, the data was visually checked for normal distribution and homogeneity of variance. A transformation of the data was not necessary before doing an analysis of variance (ANOVA). The Tukey-HSD test ($p \leq 0.05$) was performed to compare the means of the different treatments. The weed control efficacy (WCE), *A. myosuroides* control efficacy (ACE), and volunteer wheat control efficacy (VCE) was calculated according to Rasmussen (1991) and Machleb et al. (2018):

$$\text{WCE, ACE, VCE (\%)} = 100 - \text{wt}\ (0.01 \times \text{wc})^{-1} \qquad (1)$$

whereby wt is the weed, *A. myosuroides* or volunteer wheat density (weeds m^{-2}) of the weed management treatments, and wc is the weed, *A. myosuroides* or volunteer wheat density (weeds m^{-2}) of the untreated control plots.

2.3 Results

Total Weed Suppression

Even though a diverse crop rotation was conducted at both experimental field sites, including winter and spring crops, *A. myosuroides* was the most dominant monocotyledons weed species, besides volunteer wheat. Other than that, dicotyledons like *Lamium purpureum* L., *Veronica persica* Poir., *Stellaria media* Vill., *Thalaspi arvense* L., and *Raphanus raphanistrum* L. were the dominant weed species (Table 6). The untreated control plots at the field Binsen showed a mean weed infestation of 96.9 weeds m^{-2} (averaged over all counting dates). The WCE of all soil tillage treatments (flat soil tillage (FST), deep soil tillage (DST) and ploughing (PL)) at 73 DAH was between 1-76%, which was significantly lower (Figure 1) than for both glyphosate and the CC treatments. The FST and DST treatments showed an improved WCE with up to 82% at 109 and 135 DAH. Nevertheless, repeated tillage (FSL, DST) treatments resulted in lower WCE than the CC and the GLY+GLY (dual glyphosate application) treatments throughout the season. The CC+NT (cover crop mixture + no-till) treatment showed a WCE of 88% (135 DAH). The GLY+GLY treatment showed the highest WCE with more than 97% (109 DAH).

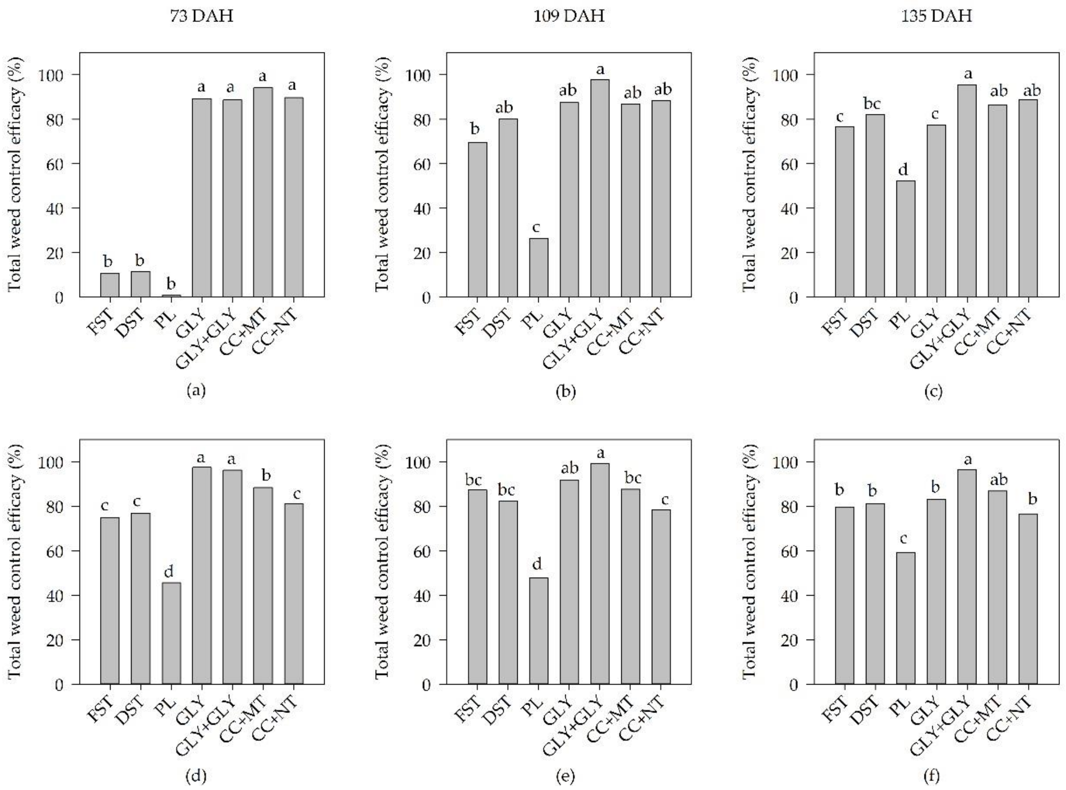


Figure 1. Average total weed control efficacy of the treatments flat soil tillage (FST), deep soil tillage (DST), ploughing (PL), single glyphosate application (GLY), dual glyphosate application (GLY+GLY), cover crop mixture + mulch-till (CC+MT), and cover crop mixture + no-till (CC+NT) at the two trials at the fields (a-c) Binsen and (d-f) Risp. (a,d) 73, (b,e) 109, and (c,f) 135 days after harvest (DAH). Different small letters within one graph show significant differences according to Tukey-HSD test ($p \leq 0.05$). Means with identical letters do not differ significantly.

The untreated control plots at the trial at field Risp showed a generally higher mean weed infestation of 183.7 weeds m^{-2} (averaged over all counting dates). Similar to the trial at the field Binsen the GLY (single glyphosate application) and GLY+GLY performed significantly best, with a WCE of approximately 97% 73 DAH. Whereby the dual glyphosate application (GLY+GLY) increased the WCE 135 DAH up to 99%, the single treatment (GLY) reduced the WCE and showed no significant differences according to the WCE, compared to the CC and the repeated tillage (FST, DST) treatments 135 DAH. The CC+NT treatments seem to reduce weeds less efficient than the CC+MT (cover crop mixture + mulch-till) treatments. This trend was only significant at the field site at Risp 73 DAH. The PL treatments performed always significantly worse, at both trials (excluding the field Binsen 73 DAH), resulting in a WCE reaching a maximum of 59% 135 DAH at the field site at Risp. The factor straw was not significant, therefore Figure 1 is giving average values for total WCE, including treatments with straw and those with straw removal.

A. myosuroides Suppression

The untreated control at the field Binsen showed an average number of *A. myosuroides* with 7.1 plants m^{-2} (73, 109, and 135 DAH). Whereas all weed control practices were able to reduce the total amount of weeds, compared to the control, treatments like FST and DST increased the number of *A. myosuroides* to 20.6 and 18.7 plants m^{-2} (73, 109, and 135 DAH at field Binsen), respectively. The control treatments at the field Risp had a higher amount of *A. myosuroides* with 8.6 plants m^{-2}. At both trials the repeated stubble tillage (FST, DST) and the PL treatment achieved a significant increase of *A. myosuroides* 73 DAH (Table 3). The CC treatments showed the highest ACE from 91.7 up to 100%. Both glyphosate treatments (GLY and GLY+GLY) are not showing the same efficacy against *A. myosuroides* as for the total weed control. The presence of straw reduced the number of *A. myosuroides* plants significantly within the FST and the DST treatments at the field Binsen.

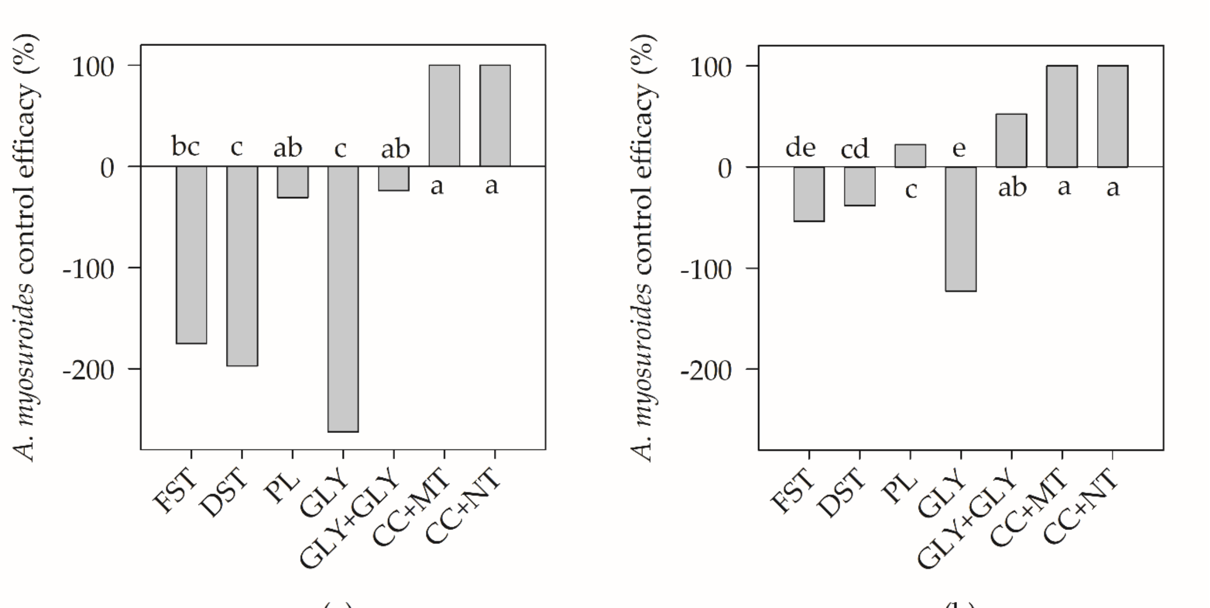
Table 3. Average *Alopecurus myosuroides* Huds. control efficacy of flat soil tillage (FST), deep soil tillage (DST), ploughing (PL), single glyphosate application (GLY), dual glyphosate application (GLY+GLY), cover crop mixture + mulch-till (CC+MT) and crop mixture + no-till (CC+NT) treatments in combination with the presence (+) or absence (-) of straw 73 days after harvest (DAH) at the two trials at the fields Binsen and Risp. Different small letters within one column show significant differences according to Tukey-HSD test ($p \leq 0.05$). Means with identical letters do not differ significantly. Different capital letters show significant differences within one experiment and within one treatment according to the presence or absence of straw. Means with no capital letter do not differ according to the Tukey-HSD test ($p \leq 0.05$).

Treatment	**73 DAH**			
	Binsen		**Risp**	
	- Straw	**+ Straw**	**- Straw**	**+ Straw**
FST	-603.5^{cB}	-244.5^{bA}	-279.0^{d}	-299.0^{cd}
DST	-860.6^{dB}	-337.7^{bA}	-114.0^{bcd}	-500.4^{d}
PL	-356.4^{b}	-230.4^{b}	-198.1^{cd}	-185.9^{bcd}
GLY	-33.0^{a}	45.2^{a}	28.1^{ab}	24.8^{ab}
GLY+GLY	-31.6^{a}	33.3^{a}	6.7^{abc}	-45.5^{abc}
CC+MT	100.0^{a}	100.0^{a}	100.0^{a}	97.4^{a}
CC+NT	100.0^{a}	95.8^{a}	91.7^{a}	94.1^{a}

The factor straw had a significant effect on the suppression of *A. myosuroides* at the field Risp 109 DAH within the DST and the GLY treatments (Table 4). The other treatments at field Risp and also at field Binsen were not affected by the presence or absence of straw. At both trials 109 DAH the GLY+GLY treatment showed an ACE up to 80.8%. Whereby, the GLY treatment was increasing the amount of *A. myosuroides* compared to the control, which resulted in a minimum ACE of -119.8% (field Risp). The CC treatments again performed best with an ACE between 94.4-100% (both trials). Both CC treatments show an ACE of 100% at both field trials 135 DAH (Figure 2). FST and DST treatments increased the amount of *A. myosuroides*, compared to the control. ACE for the FST treatment was -175.0% at the field Binsen and -54.7% at the field Risp (135 DAH). The GLY treatment was also inducing an increase of *A. myosuroides* plants compared to the control, which showed an ACE of -262.5% (field Binsen). The GLY+GLY treatment showed an ACE up to 52.2% (field Risp). The absence or presence of straw had no significant effect on the ACE at both trials 135 DAH.

Table 4. Average *Alopecurus myosuroides* Huds. control efficacy of flat soil tillage (FST), deep soil tillage (DST), ploughing (PL), single glyphosate application (GLY), dual glyphosate application (GLY+GLY), cover crop mixture + mulch-till (CC+MT) and crop mixture + no-till (CC+NT) treatments in combination with the presence (+) or absence (-) of straw 109 days after harvest (DAH) for the two trials at the fields Binsen and Risp. Different small letters within one column show significant differences according to Tukey-HSD test ($p \leq 0.05$). Means with identical letters do not differ significantly. Different capital letters show significant differences within one experiment and within one treatment according to the presence or absence of straw. Means with no capital letter do not differ according to Tukey-HSD test.

	109 DAH			
	Binsen		**Risp**	
	- Straw	**+ Straw**	**- Straw**	**+ Straw**
FST	-19.0 ^{a}	-6.7 ^{a}	47.4 ^{abc}	21.5 ^{bc}
DST	-1.4 ^{a}	-3.4 ^{a}	13.3 ^{bcA}	-40.7 ^{cB}
PL	-160.2 ^{b}	-182.5 ^{b}	-14.1 ^{c}	-44.1 ^{c}
GLY	-13.0 ^{a}	-4.2 ^{a}	-119.8 ^{dB}	-46.3 ^{cA}
GLY+GLY	75.5 ^{a}	60.0 ^{a}	80.8 ^{ab}	64.4 ^{ab}
CC+MT	100.0 ^{a}	96.7 ^{a}	100.0 ^{a}	100.0 ^{a}
CC+NT	94.4 ^{a}	100.0 ^{a}	96.7 ^{a}	96.7 ^{ab}

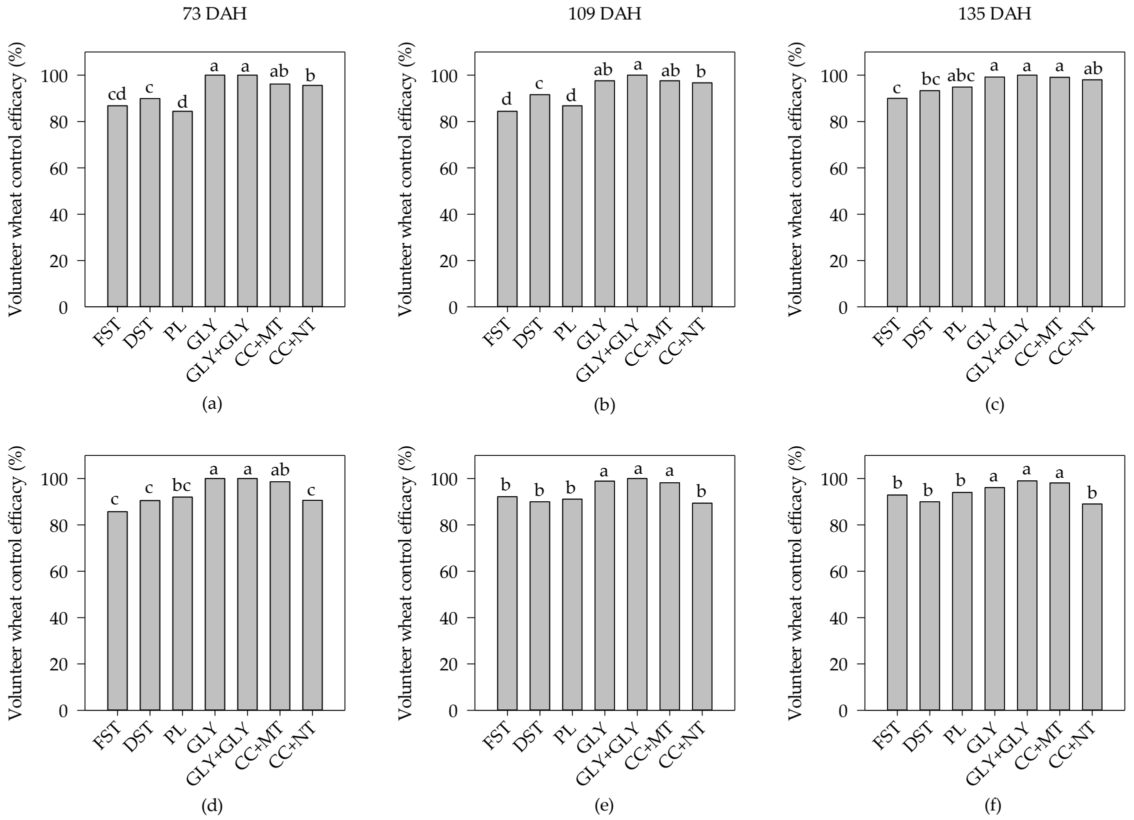


(a) (b)

Figure 2. Average *Alopecurus myosuroides* Huds. (*A. myosuroides*) control efficacy of flat soil tillage (FST), deep soil tillage (DST), ploughing (PL), single glyphosate application (GLY), dual glyphosate application (GLY + GLY), cover crop mixture + mulch-till (CC+MT) and crop mixture + no-till (CC+NT) treatments at the fields (a) Binsen and (b) Risp 135 days after harvest. Different small letters within one graph show significant differences according to the Tukey-HSD test ($p \leq 0.05$). Means with identical letters do not differ significantly.

Volunteer Wheat Suppression

Volunteer wheat was the main weed within both trials. The amount of volunteer wheat achieved 72.9 (field Binsen) and 138.6 plants m^{-2} (field Risp), averaged over the three counting dates. At both trials and all counting dates, the GLY+GLY treatments had a VCE of 100% (Figure 3). The GLY and CC+MT treatments achieved similar results with a VCE of 99.2% at field Binsen 135 DAH. The VCE at the field Risp for the GLY and CC+MT treatments were only slightly lower with 96.1 and 98.1%, respectively (135 DAH). The CC+NT treatments, especially at the trial at field Risp, showed significantly less VCE, compared to both glyphosate (GLY and GLY+GLY) and the CC+MT treatments. Generally, all treatments were able to reduce the amount of volunteer wheat and reached at least 84.4% VCE. The absence or presence of straw had no significant effect according to VCE at both trials (73, 109, and 135 DAH).



(a) (b) (c)

(d) (e) (f)

Figure 3. Average volunteer wheat control efficacy of flat soil tillage (FST), deep soil tillage (DST), ploughing (PL), single glyphosate application (GLY), dual glyphosate application (GLY + GLY), cover crop mixture + mulch-till (CC+MT) and crop mixture + no-till (CC+NT) treatments at the two trials at the fields (a-c) Binsen and (d-f) Risp. (a,d) 73, (b,e) 109 and (c,f) 135 days after harvest (DAH). Different small letters within one graph show significant differences according to the Tukey-HSD test ($p \leq 0.05$). Means with identical letters do not differ significantly.

CC Biomass

Even though the CC+NT treatment showed in some cases significantly less WCE and VCE, compared to the CC+MT treatment, the fresh CC biomass was not significantly different between those two treatments (Table 5). The factor straw had no statistical impact on the fresh CC biomass. The CC+MT treatment with the presence of straw at the field Binsen and Risp had a fresh CC biomass of 26.9 and 30.5 t ha^{-1}, respectively. The CC+NT treatments, also with straw, showed fresh biomass values of 25.9 (field Binsen) and 27.3 t ha^{-1} (field Risp). Neither the sowing technique (no-till or mulch-till) of CCs, nor the presence or absence of straw had an impact on the fresh weight of weeds.

Table 5. The fresh cover crop biomass (t ha^{-1}) 8 (CC+NT) and 9 (CC+MT) weeks after sowing for the trials at the fields Binsen and Risp. CC+MT = cover crop mixture + mulch-till. CC+NT = cover crop mixture + no-till. - straw = straw removal after harvest. + straw = no straw removal from the previous crop. n.s. = means do not differ significantly within one experiment based on the Tukey-HSD test ($p \leq 0.05$).

Treatments		**Fresh Cover Crop Biomass**	
		Binsen	**Risp**
CC+MT	- straw	32.0 $^{n.s.}$ (2.8)	28.2 $^{n.s.}$ (4.0)
	+ straw	26.9 $^{n.s.}$ (3.8)	30.5 $^{n.s.}$ (9.3)
CC+NT	- straw	33.1 $^{n.s.}$ (0.9)	29.0 $^{n.s.}$ (8.9)
	+ straw	25.9 $^{n.s.}$ (3.6)	27.3 $^{n.s.}$ (4.5)

2.4 Discussion

Stubble management can have a big impact on weed dynamics (Melander et al., 2013). The result of postharvest tillage on annual weeds mainly relates to the weed flora, the seed bank, and the dormancy status of the seeds (Melander et al., 2013). Flat postharvest tillage incorporates crop residues and stimulates volunteer wheat to germinate. Multiple soil tillage induces weed seeds for germination and destroys and buries them at the subsequent tillage. This might decrease the total weed seed amount in the soil.

No clear differences concerning weed suppression were found between flat (FST) and deep stubble (DST) cultivation, which had also been demonstrated by Boström (1999). In the past, the shallow plough, as stubble tillage practise, was seen as most effective tool for weed management in Germany and Austria, as reported by Gruber et al. (2012). Within our study ploughing (PL) showed worst results concerning WCE among all treatments. It is therefore not reasonable to recommend a deep soil tillage (including ploughing), which is labor intense and costly and does not provide benefits for weed control and soil conservation. In this study, ploughing was done early after harvest. However, a late treatment before weed seed maturity might improve the performance. The generally moderate performance of all mechanical treatments in comparison with the chemical and the biological treatments might be caused by the wet weather conditions during autumn. Cirujeda and Taberner (2006) who harrowed in cereals and state that a high WCE of harrowing is attributed to dry conditions after harrowing. From time to time inversion tillage or stubble management might be useful in order to control weeds in highly infested fields (Gruber et al., 2012). Ploughing, especially in combination with stubble tillage (Melander et al., 2012), is a useful tool against perennial and root spreading weeds. At both field trials, annual weeds were dominant, which allows a reduction of the tillage intensity Gruber and Claupein (2009) and a conservation stubble management with reduced soil disturbance. Pekrun and Claupein (2006) recommend to leave the stubble undisturbed. In terms of a biological weed control strategy, keeping the freshly produced weed seeds on the soil surface enhances biodiversity and increases seed predation as biological weed control (Westerman et al., 2003).

The experiments had shown that both CC treatments (CC+NT and CC+MT) achieved an effective weed control during the crop-free period from August until December. In contrast to Brust et al. (2011; 2014) CCs were also able to suppress volunteer wheat. Especially *A. myosuroides*, which tend to be the most challenging grass weed, was successfully controlled by CCs, whereas stubble tillage and glyphosate application mostly failed this effect. The CC treatments reached an ACE up to 100% and a WCE up to 94%. The weed suppression potential of CCs has been proven by several studies (Brust, Claupein et al., 2014; Kunz et al., 2016; Melander et al., 2013). Winter CC cultivation has the potential to shift the use of herbicides towards a postemergence herbicide program (Teasdale, 1996). Weed seed germination and establishment is reduced in cover-cropping systems, but the amount of weed seeds in the soil may increase in the upper layer, especially in no-tillage systems. The success of CCs concerning their WCE is site specific and relates to the CC chosen. Further, it depends on the present weed species and the management at the field site (Bàrberi, 2002). The weather conditions at both field sites, with sufficient amount and distribution of rainfall and the long growing period, were very suitable to achieve a dense canopy and competitive plant stand to suppress weeds. The biomass production of CCs, does not necessarily need to correlate with their weed suppression ability (Finney et al., 2016; Kunz et al., 2016). However, biomass-driven CCs are generally more competitive (Finney et al., 2016; Teasdale, 1996). Instead of single CCs species, a species mixture was used within this study. By combining different CC species with specific advantages in CC mixtures, the benefits concerning weed, soil, nutrient, and pest management may increase (Bàrberi and Mazzoncini, 2001; Malézieux et al., 2009).

The continuous loss of herbicides in the EU (Melander et al., 2013) and the increasing problems with herbicide resistant weeds will raise the awareness of producers to strengthen their focus on non-chemical weed management. The GLY+GLY treatment achieved the significantly highest WCE within this experiment. However, a single glyphosate application (GLY) was not sufficient, in particular, to control *A. myosuroides* weeds. *A. myosuroides* plants emerge in several flushes during autumn, when the climate conditions are favorable (Colbach et al., 2006). Applying glyphosate too early might miss most of the plants. Furthermore, this study demonstrated that at both trials, during autumn and at the end of the growing period, CCs (especially CC+MT) had similar effects on WCE, ACE, and VCE as the chemical treatments. The CC+NT treatment was only showing a slightly weaker WCE and VCE than the CC+MT treatment. Nevertheless, glyphosate is a useful tool within no-till and reduced tillage systems.

The wheat residue management (presence or absence of straw) had a minor effect on the success of either mechanical, chemical, or biological weed control practices. Even though burning the straw on the field is used in some regions and it might result in decreasing weed numbers, it can have some negative side effects especially concerning the carbon gas emissions. The baling of straw is not achieving a decrease of the weed infestation (Moss, 1979), which was also demonstrated within this study.

Within this study, the effects of postharvest weed control on the previous spring crop season were not evaluated, but might deliver interesting insights to see whether the CC treatments preserved weed seeds, instead of reducing the weed seed bank for the repeated stubble tillage treatments (FSL, DST).

2.5 Conclusions

The flat soil tillage with rotary harrow (FST) and the deep soil tillage with wing share cultivation (DSL) treatments did not show satisfying results concerning WCE and ACE, compared to the chemical and biological methods, but seemed to be a suitable tool for volunteer wheat control. The cover crop (CC) suppression performance for total weed and especially for *A. myosuroides* showed, that even conservation practices have the potential to minimize future weed control challenges. Their success mainly attributes to their fast and competitive development, which is determined by external factors. In a season with unfavorable growing conditions for CCs, stubble tillage and glyphosate applications might be more efficient weed control practices. Even though the weed suppression ability of CCs is often unpredictable, it is worthwhile to do cover-cropping in terms of soil conservation and biodiversity. The effect of non-chemical weed management in reduced and no-till systems still needs a better understanding for weed dynamics (Melander et al., 2013). Long-term experiments will help to show how continuous stubble tillage, herbicide application and cover-cropping will affect the weed density and the weed community and which combinations will enable a sufficient and sustainable weed control.

Author Contributions: A.S. did the statistical analysis and wrote the manuscript. M.S. was responsible for the field experiments and data collection. M.H.M. helped writing the abstract and revised the manuscript. G.G.P. helped analyzing the data and revising the manuscript. R.G. supervised the experiments and revised the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table 6. Mean number of weed species (averaged over all counting dates) per m^2 for the eight treatments (averaged for the treatments with the presence and the absence of straw) at the field sites Binsen and Risp. 1: untreated control; 2: flat soil tillage; 3: deep soil tillage; 4: ploughing; 5: single glyphosate application; 6: dual glyphosate application; 7: cover crop mixture + mulch-till; 8: cover crop mixture + no-till. *Alopecurus myosuroides* Huds. (*A. myosuroides), Veronica persica* Poir. *(V. Persica), Thalaspi arvense* L. (*T. arvense*), *Lamium purpureum* L. (*L. purpureum*), *Stellaria media* Vill. (*S. media*), *Raphanus raphanistrum* L. (*R. raphanistrum*). Others: *Cirsium arvense* (L.) Scop., *Sonchus arvensis* L., *Matricaria chamomilla* L., *Euphorbia helioscopia* L., *Borago officinalis* L.

	Binsen								**Risp**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
A. myosuroides	7	21	19	15	13	6	2	1	9	14	14	9	14	5	1	2
Volunteer wheat	73	8	6	6	4	4	1	2	139	16	18	11	10	9	3	14
V. persica	6	4	2	7	-	-	6	3	12	5	7	14	2	-	11	10
T. arvense	2	-	-	14	-	1	-	-	5	-	-	11	-	-	-	-
L. purpureum	3	4	2	5	-	-	4	4	5	4	6	13	1	1	7	12
S. media	2	-	1	8	1	1	-	-	4	-	-	12	-	-	1	1
R. raphanistrum	1	1	1	3	-	-	-	-	2	-	1	3	-	-	-	-
Others	3	1	-	2	-	-	-	-	7	-	-	5	-	-	-	-

Chapter 3

A critical study of cover crop weed suppression during and after cover crop growth

Alexandra Schappert[1], Miriam H. Messelhäuser[1], Dominic J. Sturm[1], Marcus Saile[1] and Roland Gerhards[1]

[1] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany

Submitted to: *Weed Technology* (2020)

3 A critical study of cover crop weed suppression during and after cover crop growth

Alexandra Schappert[1], Miriam H. Messelhäuser[1], Dominic J. Sturm[1], Marcus Saile[1] and Roland Gerhards[1]

[1] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany

Abstract

The performance of cover crops (CCs) on weed suppression during the cover cropping season is mainly determined by environmental conditions and the species selected. In contrast, the effects of CCs on weeds after their termination is related to the cover crop (CC) residue management. This study aims to estimate the potential of CCs, in pure stands and species mixtures, to suppress weeds during CC growth and in the following cash crop. Three field experiments were conducted in Southwest-Germany between 2015-2018, to test if CCs control weeds as effectively as chemical or mechanical weed control practices and to test if reduced or no-tillage and a temporally concerted mulching of CC residues prolongs the weed suppression until and during the early cash crop season. Additionally, the impact of CCs on crop yield was determined. Spring barley yield was not affected by different weed control practices, while corn yield was influenced by the tillage practice, regardless whether CCs were grown before or not. Oilseed radish reached a weed control efficacy of 60% and black oat was able to reduce weed coverage by 96% during the CC season compared to the no-CC control. A CC mixture, including ten CC species, sown within a no-till system reached a complete reduction of black-grass during spring barley cropping, whereas non-selective herbicide application and non-inversion tillage did not reduce black-grass completely. The results clarify that well-established CCs have the potential of being an efficient weed control measure during CC growth, and CC residues suppress weeds in the early season of the following cash crop. Reduced tillage and a temporally concerted mulching did not improve the weed suppressive effects of CC residues in spring when CCs performed poorly during growth.

Nomenclature: Black-grass, *Alopecurus myosuroides* Huds.; Buckwheat, *Fagopyrum esculentum* Moench; Black oat, *Avena strigosa* L.; Oilseed radish, *Raphanus sativus* var. *oleiformis*; Subterranean clover, *Trifolium subterraneum* L.; Corn, *Zea mays* L.; Spring barley, *Hordeum vulgare* L.

Keywords: Biodiversity, catch crop, conservation tillage, mulch, weed management.

3.1 Introduction

Winter cover crops (CCs) are worthwhile to be integrated into the crop rotation through their attributed benefits like nitrogen loss reduction and erosion and weed control induced by living CCs and their residues (Hooker et al., 2008; Kunz et al., 2017; Langdale et al., 1991; Teasdale, 1996; Teasdale and Mohler, 1993). Living CCs compete with weeds for water, nutrients, light, and space. Allelochemicals emitted by some CCs may also reduce germination and growth of weeds (Gfeller et al., 2018; Sturm et al., 2018). Non-incorporated residues remain as a mulch layer and create a physical barrier, whereby the light quality and quantity are reduced (Teasdale, 1996). The mulch layer may hinder weeds to emerge and to consequently penetrate into the soil surface. Additionally, a number of plant species used as CCs (e.g. Brassicaceae) inhibit weeds by emitting chemical compounds into the soil while residues decompose or when incorporated into the soil (Petersen et al., 2001; Sturm and Gerhards, 2016).

The success of cover cropping on weed suppression is considerable when sowing date, accompanies favorable growing conditions and suitable CC species (Brust, Claupein et al., 2014; Sturm et al., 2017). When weed suppressive effects by CC residues are expected to be insufficient and seed rain during the CC season was not reduced by poorly developed and low competitive CCs, further weed control measures, such as tillage, may be required. A field experiment was implemented to compare the effects of non-inversion and inversion tillage after cover cropping on the weed infestation during spring cropping.

The weed infestation in no-till systems is often greater than within inversion tillage systems (Cousens and Moss, 1990; Gruber et al., 2012) as weed seeds accumulate near the soil surface. In order to increase the weed suppressive effects by CCs within non-inversion tillage systems before and during the subsequent cash crop, the CC residue management needs particular consideration. The weed control efficacy by CC residues within no-till systems is mainly determined by the amount of residue soil cover, and their homogenous distribution within the field (Teasdale and Mohler, 2000). Heterogeneously deposited plant residues result in uncovered soil and might create favorable areas for weed emergence even though the mulch layer has a certain thickness (Teasdale and Mohler, 2000). CC mulching early in spring may be an option to distribute and deposit CC residues uniformly at the soil surface to improve weed control after CC growth.

The ability of CCs to control weeds and problematic weeds, such as *Alopecurus myosuroides* Huds. in particular, may increase the relevance of CCs in agricultural production systems with narrow crop rotations. *A. myosuroides* is one of the most competitive grass weeds in fall-sown crops in Europe (Chauvel et al., 2001; Moss et al., 2007). The intensive growing of winter annual crops, early sowing, and reduced tillage systems favored the occurrence of *A. myosuroides* (Lutman et al., 2013). Repeated use of herbicides with the same mode of action, results in a selection of herbicide-resistant weed populations (Evans et al., 2016; Heap, 2017; Moss and Rubin, 1993). Alternative weed control practices are required to counteract increasing *A. myosuroides* infestations, to retard herbicide resistance development and to control herbicide-resistant *A. myosuroides* populations. Including spring crops in the crop rotation may effectively decrease the infestation of *A. myosuroides* (Chauvel et al., 2001). Implementing spring crops, however, creates a crop-free period from fall-to-spring which favors the emergence of weeds and, thereby, requires additional weed control measures in fall and spring. It has been demonstrated that well-established CCs control *A. myosuroides* up to 100% during the fall-to-winter season (Schappert et al., 2018). This experiment was continued to determine if winter cover cropping also impacts *A. myosuroides* infestation during the subsequent cash crop season. If *A. myosuroides* control by CCs is still measurable after the implementation of common conventional agricultural practices before and during cash cropping, the integration of CCs as a general weed and herbicide resistance management measure may increase.

Nevertheless, to justify the use of CCs in crop rotations, the success of weed control and the impact on crop yield need to compensate the producers’ labor and costs. CCs are generally attributed as having positive effects on the following cash crop by increasing the nitrogen content (Parr et al., 2011) and improving the soil water retention (Wortman et al., 2012), particularly in non-water-limited areas (Blanco-Canqui et al., 2015; Unger and Vigil, 1998). Hashemi et al. (2013) showed that corn silage yield was 41% greater after growing oat as a CC compared to no cover cropping. Although CC residues mainly contribute to weed control within non-inversion tillage, no-till practices might, unfortunately, cause lower yields, e.g. of oat and corn (Gruber et al., 2012; Rice et al., 1986) if beneficial effects on soil moisture are not compensating slower crop emergence and densities (Gruber et al., 2012).

As the performance of CCs is often difficult to predict, producers still often use either chemical or mechanical measures, or a combination of both, to achieve reliable, season-long weed control. Therefore, it is imperative to test the added value of CCs in different regions and cropping systems. CC monocultures and mixtures were addressed within this study to improve the weed control by living CCs and CC residues. It was further explored if inversion tillage after cover cropping is required and if an adjusted mulching date within non-inversion tillage systems improves the weed suppressive effect of CC residues. The following questions were considered:

i) Is the integration of CCs into the crop rotation able to reduce the input of mechanical and chemical weed management practices? ii) Is the management of CC residues affecting the weed infestation in the subsequent spring crop? iii) Is the subsequent spring crop yield affected by winter CCs and their residue management?

3.2 Materials and methods

Experimental Sites

Experiment 1 was implemented at two field trials at Binsen (48°25`22.0”N 8°53`15.4”E) and Risp (48°25`06.3”N 8°53`48.0”E) near Hirrlingen in Southwest-Germany. Experiments 2 and 3 were located in Southwest-Germany at a research station of the University of Hohenheim ‘Ihinger Hof’ (48°44`24.0”N 8°55`12.0”E) near Renningen. Weather, experimental conditions and soil preparations are shown in Table 7. At the location Renningen, during the cover cropping season, the weed community was dominated by volunteer crops and annual broadleaf weeds including *Capsella bursa-pastoris* M., *Lamium purpureum* L., *Matricaria* spp., *Stellaria media* L., and *Veronica persica* Poir.. During the cash crop seasons, species like *A. myosuroides*, *C. bursa-pastoris*, *Chenopodium album* L., *L. purpureum*, *Matricaria* spp., and *S. media* dominated. At the locations Binsen and Risp, the weed community was mainly characterized by *A. myosuroides*, *L. purpureum*, *Raphanus raphanistrum* L., *S. media*, *Thlaspi arvense* L., and *V. persica* during the fall-to-winter season. Only *A. myosuroides* was present in spring barley as dicotyledonous weeds were controlled by herbicides.

Table 7. Weather, experimental conditions and soil preparations for Experiment 1 at the field trials Binsen & Risp and Experiments 2 and 3 at Renningen from 2015 until 2018. Precipitation (P) and temperature (T) separately shown for the cover crop (CC) and the spring crop (SC) season. CC+NT: cover crop mixture + no-till, CC+MT: cover crop mixture + mulch-till (see also treatment overview for Experiment 1 within Table 8). M1 & M2 = mulching dates 1 and 2 (see also treatment overview for Experiment 3 within Table 10).

	Binsen & Risp	**Renningen**			
	Experiment 1	**Experiment 2**		**Experiment 3**	
	2017/2018	**2015/2016**	**2016/2017**	**2016/2017**	**2017/2018**
Sum P (Aug-Dec) CC-season	295.3 mm	215.2 mm	186.9 mm	186.9 mm	268.1 mm
Sum P (Apr-Aug) SC-season	244.6 mm	337.8 mm	327.4 mm	327.4 mm	185.8 mm
Mean T (Aug-Dec) CC-season	8.9 °C	10.9 °C	9.2 °C	9.2 °C	9.1 °C
Mean T (Apr-Aug) SC-season	16.6 °C	14.4 °C	15.1 °C	15.1 °C	16.8 °C
Crop rotation	Winter wheat - CC/NoCC [a] - spring barley	Canola - CC - corn	Winter wheat - CC - corn	Winter wheat - CC - corn	Winter barley - CC - corn
Soil type	Loamy silt	Clay loam	Silty loam	Silty clay	Silty loam
Soil preparation before CC	CC+MT: stubble cultivator + rotary harrow	Stubble cultivator + deep tillage + rotary harrow		Stubble cultivator + deep tillage + rotary harrow	
Sowing date (CC)	CC+NT: 07/08/17 CC+MT: 19/08/17	21/08/15	17/08/16	19/08/16	25/08/17
Sowing depth (CC)	1-1.5 cm	2 cm	2 cm	2 cm	2 cm
Soil preparation (before SC)	Disc harrow	See Table 9	See Table 9	Rotary harrow	DynaDrive [b] + rotary harrow
Sowing date (SC)	03/04/18	06/06/16	17/05/17	17/05/2017	02/05/18
Sowing depth (SC)	2-2.5 cm	4 cm	4 cm	4.5 cm	4.5 cm

[a] See treatment overview Experiment 1 (Table 8); [b] only for M1 & M2 (Table 10)

Experimental Set-up

Cover Crops vs. Tillage and Glyphosate Treatments: Experiment 1. Experiment 1 was designed to evaluate the impact of weed management practices implemented following wheat harvest in late summer, on a subsequent barley crop planted the following spring (Table 7). Experimental treatments were arranged in a two-factorial randomized complete strip-plot design. Eight weed management treatments were implemented as the first factor (Table 8). The second factor, which was implemented as the strip, is the winter wheat straw management. The straw management included either straw removal just after the harvest or leaving straw on the field. In total, 16 treatments were set up with three replications at two locations in 2017. The plot size at the field sites was 16.5 x 5 m and 21.5 x 5 m at Binsen and Risp, respectively. At locations Binsen and Risp, the CC mixture (provided by Deutsche Saatveredelung AG (DSV), Germany) contained 45% Poaceae (*Avena strigosa* Schreb.), 18% Polygonaceae (*Fagopyrum esculentum* Moench), 17% Brassicaceae (6% *Raphanus sativus* var. *oleiformis*, 6% *Sinapis alba* L., 4% *Brassica carinata* A.Braun, 1% *Camelina sativa* Crantz), 12% Linaceae (*Linum usitatissimum* L.), 6% Boraginaceae (*Phacelia tanacetifolia* Benth.), 2% Asteraceae (*Helianthus annuus* L.). The seed producer recommends this legume-free mixture as being suitable for late sowing dates, cool growing conditions, and water production areas. Their attributed rapid growth and high biomass production are useful for weed suppression which supported choosing this mixture. Sowing, fertilization and plant protection measures were done uniformly across the entire experimental fields. Spring barley was sown at the 3rd of April at both locations. Calcium ammonium nitrate was applied with a rate of 300 kg ha^{-1} (4th of April) and 100 kg ha^{-1} (22nd of April). Tritosulfuron and florasulam (49.98 g active ingredient (ai) ha^{-1} and 3.78 g ai ha^{-1}, respectively (70 g ha^{-1} Biathlon® 4D)) were applied at the 27th of April with a tractor sprayer. Additionally, the trials were treated with a fungicide and insecticide to avoid yield losses by pests. Epoxiconazol and Xemium® (62.5 g ai ha^{-1} (1 L ha^{-1} Adexar®) and 62.5 g L^{-1}, respectively) were applied to the experimental fields at the 24th of May and thiacloprid (72 g ai ha^{-1} (0.3 L ha^{-1} Biscaya®)) at the 28th of May.

Table 8. Set-up of Experiment 1. Weed management treatments, weed control type, and treatment dates for the experimental field sites at Binsen and Risp. Weed management dates include dates for tillage, herbicide applications and sowing dates for the cover crop mixtures. (DAH = Days after cereal harvest). Based on Schappert et al. (2018).

Treatment		Weed management practices (depth in cm / concentration in L ha^{-1} / seed density kg ha^{-1})	Weed control type	Weed management (date in 2018)	Weed management (DAH)
1	Control	Weed fallow without weed management	-	-	-
2	FST	Flat soil tillage with rotary harrow (5 cm)	mechanical	08/08 06/09 14/10	8 37 75
3	DST	Deep soil tillage with wing share cultivator (15-16 cm)	mechanical	08/08 06/09 15/10	8 37 76
4	PL	Inversion soil tillage with a plow (25 cm)	mechanical	14/08	14
5	GLY	Single glyphosate treatment (4 L ha^{-1})	chemical	06/09	37
6	2*GLY	Dual glyphosate treatment (4 L ha^{-1})	chemical	06/09 04/10	37 75
7	CC+MT	Cover crop mixture + mulch-till (1-1.5 cm, 25 kg ha^{-1})	biological	19/08	19
8	CC+NT	Cover crop mixture + no-till (1-1.5 cm, 25 kg ha^{-1})	biological	07/08	7

Soil Tillage Impact after Cover Cropping: Experiment 2. Experiment 2 was designed to evaluate the impact of cover cropping implemented following canola or wheat harvest and spring-applied weed management practices after cover cropping on corn grown in the following summer (Table 7). Experimental treatments were arranged in a two-factorial randomized complete block design. Six CC treatments were implemented as the first factor (Table 9). These species represent commonly used CCs in Southwest-Germany as well as species which, under given conditions, have shown valuable characteristics in previous field trials. The second factor included three different tillage practices in spring. The 18 treatments were replicated four times. Each plot had an area of 33 m^2 (11 x 3 m). In spring 2016 and 2017, the plowing (PL) treatments were plowed on the 9th of March and 10th of February, respectively, with a depth of 30 cm. In the PL and no-till (NT) treatments, glyphosate (3.75 L ha^{-1} Roundup Powerflex®, 1,800 g acid equivalent ha^{-1}) was applied with a hand boom on the 9th of May and 25th of April in 2016 and 2017, respectively. Before corn sowing, a rotary harrow was used to prepare the seedbed within the PL treatments. A mulching unit and a rotary harrow were used at the 21st and 16th of May in 2016 and 2017, respectively, to prepare the soil within the mulch-till (MT) treatments. Corn was sown with a density of 93,200 grains ha^{-1} at the 6th of June and 17th of May in 2016 and 2017, respectively. 160 kg N ha^{-1} were applied a few days after sowing. During the corn season no weed control was performed to investigate the effects of CCs and tillage.

Table 9. Set-up of Experiment 2. Four cover crop monocultures and one mixture combined with different tillage practices after the cover crop season and before corn seeding (PL = plowing, NT = no-till, MT = mulch-till). Mixing ratios related to seed weight.

Treatment	Management practice	Cover crop	Sowing density
1	PL	Control	-
2	NT		
3	MT		
4	PL	*Fagopyrum esculentum* Moench	50 kg ha^{-1}
5	NT		
6	MT		
7	PL	*Trifolium subterraneum* L.	32 kg ha^{-1}
8	NT		
9	MT		
10	PL	*Raphanus sativus* var. *oleiformis*	25 kg ha^{-1}
11	NT		
12	MT		
13	PL	*Avena strigosa* Schreb.	120 kg ha^{-1}
14	NT		
15	MT		
16	PL	Mixture (35% *F. esculentum*, 15% *T. subterraneum*, 15% *R. sativus* var. *oleiformis*, 35% *A. strigosa*)	40 kg ha^{-1}
17	NT		
18	MT		

Adapted Mulching Date of Cover Crops: Experiment 3. Experiment 3 was conducted to estimate the impact of CCs following wheat harvest in late summer and their residue mulching on a subsequent corn crop (Table 7). The treatments were set up as a two-factorial randomized complete block design. The first factor included the same six CC treatments as used at Experiment 2 (Table 10). Three spring-applied mulching dates were implemented as the second factor. The mulching was performed with a flail mower. The 18 treatments were conducted with four repetitions. Plot size in both years was 11.5 x 3 m. CC residues were mulched at an early (M1), a medium (M2) and a late (M3) date (for mulching dates see Table 10). In 2018, the M1 and M2 treatment were treated with a soil-driven tiller (Dyna-Drive®, Bomford Turner Ltd., Worcestershire, UK) two weeks before sowing due to the high weed infestation which would have hindered sowing. Corn was sown with 93,200 grains ha^{-1}. At the 18th and 9th of May 170 kg N ha^{-1} were applied in 2017 and 2018, respectively. No other weed control practices were applied during the corn cropping season.

Table 10. Set-up of Experiment 3. Four cover crop monocultures and one mixture combined with different mulching dates after the cover crop season and before corn seeding. Mulching dates during the season 2016/2017: M1 = 14/12/16, M2 = 15/03/17, M3 = 12/05/17. Mulching dates during the season 2017/2018: M1 = 15/01/18, M2 = 02/03/18, M3 = 30/04/18**.** Mixing ratios related to seed weight.

Treatment	Mulching date	Cover crop	Sowing density
1	M1	Control	-
2	M2		
3	M3		
4	M1	*Fagopyrum esculentum* Moench	50 kg ha^{-1}
5	M2		
6	M3		
7	M1	*Trifolium subterraneum* L.	32 kg ha^{-1}
8	M2		
9	M3		
10	M1	*Raphanus sativus* var. *oleiformis*	25 kg ha^{-1}
11	M2		
12	M3		
13	M1	*Avena strigosa* Schreb.	120 kg ha^{-1}
14	M2		
15	M3		
16	M1	Mixture (35% *F. esculentum*, 15% *T. subterraneum*, 15% *R. sativus* var. *oleiformis*, 35% *A. strigosa*)	40 kg ha^{-1}
17	M2		
18	M3		

Data Collection

Cover Crops vs. Tillage and Glyphosate Treatments: Experiment 1. The densities of *A. myosuroides*, dicotyledonous weeds, and spring barley were assessed by counting plant densities 12 weeks after spring crop sowing (WAS_{SC}). Furthermore, the ears per plant of *A. myosuroides* and spring barley were estimated at the same date. All assessments were conducted with a quadrat (0.33 m^2), within three random spots per plot. Spring barley was harvested with an area of 12.5 m^2 and 25 m^2 at trials Binsen and Risp, respectively, with a plot combine harvester at the 26th of July 2018.

Soil Tillage Impact after Cover Cropping: Experiment 2 & Adapted Mulching Date of Cover Crops: Experiment 3. Weed and CC dry matter were determined by cutting the fresh biomass of a randomly chosen area with 0.25 m^2 quadrat 7 (Experiment 3) and 12 (Experiment 2 and 3) weeks after sowing of CCs (WAS_{CC}). The fresh weed and CC plant material was separately placed in an oven at 100 °C for 24 hours to get the dry matter yields. Soil coverage within the CC season in Experiment 3 was visibly estimated randomly two times per plot within an area of 0.1 m^2. Within an area of 0.1 m^2, the weed density and composition within the CC season was determined 12 WAS_{CC} in 2016. The weed dry matter during the corn season was measured by cutting the weeds within an area of 0.25 m^2 (at Experiment 2 in 2015 and 2016) and 1 m^2 (at Experiment 3 in 2016 and 2017) 8 WAS_{SC}. The corn yield in Experiment 2 was measured by harvesting 16.5 m^2 of the plot (11 x 1.5 m) using a plot-combine harvester at the 11th of October (18 WAS_{SC}) and 28th of September (19 WAS_{SC}) in 2016 and 2017, respectively. Corn at Experiment 3 was harvested with a combine from a 17.2 m^2 area (11.5 x 1.5 m) on the 28th of September (19 WAS_{SC}) and the 22nd of August (16 WAS_{SC}) in 2017 and 2018, respectively. The weed density and community at Experiment 3 within the corn season was determined twice per plot within an area of 0.1 m^2 8 WAS_{SC}.

Data Analyses

The data from all three experiments were analyzed using software R version 3.5.1 (R Core Team, 2018) and RStudio (Version 1.1.453, RStudio Team, Boston, MA, USA). Prior to analysis, the dataset was visually checked for variance homogeneity and normal distribution. The *A. myosuroides* densities at Experiment 3 in 2017 and 2018 were square-root transformed prior to using an analysis of variance (ANOVA). The data were separately analyzed for each experiment, year and sampling date. Significant differences were identified using the Tukey-

HSD test with a significance level of $p \leq 0.05$. Multiple comparisons of the means were conducted using the R add-on package lsmeans (Version 2.27 – 61). The results of the analysis for Experiment 1 are shown in Table 11.

Table 11: Results of the analysis of variance related to Experiment 1 according to factor (column) and measured parameter (row). * $p \leq 0.05$; n.s. = not significant. No interaction between factors was determined.

Parameter	**Weed management**	**Location**	**Straw management**
Alopecurus myosuroides Huds. ears	*	*	n.s.
A. myosuroides control efficacy	*	n.s.	n.s.
Barley tiller	*	n.s.	n.s.
Barley yield	n.s.	*	n.s.

The location had a significant impact on the barley yield and the *A. myosuroides* ears (Experiment 1). Therefore, those parameters were analyzed separately for the field trials Binsen and Risp. The straw management factor (Experiment 1) was not significant for the measured parameters.

As tillage and mulching were done after the CC growing season within Experiments 2 and 3, CC and weed dry matter, soil cover and weed control efficacy (WCE) during CC growth were only analyzed according to the different CC treatments. The control treatments (Experiments 2 and 3) were excluded from the CC dry matter analysis. The weed dry matter during the corn season in 2017 within Experiment 3 wasn't been recorded. Wherever there were no interactions and factor CC not significant (Experiment 2 and 3), analysis during the corn season was performed according to management practices (Experiment 2, see treatment overview Table 9) or mulching dates (Experiment 3, see treatment overview Table 10). The results of the analysis for Experiments 2 and 3 are shown in Table 12 and Table 13, respectively.

Table 12: Results of the analysis of variance related to Experiment 2 according to factor (column) and measured parameter (row). * $p \leq 0.05$; n.s. = not significant. No interaction between factors was determined.

Season	Year	Parameter	Cover crop choice	Soil tillage
Cover cropping season	2015	Weed dry matter	*	-
		Cover crop dry matter	n.s.	-
	2016	Weed dry matter	n.s.	-
		Cover crop dry matter	*	-
Corn cropping season	2016	Weed dry matter	n.s.	*
		Corn dry matter	n.s.	*
	2017	Weed dry matter	-	-
		Corn dry matter	n.s.	*

Table 13: Results of the analysis of variance related to Experiment 3 according to factor (column) and measured parameter (row). * $p \leq 0.05$; n.s. = not significant. No interaction between factors was determined.

Season	Year	Parameter	Cover crop choice	Mulching date
Cover cropping season	2016	Weed dry matter	*	-
		Weed soil cover	*	-
		Weed control efficacy	*	-
		Cover crop dry matter	*	-
		Cover crop soil cover	*	-
	2017	Weed dry matter	*	-
		Weed soil cover	*	-
		Cover crop dry matter	*	-
		Cover crop soil cover	*	-
Corn cropping season	2017	Weed dry matter	n.s.	n.s.
		Total, *A. myosuroides*, monocotyledonous and dicotyledonous weed density	n.s.	n.s.
		Corn dry matter	n.s.	*
	2018	Weed dry matter	n.s.	n.s.
		Total weed density	n.s.	n.s.
		A. myosuroides density	n.s.	*
		Monocotyledonous weed density	n.s.	*
		Dicotyledonous weed density	n.s.	*
		Corn dry matter	n.s.	n.s.

The WCE and *A. myosuroides* control efficacy (ACE) were calculated according to Rasmussen (1991) as:

$$\text{WCE, ACE (\%)} = 100 - wt\,(0.01 \times wc)^{-1} \qquad (2)$$

Wt is the weed (*A. myosuroides*) density (plants m^{-2}) of the weed management treatments and wc the weed (*A. myosuroides*) density (plants m^{-2}) of the control treatments.

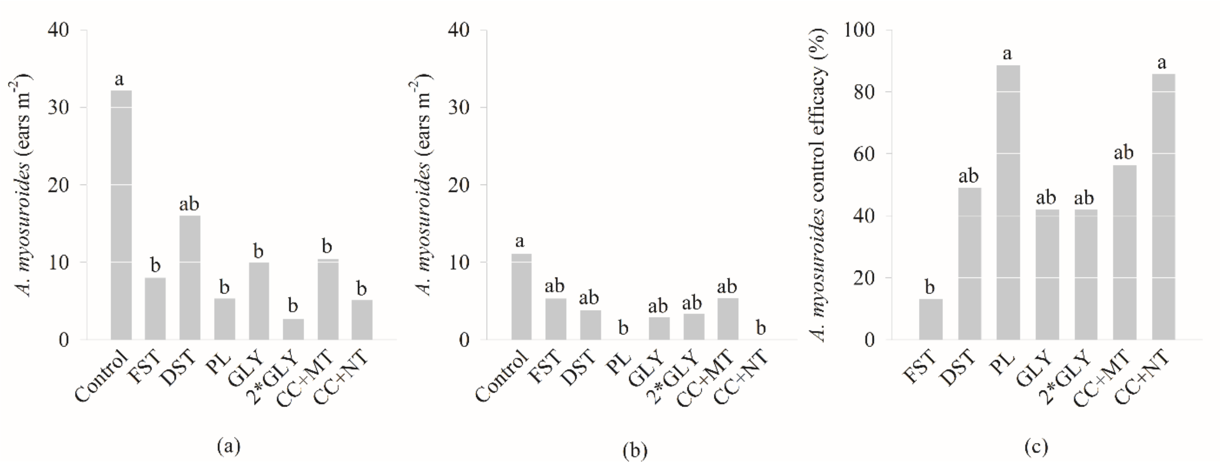
3.3 Results and discussion

Cover Crops vs. Tillage and Glyphosate Treatments: Experiment 1

A. myosuroides was controlled by 13-89% within Experiment 1 (Figure 4). The control treatment at Binsen showed an average of 32.2 *A. myosuroides* ears m^{-2}. All weed control practices at the field trial Binsen, except for the DST treatment (16 ears m^{-2}), reduced *A. myosuroides* ears m^{-2}. The treatments PL and CC+NT achieved a reduction of *A. myosuroides* ears m^{-2} at both field trials (Figure 4 a, b). The PL treatment showed the greatest ACE with 89%, which was greater than the worst-performing FST treatment with 13% ACE. Our results are generally consistent with previous research. For example, Lutman et al. (2013) showed that moldboard plowing reduced the number of *A. myosuroides* plants in the subsequent crop by 69% compared with a non-inversion tillage system. Moss (1979) reported that *A. myosuroides* was reduced from 557 plants m^{-2} within a shallow, tine treatment to 20 plants m^{-2} within a plowing treatment. Shallow tillage practices rather mix the upper soil layer, causing a horizontal distribution and an accumulation of weed seeds near the soil surface (Colbach et al., 2014; Cousens and Moss, 1990; Mohler and Galford, 1997). In order to bury the accumulated weed seeds, it may be recommended to combine shallow tillage practices with plowing every three to five years (Cousens and Moss, 1990; Gruber and Claupein, 2009). It is also expected that the increased *A. myosuroides* density in the plowing treatments during the fallow season in fall (Schappert et al., 2018) decreased viable seeds in the upper soil layer which resulted in a low number of *A. myosuroides* ears during cash cropping.

The CC+NT treatment reached an ACE of 86%. The mechanisms responsible for strong suppression of *A. myosuroides* by the CC+NT treatment are unclear but may have been a result of the effective *A. myosuroides* control during CC growth and suppressive effects after CC termination. Chemical compounds from the CC residues might have impacted on the *A. myosuroides* control in summer. However, allelopathic active compounds like isothiocyanates are reported to disappear rapidly (Brown and Morra, 1995; Petersen et al., 2001), in comparison to the decomposition of residues (Yenish et al., 1995). Concluding, weed control after cover cropping is more likely to the physical barrier, created by the mulch layer, than to the presence of active allelopathic compounds released from CC residues. CCs developed well from fall-to-winter and produced fresh matter amounts of more than 25 t ha^{-1} (Schappert et al., 2018). Tillage prior to the cash crop sowing mixed the CC residues into the upper soil layer, whereby beneficial effects on weed control by the CC mulch layer decreased. However, Kruidhof et al. (2009) showed that the incorporation of CCs, e.g. *Brassica napus* L., achieves higher weed suppression than a mulch layer of the respective species.

Further research is necessary to reveal the impact of CCs on *A. myosuroides* control after CC termination, which might contribute to further herbicide savings.



(a) (b) (c)

Figure 4. *Alopecurus myosuroides* Huds. (*A. myosuroides*) ears m^{-2} within Experiment 1 at the field trials Binsen (a) and Risp (b). *A. myosuroides* control efficacy is shown in (c) averaged for the two field trials. Treatments: no cover crop control (Control), flat soil tillage (FST), deep soil tillage (DST), plowing (PL), single glyphosate application (GLY), dual glyphosate application (2*GLY), cover crop mixture + mulch-till (CC+MT) and crop mixture + no-till (CC+NT). Small letters within one graph show significant differences according to Tukey-HSD test ($p \leq 0.05$).

With a range between 219-263 tillers m^{-2}, all treatments were able to increase tillering of spring barley compared to the control (Figure 5 a). The average spring barley yield was between 5.3 t ha^{-1} (Binsen) and 5.9 t ha^{-1} (Risp) (Figure 5 b). No differences in yield were observed between the treatments (Table 11). Therefore, one or two glyphosate applications (treatments: GLY and 2*GLY) in fall did not improve *A. myosuroides* control and spring barley yield compared to either CCs or tillage methods. Therefore, CCs or tillage are reasonable options in order to control *A. myosuroides* and to retard the selection of glyphosate-resistant populations. Whereby, tillage is mostly implemented for weed control and seed bed preparation, CCs offer numerous advantages such as building up soil organic matter or breaking disease and pest cycles if well managed (Snapp et al., 2005). This can make a valuable contribution to agricultural production systems.

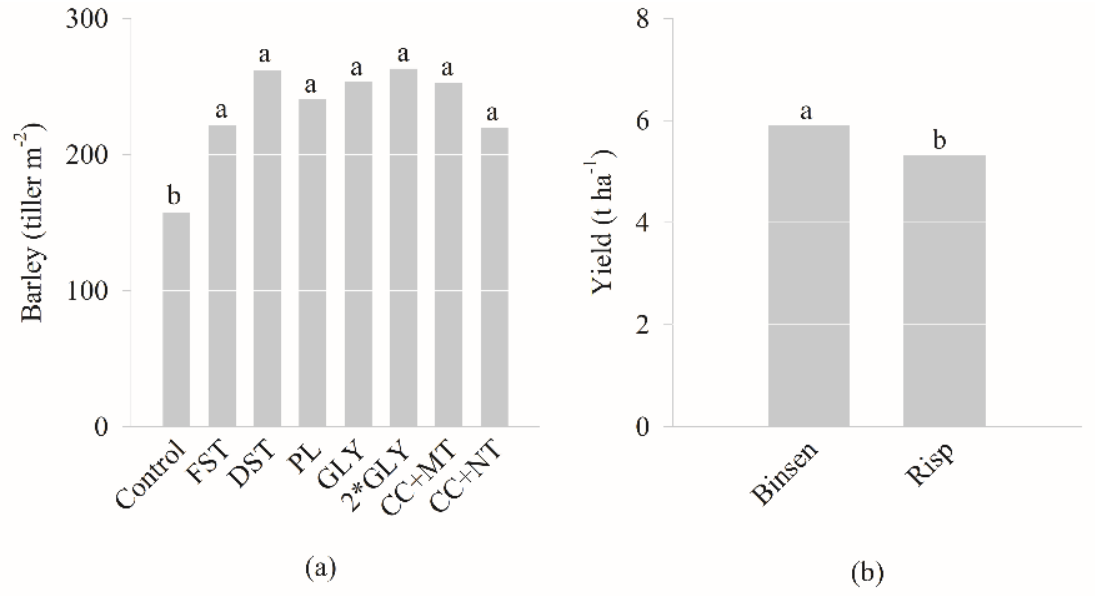


Figure 5. Number of barley tillers (a) within Experiment 1 of the treatments untreated control (Control), flat soil tillage (FST), deep soil tillage (DST), plowing (PL), single glyphosate application (GLY), dual glyphosate application (2*GLY), cover crop mixture + mulch-till (CC+MT) and crop mixture + no-till (CC+NT) averaged for Binsen and Risp. Average yield across all treatments for the field trials Binsen and Risp (b). Small letters within one graph show significant differences according to Tukey-HSD test ($p \leq 0.05$).

Soil Tillage Impact after Cover Cropping: Experiment 2

With an average CC dry matter between 1402-1602 kg ha^{-1}, there were no significant differences between the CC treatments in 2015 12 weeks after cover crop planting (Figure 6). All CC treatments, except for the *Trifolium subterraneum* L. treatment, were able to reduce weed dry matter. Baraibar et al. (2018) also observed the highest weed dry matter within a red clover treatment in comparison with grass, legume and cruciferous CCs. In 2016, none of the CC treatments were able to reduce the weed dry matter compared to the control treatment.

While the CC mixture in Experiment 1 showed great potential for weed control during CC growth (Schappert et al., 2018) and after termination (Figure 4), weed suppressive effects by CCs after termination within Experiment 2 were not detected during either experimental seasons (Table 12). CC performance during the fall-to-winter was probably too weak in order to provide weed suppressive effects after termination.

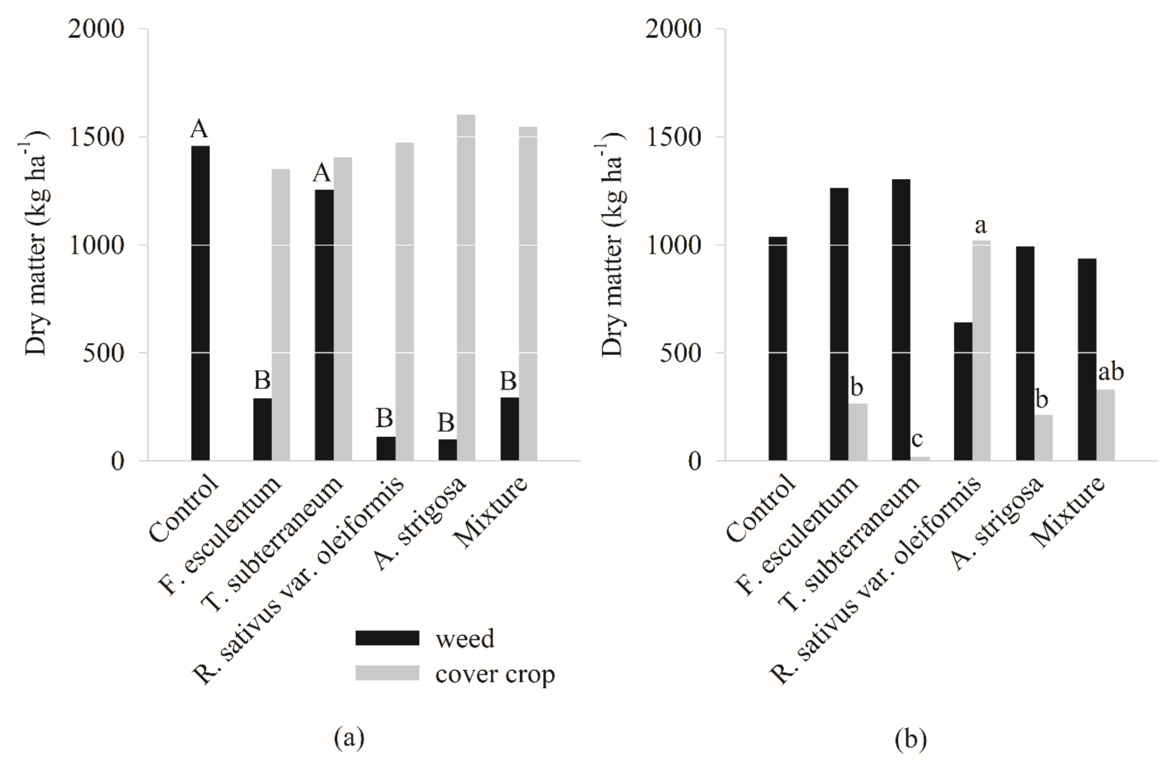


Figure 6. Weed and cover crop dry matter 12 weeks after sowing during the cover crop season within Experiment 2 in 2015 (a) and 2016 (b). Capital letters within one graph show significant differences among the weed dry matter according to Tukey-HSD test ($p \leq 0.05$). Small letters within one graph show significant differences among the cover crop dry matter. Bars with no letters are not significantly different.

As the performance of CCs is dependent on the location and the year, CCs are not always a reliable tool for weed control (Dorn et al., 2015) and are expected to arouse additional weed control strategies after termination. Tillage practices in spring impacted weeds during the corn season, independent from the CCs grown (Figure 7 a). Within the corn season in 2016, the PL and the MT treatments (Experiment 2) achieved the greatest weed dry matter with 2226 kg ha^{-1} and 2202 kg ha^{-1}, respectively. The NT treatment showed the lowest weed dry matter (1182 kg ha^{-1}) and the greatest corn dry matter with 11 t ha^{-1} in 2016 (Figure 7 b). However, the performance of the tillage treatments on the corn yield changed in the following season (2017).

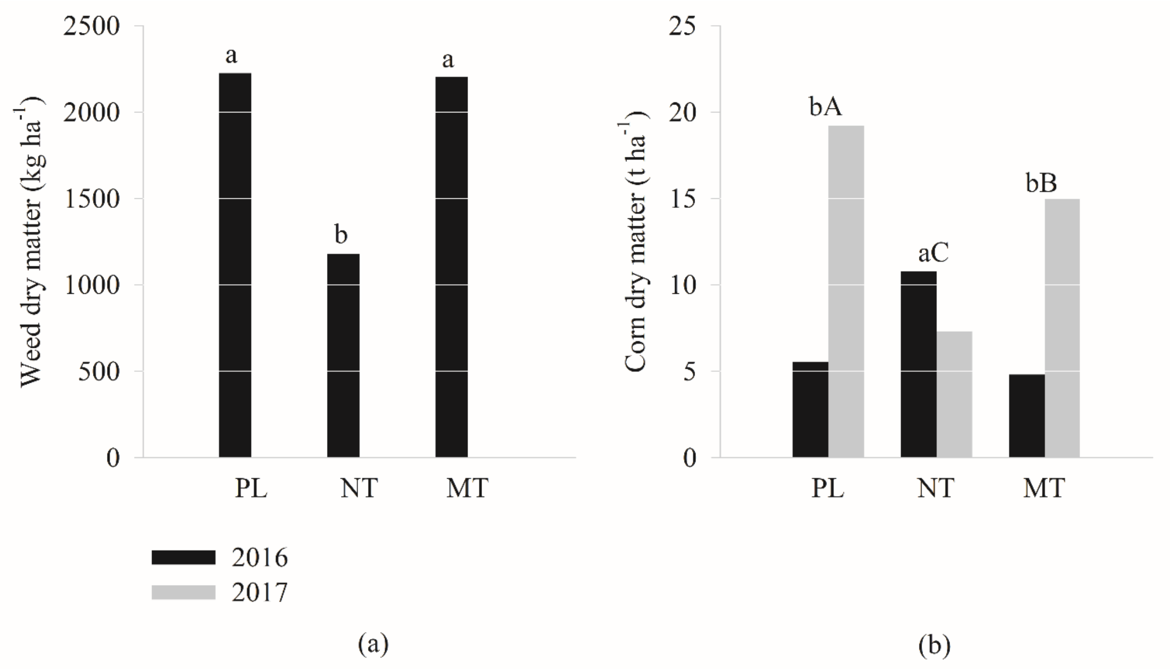


Figure 7. Weed (a) (in 2016) and corn (b) (in 2016 and 2017) dry matter at corn harvest within Experiment 2. Small letters within the graph (a) show significant differences in weed dry matter according to Tukey-HSD test ($p \leq 0.05$). Small letters within the graph (b) show significant differences in corn dry matter within the year 2016. Capital letters within (b) show significant differences in corn dry matter within the year 2017.

In 2017, the NT treatment showed the least and the PL treatment the greatest corn dry matter with 7 and 19 t ha^{-1}, respectively. Weather conditions and the sowing date might have encouraged the seasonal differences between the tillage treatments. The corn yield variability, according to Kravchenko et al. (2005), is mainly affected by the spring-early summer precipitation in well-managed fields. Within the first 5 WAS$_{SC}$ in 2016 the rainfall amount reached 78 mm. In comparison, the accumulated precipitation in 2017 was only 33 mm (5 WAS$_{SC}$). Hussain et al. (1999) showed that the corn yield within a no-till practice is greater in dry years, whereby the yield within moldboard-plowed treatments increased within wetter conditions. Greater soil moisture contents within no-till treatments caused by increased water infiltration, decreased runoff and evaporation compared to conventional tillage systems (Blevins et al., 1971; Hill, 1990) seem reasonable. However, the NT treatment showed the greatest yield during the 2016 season and the least corn yield in the dry 2017 season. The differences in yield seem, therefore, not be explainable by the water availability alone and might have additional reasons. Soil tillage or no-tillage have a major effect on the nitrogen cycle (House et al., 1984), which is linked to lower nitrogen availabilities in the no-till system during the early years after implementation (Rice et al., 1986). However, with a focus on the long-time average, tillage (including no-till) may not show any effect on the corn yield (Hussain et al., 1999).

Adapted Mulching Date of Cover Crops: Experiment 3

The ANOVA results show that the CC choice impacted on weed and CC dry matter and soil cover in both experiment seasons (Table 13). CC establishment and weed infestation were much lower in 2016 than in 2017, which resulted in a maximum weed soil cover of 6% (control) in 2016 and 57% in 2017 (12 WAS_{CC}) (Figure 8 b, d). *A. strigosa* achieved the greatest weed coverage reduction of 96% (2017) (Figure 8 d). In 2016, the greatest CC dry matter was produced by *R. sativus* var. *oleiformis*, *F. esculentum*, and the mixture with 1738 kg ha^{-1}, 1477 kg ha^{-1}, and 1418 kg ha^{-1}, respectively (Figure 8 a). The CCs *A. strigosa*, *R. sativus* var. *oleiformis* and the CC mixture achieved the greatest CC dry matter with 1178 kg ha^{-1}, 1083 kg ha^{-1} and 975 kg ha^{-1} in 2017, respectively. Except for *T. subterraneum*, all treatments were able to reduce the weed dry matter compared to the control 12 WAS_{CC} in 2016 and 2017 (Figure 8 a, c).

According to Brust, Claupein et al. (2014), Brassicaceae species (including *R. sativus* var. *oleiformis*) generally produce high dry matter yields, which result in effective weed control. The WCE in 2016 (12 WAS_{CC}) of *R. sativus* var. *oleiformis*, *A. strigosa*, and the CC mixture was significantly better (53-61%) than of *F. esculentum* and *T. subterraneum*, which only reached 2-3% WCE (Figure 9). Although, none of the CC produced high biomass yields, differences between the treatments indicate suitabilities of single species being suitable as a weed control measure. Across Experiments 2 and 3, *R. sativus* var. *oleiformis* showed the greatest potential in generating high biomass yields, reliable soil cover/plant establishment, and weed reduction ability. Out of the three years presented, *A. strigosa* seems to have a lower resilience against dry conditions compared to *R. sativus* var. *oleiformis*, which was reflected in low dry matter yields (Experiments 2 and 3) within the cover cropping season in 2016. Nevertheless, the allelopathic potential of CCs may compensate the lower dry matters yields and soil cover which still results in efficient weed control (Schulz et al., 2013). Therefore, a low ratio of *A. strigosa* in mixtures might support sufficient weed control and allow the remaining mixing partners to fulfill additional ecosystem services (Baraibar et al., 2018) like nitrogen fixation and a prevention of soil erosion. The mixture shown within Experiments 2 and 3 achieved a similar weed control than the two most efficient single sown CCs. Due to the resilience of species combinations against severe weather conditions and producers' operations, mixtures may be advisable as they show a higher average weed control ability across seasons than CC pure stands (Wortman et al., 2012).

During the subsequent corn season, CC choice did not influence weed dry matter, density and corn dry matter. All treatments were minimum-tilled before corn sowing, whereby weed suppressive effects by CC mulch seem to have vanished. Additionally, not much biomass was produced by CCs during both experiment seasons. The residue amount and the mulch soil coverage are the main drivers influencing weed infestations after cover cropping (Kunz et al., 2017; Mirsky et al., 2011; Weber et al., 2017). The mulching dates did not impact on weed dry matter and total weed density (Table 13). Weed dry matter ranged between 901-1007 kg ha^{-1} in 2017 and 958-1256 kg ha^{-1} in 2018 (Figure 10 a). Within the corn cropping season in 2017, the weed density was very low (Table 14). A maximum of 16.3 weeds m^{-2} (M3) was counted in 2017 compared to a maximum of 122.1 weeds m^{-2} (M3) in 2018. The weed community was affected by the mulching dates in 2018 (Table 14). Whereby, the M3 treatment showed greater densities of *A. myosuroides* and monocotyledonous weeds, but reduced dicotyledonous weed density compared to the treatments M1 and M2. An explanation could be that the M1 and M2 treatments received a supplementary soil tillage treatment in 2018 two weeks before sowing in order to prepare an appropriate seedbed. Thereby, the additional mixing (M1, M2) of the upper soil layer may have created favorable conditions, especially to dicotyledonous weeds. In contrast, the M3 was left fallow until two days before sowing which seemed to have encouraged the dispersal and emergence of monocotyledonous weeds, including *A. myosuroides*.

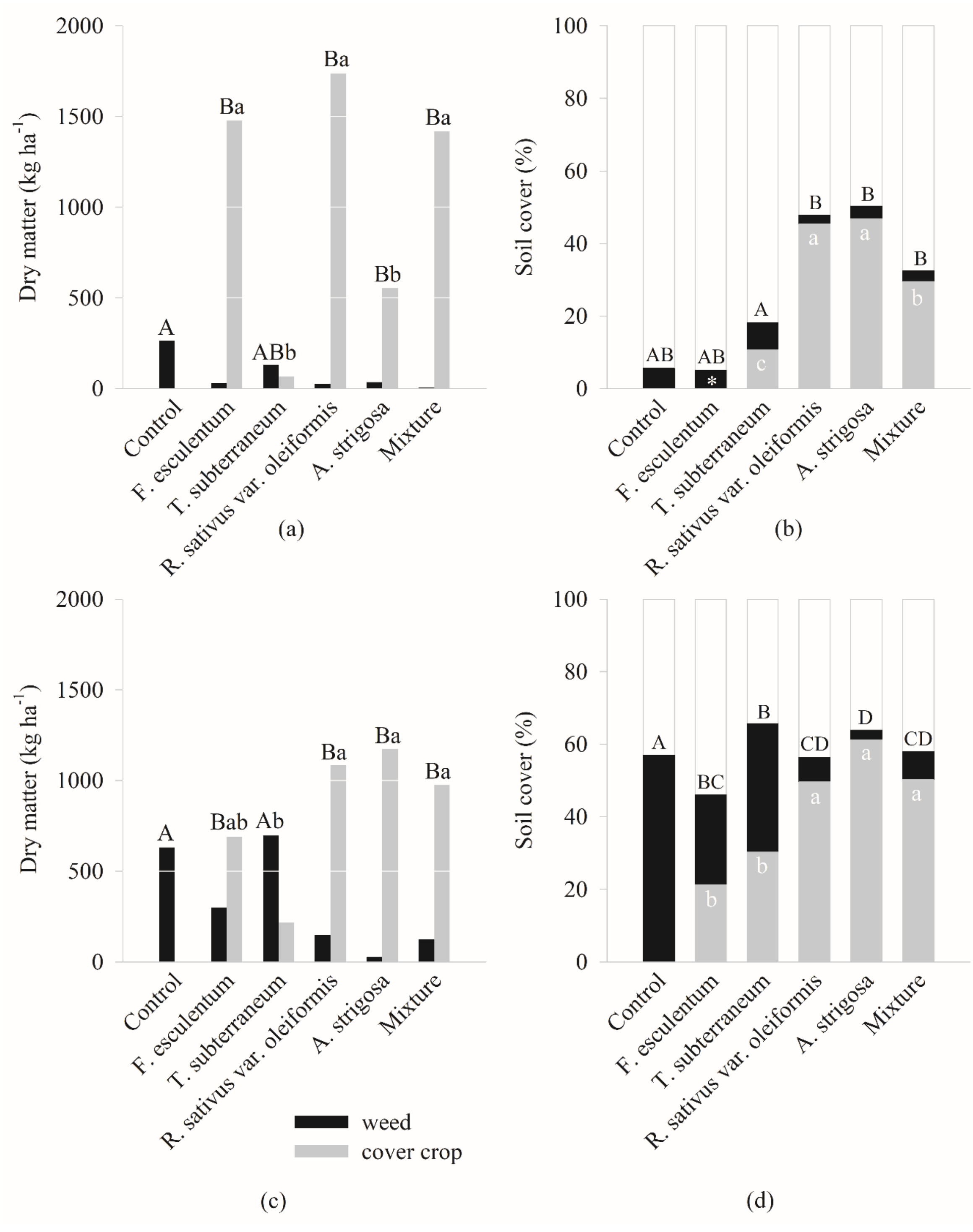


Figure 8. Weed and cover crop dry matter within Experiment 3 12 weeks after sowing in 2016 (a) and 2017 (c). Weed and cover crop soil cover are shown for the year 2016 (b) and 2017 (d). Capital letters within one graph show significant differences within the weed dry matter/soil cover according to Tukey-HSD test ($p \leq 0.05$). Small letters show significant differences within the cover crop dry matter/soil cover. * = missing data of *F. esculentum* in (b).

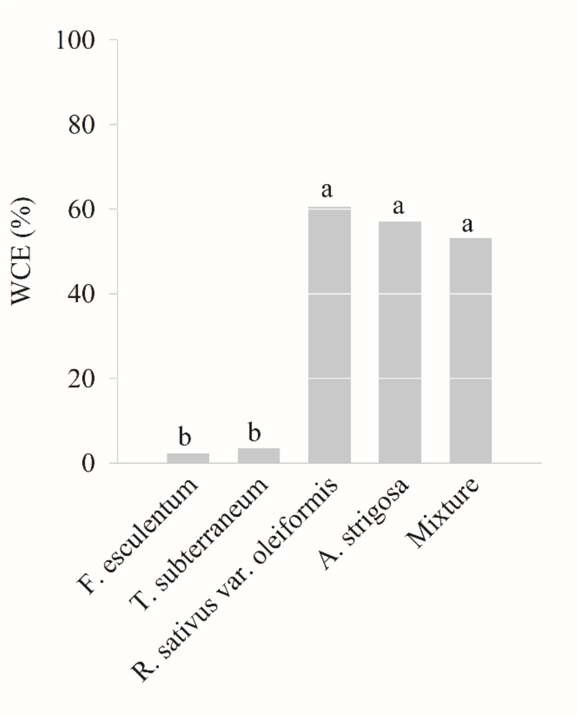


Figure 9. Weed control efficacy (WCE) 12 weeks after sowing during the cover crop season 2016 within Experiment 3. Small letters show significant differences according to Tukey-HSD test ($p \leq 0.05$).

Table 14. Weed density (plants m^{-2}) within Experiment 3 during the corn cropping season 8 weeks after sowing in 2017 and 2018. Mulching dates during the season 2016/2017: M1 = 14/12/16, M2 = 15/03/17, M3 = 12/05/17. Mulching dates during the season 2017/2018: M1 = 15/01/18, M2 = 02/03/18, M3 = 30/04/18. ALOMY = *Alopecurus myosuroides* Huds., Monocot = monocotyledonous weeds, Dicot = dicotyledonous weeds (weed community see chapter: Experimental Sites). Capital letters show significant differences within one column according to Tukey-HSD test ($p \leq 0.05$). Means with no letters do not differ significantly. NS = not significant.

	2017 ^{NS}				**2018**			
Treatment	**ALOMY**	**Monocot**	**Dicot**	**Total**	**ALOMY**	**Monocot**	**Dicot**	**Total ^{NS}**
M1	1.1	1.4	14.2	15.6	1.1 ^{B}	14.9 ^{B}	105.0 ^{A}	118.7
M2	1.4	1.7	11.8	13.5	1.5 ^{B}	14.7 ^{B}	96.3 ^{A}	110.7
M3	1.8	2.0	15.0	16.3	5.3 ^{A}	55.3 ^{A}	73.2 ^{B}	122.1

In 2018, the corn dry matter was 45-48% lower (averaged over all treatments) compared to the 2017 season and reached a maximum of 9 t ha^{-1} (M1) (Figure 10 b). Marcillo and Miguez (2017) evaluated the effects of winter CCs on corn yield within a meta-analysis, using publications from 1965 until 2004. They concluded that winter CCs may have a negative, neutral, and positive impact on corn yield depending on the region, management practices, nitrogen fertilization, tillage, CC species, CC sowing, and termination date. Whereby Kuo and Jellum

(2000) argued that the nitrogen availability changed by CCs is the main trigger for an increase of corn biomass. The CC species used within Experiment 2 and 3 did not show any effect on the corn yield, while Marcillo and Miguez (2017) were distinguishing the effect on the corn yield according to the CCs used. Grass species, for example, have a neutral effect, while legumes reach an overall positive effect on the corn yield (Marcillo and Miguez, 2017), due to the additional atmospheric nitrogen fixation (Parr et al., 2011). CC mixtures may reach 13% greater corn yields compared to no-CC systems (Marcillo and Miguez, 2017), related to the biomass produced and the date of termination. Sainju and Singh (2001) observed that a delayed termination of CCs increased silage corn yield and nitrogen uptake within no-till systems. Corn dry matter was significantly increased in the M3 treatment compared to the M2 treatment and reached 17 t ha^{-1}. Also Parr et al. (2011) demonstrated that a late termination with a roller-crimper of winter-hardy legume CCs may increase corn yield even though sowing needs to be delayed. These findings agree with the results from Marcillo and Miguez (2017) who investigated a yield increase of about 30% if the mixture was terminated immediately before the sowing of corn. Applications of 200 kg N ha^{-1} or more negates the impact of CCs as N is then non-limiting (Marcillo and Miguez, 2017), which was also observed within this study as the CCs did not affect the corn yield. Continuous cover cropping with no or superficial soil disturbance and reduced fertilization might help to finally estimate the effects of CCs on corn yield.

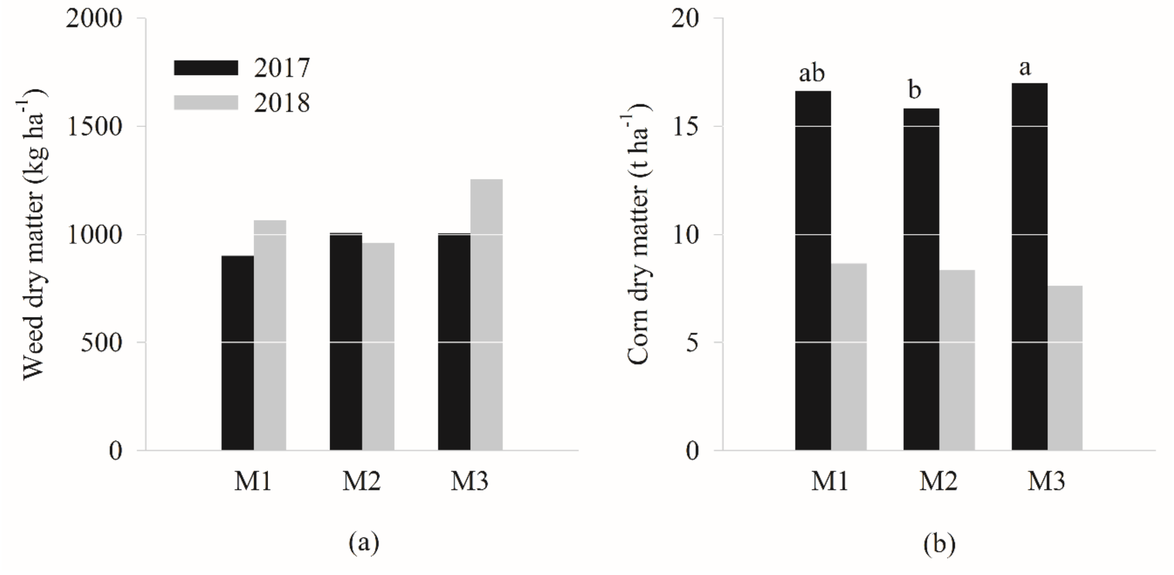


Figure 10. Weed dry matter 8 weeks after sowing (a) and corn dry matter at corn harvest (b) within Experiment 3 in 2017 and 2018. Mulching dates during the season 2016/2017: M1 = 14/12/16, M2 = 15/03/17, M3 = 12/05/17. Mulching dates during the season 2017/2018: M1 = 15/01/18, M2 = 02/03/18, M3 = 30/04/18. Small letters within graph (b) show significant differences within one year according to Tukey-HSD test ($p \leq 0.05$). Bars with no letters are not significantly different.

Impact of CCs and their Management on Weed Control and Crop Yield

Winter CCs were an efficient weed control measure during the fall to winter season. Weed suppression, however, did widely vary according to CC species and the seasonal amount of precipitation. The single sown *A. strigosa*, *R. sativus* var. *oleiformis*, and the species mixture showed the greatest and most reliable weed suppression during the cover cropping seasons. The CC mixture used at Experiment 1 demonstrated that well-established CCs do have a great potential to reduce *A. myosuroides* in the subsequent cash crop. This justifies substituting fall-applied chemical weed control measures by CCs and encourages CCs to be integrated within herbicide resistance management strategies. However, weed suppressive effects after CC termination were different among the experiments. Neither the single species nor the mixture used for cover cropping at Experiments 2 and 3 had an impact on the weed infestation during the corn cropping seasons. CCs were identified as being suitable to integrate within non-inversion systems when inversion tillage did not improve weed control after CC termination and when CCs did not show weed suppressive effects during CC growth. Management practices, like an adjusted mulching date of CC residues, failed in expanding weed suppressive effects from winter until spring cropping. In conclusion, CC establishment and weed suppression performance from fall-to-winter need to increase in order to benefit from weed suppressive effects after CC termination. Further research is required to identify CC management strategies (sowing date, seed density, sowing technique, species selection, mixing strategies and fertilization) to provide reliable high CC biomass production. This will most likely also increase their impact on weeds within the subsequent spring crop. Growing of winter-hardy CCs might be considerable if weed suppression by CCs after their termination is especially intended. The corn and the spring barley yields were not affected by either well or poor performing CCs. This encourages testing different CC strategies without expecting crop yield losses.

Acknowledgments: We are very grateful to the Weed Science group at the University of Hohenheim and the research station 'Ihinger Hof' for assisting with the data collection and the field support. We kindly thank Laura Janz, Lena Nicolai and Sarah Kalmbach for data acquisition and Gerassimos G. Peteinatos for manuscript revising. This research was financially supported by the 'Ministerium für Ländlichen Raum, Ernährung und Verbraucherschutz Baden-Württemberg (MLR)' within the project 'Conservation Agriculture' and the Research Training Group 'Water-People-Agriculture' at the University of Hohenheim funded by the Anton & Petra-Ehrmann foundation. No conflicts of interest have been declared.

Chapter 4

Weed control ability of single sown cover crops compared to species mixtures

Alexandra Schappert[1], Matthias Schumacher[1] and Roland Gerhards[1]

[1] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany

Published in: *Agronomy* (2019), 9 (6), 294

The original publication is available at:
www.mdpi.com/journal/agronomy, doi: 10.3390/agronomy9060294

4 Weed control ability of single sown cover crops compared to species mixtures

Alexandra Schappert[1], Matthias Schumacher[1] and Roland Gerhards[1]

[1] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany

Abstract

To achieve efficient weed control by cover cropping, the plant species chosen need particular consideration. Combing different cover crop (CC) species in mixtures may increase the number of provided ecosystem services, including a reliable suppression of weeds. We tested the weed suppression ability of single CC species and mixtures in a field trial during the autumn-to-winter growing season in 2016 and 2017. *Anethum graveolens* L. (dill), *Raphanus sativus* var. *oleiformis* Pers. (oilseed radish), *Avena strigosa* Schreb. (black oat), *Carthamus tinctorius* L. (safflower), *Vicia sativa* L. (vetch) and *Phacelia tanacetifolia* Benth. (phacelia) were sown in monocultures, as well as in mixtures with three or six species. Treatments with favorable establishment and above-average biomass yields tended to suppress weeds by showing lower weed dry matter and weed numbers. The highest weed control efficacy within the monocultures was reached in 2017 by black oat and oilseed radish with 72% and 83%, respectively. The mixture treatments reached a generally lower soil cover, aboveground dry matter and weed control efficacy (with an average of 57% in 2017). Even though mixtures were not as effective as the best performing single sown CCs, species combinations increased resilience against adverse weather conditions, an advantage to achieving efficient weed control over a long-term period. Therefore, the species composition within mixtures is more relevant than the number of species included.

Keywords: biological; catch crop; plant diversity; weed management

4.1 Introduction

The incorporation of cover crops (CCs) into crop rotations has become a practical strategy by producers. The European Union further promotes the use of CCs in agriculture by their “greening” strategy (Regulation (EU) No 1307/2013 of the European Parliament of the Council of 17 December 2013). The increasing interest of producers and researchers in CCs might have been encouraged by the manifold positive aspects which are attributed to cover cropping. CCs are normally grown between two main crops to reduce erosion and to improve soil characteristics like nitrogen content, phosphor availability and soil structure (Hartwig and Ammon, 2002). Additionally, they serve as a pollen and nectar source for pollinators and overwintering habitat for beneficials (Dunbar et al., 2017; Ellis and Barbercheck, 2015). They also provide services that reduce pests, pathogens and weeds (Farooq et al., 2011; Fourie et al., 2016). CCs offer different temporal and spatial (niche) possibilities as well as physical and biochemical mechanisms to control weeds.

After sowing, CCs provide direct weed control during their establishment by releasing allelochemical compounds into the environment (Gfeller et al., 2018) and competing with weeds for light, water, nutrients and space (Blanco-Canqui et al., 2015). This can severely hamper the development of weeds (Brennan and Smith, 2005) or even prevent them from emerging. Some cover crop (CC) species are able to survive the harsh conditions over winter and continue to provide this service in early spring. CCs are normally terminated by mechanical or chemical methods before sowing of the next main crop. In any case, CC residues are either incorporated into the soil or retained on the soil surface (Creamer et al., 1996). Under both strategies, plant residues continue to release the remaining allelochemicals that are contained in the dead plant material (Putnam et al., 1983; Tabaglio et al., 2013). If CC residues are left on the soil surface, they additionally act as a physical layer that small weed seedlings need to penetrate (Teasdale et al., 1991; Teasdale and Mohler, 1993). This slows down the development of the weed populations in spring after the main crop has already been sown (Wayman et al., 2015). Therefore, CCs are able to affect weed populations from their sowing date until a certain time after the subsequent main crop is established (Falquet et al., 2015). Naturally, the weed suppressive ability of a CC depends on several environmental influences that determine, e.g., the level and activity of allelochemicals (Belz, 2007), the speed of CC development and the build-up of biomass (Hiltbrunner et al., 2007). Under unfavorable conditions, a single sown CC might not be able to provide a sufficient level of weed suppression.

Crop stands of single CC species are not able to buffer rapidly changing environmental conditions. Therefore, many studies have investigated the adaptability of mixtures (Finckh et al., 2000; Hajjar et al., 2008; Tilman et al., 2001). Higher species diversity increases the likelihood that some of the species in a mixture are more productive, because they are better adapted to a certain set of environmental conditions (sampling effect) (Huston, 1997; Tilman et al., 1997). The CC species *Vicia sativa* L. and *Phacelia tanacetifolia* Benth. were not germinating well under high temperatures, whereas *Guizotia abyssinica* (L.f.) Cass. performed well (Tribouillois et al., 2016). Combinations of contrasting species in regard to environmental conditions, therefore, might provide resilience to weather conditions and provide stability in their service provision. The conditions that drive CC species performance are also dependent on agronomic measures such as sowing date and termination method (Constantin, Le Bas et al., 2015). CC mixtures might not only be resilient to environmental conditions, but also to failures in the conductance of agronomic measures by the producer. One of the upcoming major challenges will be the handling of climate change and extreme weather events in agriculture (Stott et al., 2004) and the question of how to design appropriate CC mixtures to deal with them. Additionally, more diverse mixtures host species that have different acquisition and competition strategies. The “niche complementarity” (MacArthur and Levins, 1967) describes the actual function of a mixture based on the traits of the single species. The more diverse or different the setup of these traits for every single species within a mixture, the more likely it is that they occupy different niches and are more productive. CC species with different plant canopy features might intercept and use light more efficiently and therefore reduce the availability of light on the soil surface, leading to a reduced emergence of weeds. The unique root growth patterns and abilities to take up and mobilize nutrients in the soil by CC species in mixtures might be able to use nutrients more efficiently and consequently leave fewer resources for weeds (Abraham and Singh, 1984; Tribouillois et al., 2015). Regarding weed suppressive abilities, cereal species are often more effective than legume species (Baraibar et al., 2018; Brainard et al., 2011; Ofori and Stern, 1987), which makes the former preferable components of CC mixtures dedicated to controlling weeds while the latter can add value by fixing nitrogen. It might also be possible to combine CC species with predominant physical or biochemical effects to further enhance the weed control abilities of these mixtures. Poaceae and Brassicaceae species have proven to be allelopathic (Belz, 2007; Hartwig and Ammon, 2002), while others like vetch (*Vicia villosa* Roth) seem to act predominantly via competition (Inderjit and Asakawa, 2001). As the weed control efficiency is dependent on both of these effects, the use of CC mixtures was already advised and examined by several authors (Baraibar et al., 2018; Kunz et al., 2016). One, yet unsolved, issue is how to separate between competition and biochemical effects and their contribution to weed control in the field (Sturm et al., 2018; Tschuy et al., 2014). Another important question is: which traits of CCs are affecting their level of weed control? The usual reasoning that higher biomass production leads to a higher competitive ability and therefore more efficient weed control (Teasdale, 1996) might not hold true in all cases. Several recent studies reported no correlation between biomass and weed reduction (Baraibar et al., 2018; Kunz et al., 2016). There might be other or additional factors that may determine the level of weed control.

Sampling effect and niche complementarity have been examined well in natural plant communities (Hooper et al., 2005; Tilman, 1999), but also to some extend for agricultural systems (Hector et al., 1999; Prieto et al., 2015). All these systems, natural and agricultural alike, perform ecosystem services based on the functions that the plants provide and these are often enhanced if species diversity is increased. A combination of the effects of species mixtures with the multiple advantages that CCs offer, can result in a very productive CC stand. This productivity does not normally lead to a harvest good, but might enhance the services provided by the CCs (Blesh, 2018). How many CC species or which particular traits are necessary to ensure weed control is still under investigation (Baraibar et al., 2018; Finney and Kaye, 2017; Holmes et al., 2017; Wortman et al., 2012). Ultimately, carefully designed species mixtures may be more stable in terms of weed control efficiency and reaction to changing weather conditions than single sown CCs, providing reassurance for the producer. Recognizing this great potential of CC mixtures along with the still scarce knowledge on service provision and reaction to climate, this study investigated the weed control ability of single sown CCs and CC mixtures in two very contrasting years. Within the study, the following hypotheses were investigated: i) CC dry matter does not determine the weed suppression ability; ii) mixtures have a better ability to suppress weeds in comparison to CC monocultures; iii) species-rich mixtures suppress weeds more efficiently than species-poor mixtures.

4.2 Materials and methods

Experimental Sites

The experimental field trials were conducted at the research station of the University of Hohenheim (48.74° N, 8.92° E, 475 m a.s.l.) in Southwest-Germany from August until December 2016 and 2017. After CC sowing in 2016 a long dry period followed. During the cover cropping season in 2017 the frequency and the amount of water provided ideal growing conditions for the CCs (Figure 11).

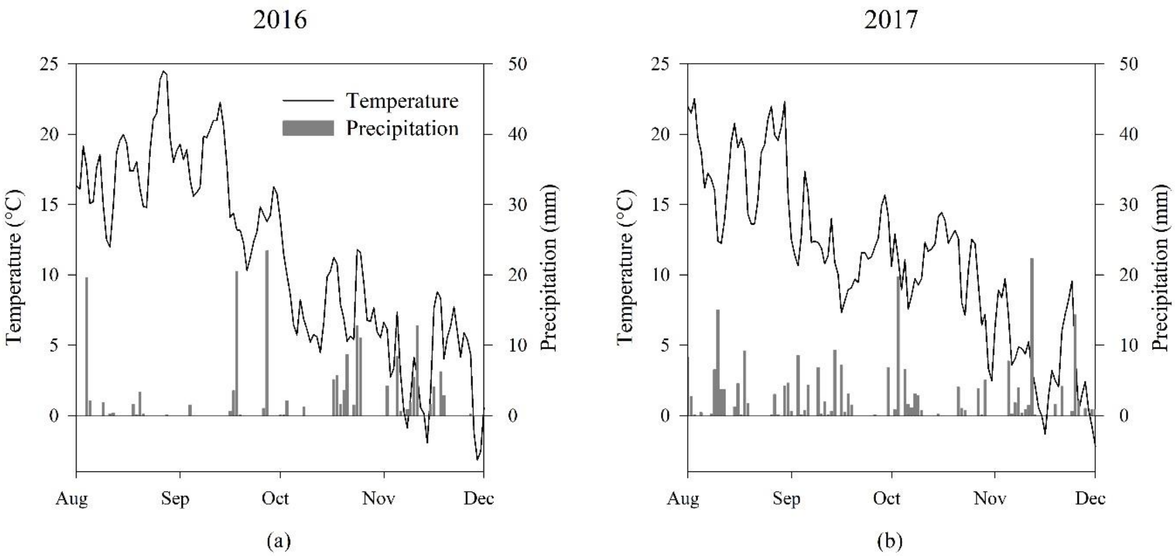


Figure 11. Temperature and precipitation from August to December 2016 (a) and 2017 (b).

The soil type at the field site during the season 2016 was classified as a silty clay (6% sand, 53% silt and 41% clay). During the 2017 season, the field site was classified as a silty loamy soil (27% sand, 48% silt and 25% clay). Table 15 shows details about the crop rotation and field preparations.

Table 15. Experimental set-up and conditions for the field trials in Southwest Germany in 2016 and 2017.

	2016	2017
Crop rotation	Winter wheat-cover crop	Winter barley-cover crop
Cereal harvest date	8 August 2016	5 August 2017
Soil preparation (depth)	Stubble cultivator + deep tillage (15 cm) + power harrow (6-8 cm)	Stubble cultivator + deep tillage (15 cm) + power harrow (6-8 cm)
Sowing date	19 August 2016	25 August 2017
Sowing depth	2 cm	2 cm

Six CCs (provided by Deutsche Saatveredelung AG (DSV)): *Anethum graveolens* L. (*A. graveolens*), *Raphanus sativus* var. *oleiformis* Pers. (*R. sativus*), *Avena strigosa* Schreb. (*A. strigosa*), *Carthamus tinctorius* L. (*C. tinctorius*), *Vicia sativa* L. (*V. sativa*) and *Phacelia tanacetifolia* Benth. (*P. tanacetifolia*) were sown in both years (Table 16) in monocultures and in five mixtures including the same species as for the monocropping treatments. The untreated control treatment was left as a weed fallow without CCs. The mixing ratios refer to the seed weight and recommend seeding densities as for the single sown CCs.

Table 16. Twelve treatments including an untreated control treatment without cover crops, six single sown cover crops and five cover crop mixtures.

Treatment	Crop Species	Seed Density (kg ha^{-1})
Control	Without cover crops	-
A. graveolens	Single sown *Anethum graveolens* L.	25
R. sativus	Single sown *Raphanus sativus* var. *oleiformis* Pers.	25
A. strigosa	Single sown *Avena strigosa* Schreb.	120
C. tinctorius	Single sown *Carthamus tinctorius* L.	40
V. sativa	Single sown *Vicia sativa* L.	100
P. tanacetifolia	Single sown *Phacelia tanacetifolia* Benth.	10
Mixture 1	Mixture with 33% *A. graveolens*, 33% *R. sativus*, 33% *A. strigosa*	57
Mixture 2	Mixture with 33% *P. tanacetifolia*, 33% *C. tinctorius*, 33% *V. sativa*	50
Mixture 3	50% Mixture 1, 50% Mixture 2	53
Mixture 4	20% Mixture 1, 80% Mixture 2	51
Mixture 5	80% Mixture 1, 20% Mixture 2	55

Data Collection

Percent of soil coverage by CCs was estimated four times in a 0.1 m^2 area randomly selected in each plot. Soil coverage was recorded seven (2016) and four times (2017) after sowing until 12 weeks after sowing (WAS). Seven and 12 WAS the weed density and community were determined. Fresh matter of CCs and weeds was cut 7 and 12 WAS within an area of 0.25 m^2. The fresh matter was cleaned with water and afterwards placed in the oven at 100 °C for 24 h to obtain biomass on a dry matter basis.

Data Analysis

The data were analyzed with the software R (Version 3.5.1). Normal distribution and homogeneity of variance were visually checked before analyzing the data. Linear regression was used to test for correlations. A log data transformation, prior to using an analysis of variance (ANOVA), was necessary for the weed density (12 WAS 2017) data. Means of different treatments were compared using the Tukey-HSD test ($p \leq 0.05$). According to Rasmussen (1991), the weed control efficacy (WCE) based on the weed density was calculated as

$$\text{WCE (\%)} = 100 - wt\,(0.01 \text{ x } wc)^{-1} \qquad (3)$$

where by *wt* is the weed density (weeds m^{-2}) of the weed management treatments and *wc* the weed density (weeds m^{-2}) of the untreated control.

4.3 Results

Cover Crop and Weed Development

At the beginning of the CC growing season in 2016, the *R. sativus* and *P. tanacetifolia* treatments displayed the highest soil cover among the single sown CCs (Figure 12). The *P. tanacetifolia* treatment had the highest soil cover (79%) during the beginning of November while *R. sativus* reached a maximum of 50% soil cover during this same period. In 2017, the *A. strigosa* and the *P. tanacetifolia* treatments reached the highest soil cover among all treatments with a maximum of 92 and 83%, respectively, in late November. The mixtures generally showed less soil cover than the best performing single sown CC treatments in both years. The soil cover of the mixtures was generally quite homogeneously distributed and ranged between 39-67% (4 November) in 2016 and 68-79% (15 November) in 2017.

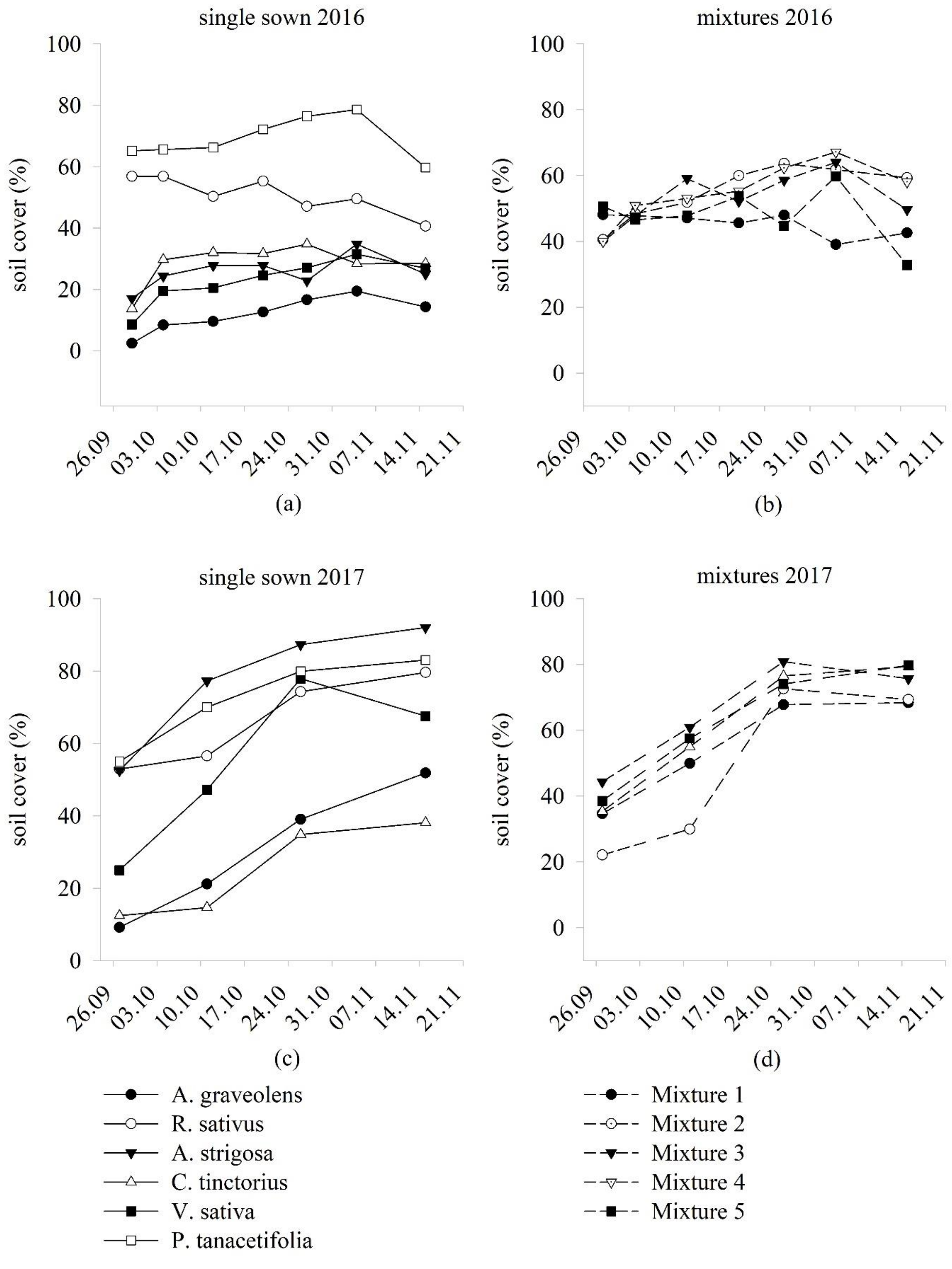


Figure 12. Cover crop soil cover (%) for the six single sown cover crops (a,c) and the five mixtures (b,d) from the end of September until the end of November in 2016 (a,b) and 2017 (c,d). Dates in the *x*-axis in the format dd.MM.

In both years, volunteer crops like *Brassica napus* L. (2016), *Triticum aestivum* L. (2016) and *Hordeum vulgare* L. (2017) belonged to the dominant weeds. Dicotyledonous weeds were the dominant weed species in addition to volunteer crops. In 2016, the dominant weed species were *Galium aparine* L., *Chenopodium album* L., *Veronica persica* Poir. and *Capsella bursa-pastoris* (L.) Medik.. In 2017, there was a broader species diversity, including species like *Matricaria spp.*, *Lamium purpureum* L., *Capsella bursa-pastoris* (L.) Medik., *Veronica persica* Poir., *Stellaria media* Vill., *Chenopodium album* L. and *Cirsium arvense* (L.) Scop. The untreated control treatment in 2016 showed a mean weed infestation of 62.5 plants m^{-2} (Table 17). In 2017, the untreated control showed a 10-times higher (678.8 plants m^{-2} 12 WAS) weed density than in 2016. In 2016, the significantly lowest number of weeds was counted in the *R. sativus* (13.1 plants m^{-2}) and Mixture 4 (14.4 plants m^{-2}) treatments. In 2017, the significantly lowest number of weeds was observed in the *A. strigosa* treatment with 112.5 plants m^{-2}. Similarly, high weed densities as in the untreated control were counted in the *A. graveolens*, *C. tinctorius* and *V. sativa* treatments, which had shown a generally weak performance within the two years regarding CC soil cover and CC dry matter. There were no significant differences between any treatments concerning total weed density 7 WAS in 2017.

Table 17. Total weed density for the six single sown and five cover crop mixtures 12 weeks after sowing in 2016 and 2017. Different capital letters within one column show significant differences according to Tukey-HSD test ($p \leq 0.05$).

Treatments	**Total Weed Density (Plants m^{-2})**	
	2016	2017
Control	62.5 ^{A}	678.8 ^{A}
A. graveolens	49.9 ^{AB}	433.8 ^{ABC}
R. sativus	13.1 ^{C}	196.6 ^{BC}
A. strigosa	29.4 ^{BC}	112.5 ^{C}
C. tinctorius	41.9 ^{ABC}	452.5 ^{ABC}
V. sativa	37.5 ^{ABC}	483.8 ^{AB}
P. tanacetifolia	20.0 ^{BC}	382.5 ^{ABC}
Mixture 1	30.0 ^{BC}	168.8 ^{BC}
Mixture 2	25.6 ^{BC}	370.0 ^{ABC}
Mixture 3	28.8 ^{BC}	326.3 ^{ABC}
Mixture 4	14.4 ^{C}	237.5 ^{ABC}
Mixture 5	27.5 ^{BC}	272.5 ^{ABC}

The weed densities 12 WAS in 2016 and 2017 showed a correlation with an R^2 of 0.58. The regression between those two parameters was significant ($p = 0.004$), which shows that the occurrence of weeds within the treatments was not random within both years.

Due to the four weeks of drought after sowing in 2016, the CCs were only sparsely developed 7 WAS (Figure 13a). The *R. sativus* treatment reached the significantly highest aboveground dry matter (1210 kg ha^{-1}) 7 WAS in 2016. Except for the *A. graveolens* and Mixture 2 treatment, all treatments were able to significantly reduce the dry matter amount of weeds (7 WAS) compared to the untreated control. The generally low weed infestation and the poor growing conditions in 2016 season led to a maximum weed dry matter of 206 kg ha^{-1}.

None of the CC treatments were able to show a significantly lower weed dry matter than the untreated control 12 WAS in 2016 (Figure 13b). The *R. sativus* and *P. tanacetifolia* treatments reached the significantly highest amount of CC dry matter within the single sown species with 1626 and 2068 kg ha^{-1}, respectively. Among all treatments, Mixture 2 and 3 achieved with 2396 and 2350 kg ha^{-1} the highest amount of CC dry matter.

The amount of weed dry matter of the untreated control 7 WAS in 2017 was, with 467 kg ha^{-1}, almost twice as high as 7 WAS in 2016 (Figure 13c). Among the single sown CCs, only the treatments *R. sativus* and *A. strigosa,* with 1247 and 1450 kg ha^{-1} aboveground dry matter, respectively, were able to significantly reduce the amount of weed dry matter compared to the untreated control 7 WAS in 2017. Compared to the untreated control all mixtures, except for Mixture 2, significantly reduced the weed dry matter.

In 2017, the *P. tanacetifolia* treatment had the highest amount of CC dry matter with 2247 kg ha^{-1} but did not significantly reduce the amount of weed dry matter compared to the untreated control 12 WAS (Figure 13d). The treatment *A. strigosa* showed the lowest amount of weed dry matter with 97 kg ha^{-1} among all treatments and reached an aboveground dry matter of 2197 kg ha^{-1}. The mixtures, except for Mixture 4, were able to significantly reduce the dry matter of weeds compared to the untreated control, but showed generally lower numbers of CC dry matter compared to the previous year, reaching a maximum of 1674 kg ha^{-1} (Mixture 1).

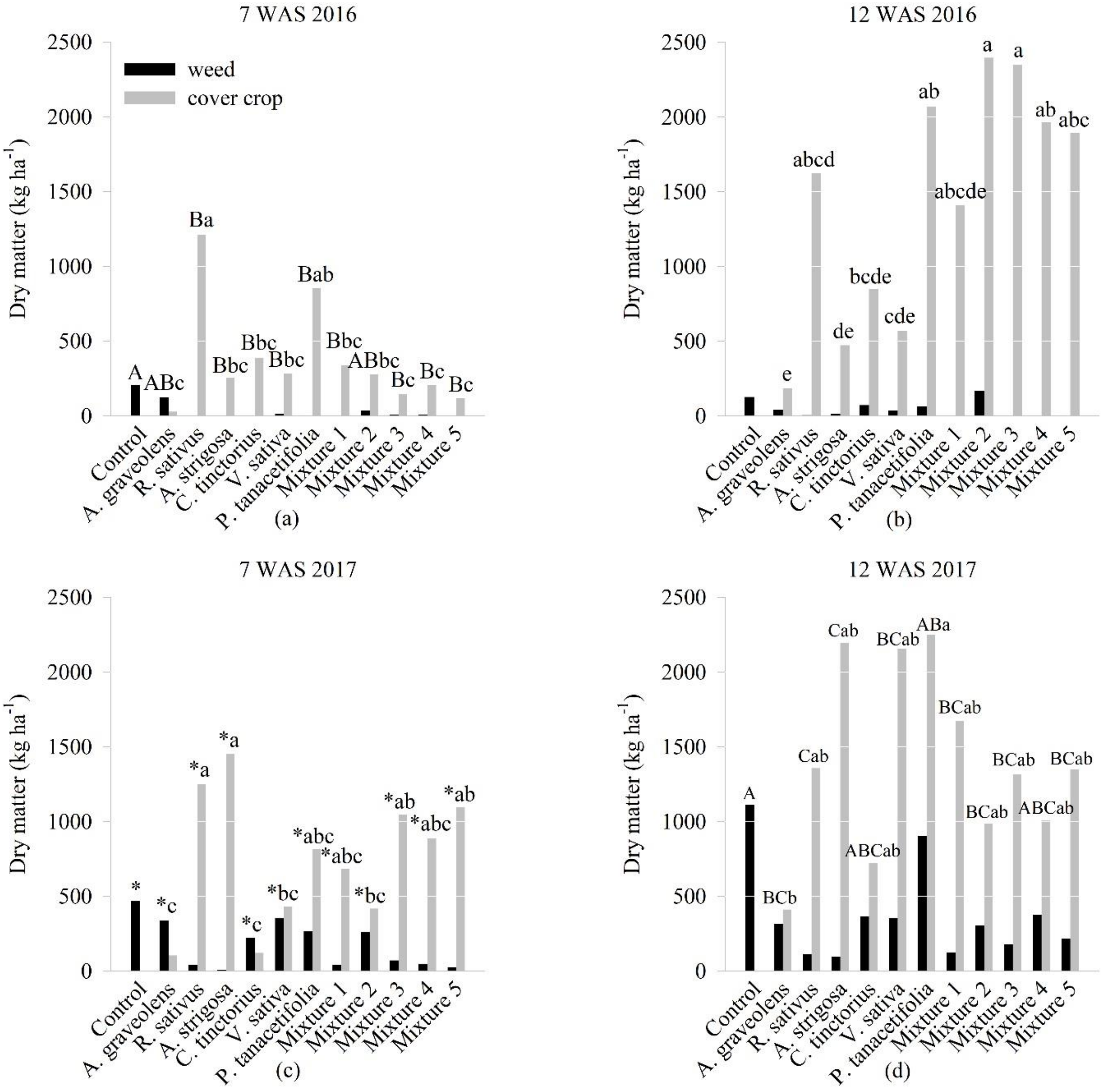


Figure 13. Cover crop (grey) and weed (black) aboveground dry matter in kg ha^{-1} for the six single sown and five cover crop mixtures 7 weeks after sowing (WAS) in 2016 (a)/2017 (c) and 12 WAS in 2016 (b)/2017 (d). Different small letters within one graph show significant differences concerning the cover crop dry matter according to Tukey-HSD test ($p \leq 0.05$). Different capital letters within one graph show significant differences concerning the weed dry matter according to Tukey-HSD test ($p \leq 0.05$). Means for weed dry matter with no capital letters do not differ significantly. * Due to space limitations in the graph (c): Control ^{A}, *A. graveolens* ^{ABC}, *R. sativus* ^{BCD}, *A. strigosa* ^{D}, *C. tinctorius* ^{ABCD}, *V. sativa* ^{AB}, *P. tanacetifolia* ^{ABCD}, Mixture 1 ^{BCD}, Mixture 2 ^{ABCD}, Mixture 3 ^{BCD}, Mixture 4 ^{BCD}, Mixture 5 ^{CD}.

Weed Control Efficacy

In 2016, among the mixtures, the highest WCE was reached 12 WAS by the Mixture 4 treatment with 47% (Figure 14). Across all treatments, the *R. sativus* treatment had the highest WCE with

60%. The highest WCE 12 WAS in 2017 among all treatments was reached by the *A. strigosa* treatment with 83% followed by the treatments Mixture 1 and *R. sativus* with 75% and 72%, respectively. The differences in WCE between the treatments were not significant in 2016 and 2017 (12 WAS).

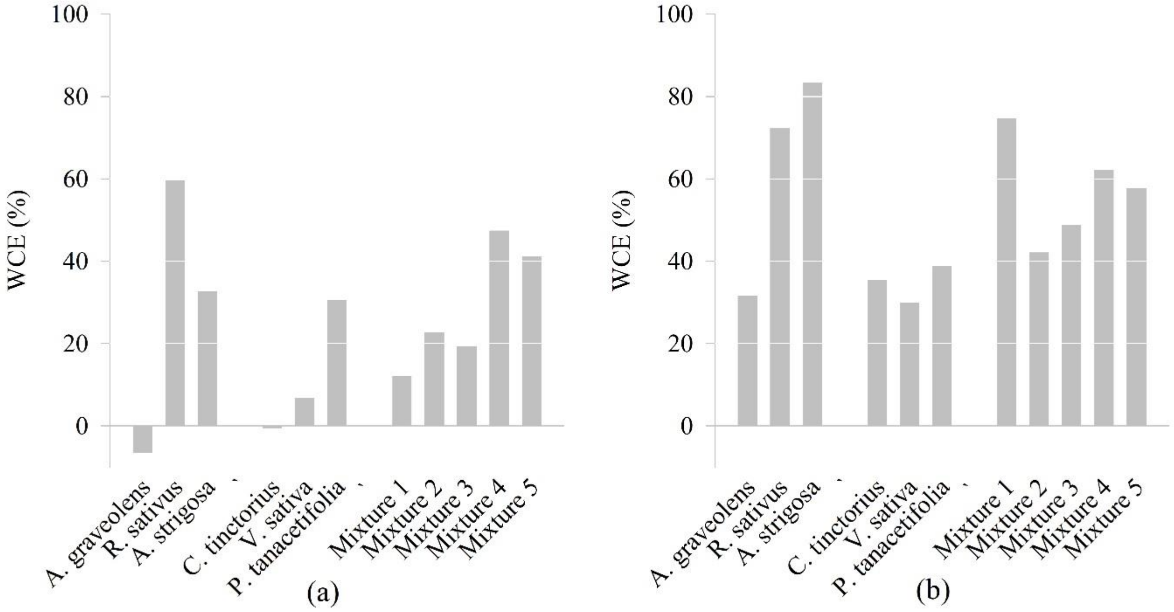


Figure 14. Weed control efficacy (WCE) of the six single sown and five cover crop mixtures 12 weeks after sowing in 2016 (a) and 2017 (b). Means with no letters do not differ significantly according to Tukey-HSD test ($p \leq 0.05$).

4.4 Discussion

The highest WCE within both years was achieved by the *A. strigosa* treatment with 83% (12 WAS in 2017). Brust and Gerhards (2012) showed a similarly high weed suppression ability of *A. strigosa* with 90%. CCs seem to be able to significantly reduce the number of weeds but have not shown complete weed control within this study due to a severe drought period after sowing in 2016 and the generally high weed infestation in the 2017 season.

As expected, the CC dry matter is not necessarily a predictor of the weed suppression ability. No correlations between CC biomass and weed dry matter/density were determined. This agrees with Kunz et al. (2016) and Baraibar et al. (2018) who also did not find correlations between CC dry matter and weed density. Finney et al. (2016) pointed out that biomass driven CCs do generally have a more effective weed suppression potential. However, it seems like this is only relevant to a certain extent. Gfeller et al. (2018) name the threshold of 3 t ha^{-1}, until which the

CC biomass and the suppression of *Amaranthus retroflexus* L. were negatively correlated. Onwards, other parameters, like chemical or other physical parameters might have a higher importance to contribute to an efficient weed control. Within their study, also some CCs with low biomass yields, like Brassicaceae and *A. strigosa*, were able to achieve an efficient weed control against *Amaranthus retroflexus* L. (Gfeller et al., 2018). This agrees with the data presented for the season 2016, whereby the *A. strigosa* treatment reached a WCE of 33% (average WCE across all treatments: 24%), with a simultaneously low amount of dry matter. This might be attributed to the allelopathic potential of *A. strigosa* (Gfeller et al., 2018; Rueda-Ayala et al., 2015). *R. sativus* was, within the experiment, one of the most efficient single sown CC, reaching an average WCE within the two seasons of 66% (12 WAS). *R. sativus* is able to reach weed suppression efficacies of more than 90% (Brust, Claupein et al., 2014; Sturm et al., 2017) under ideal conditions and sowing dates. This is probably caused by the relatively high dry matter production (negative correlation between weed and brassica CC biomass (Baraibar et al., 2018)) and the well-reported allelopathic potential of Brassicaceae species (Haramoto and Gallandt, 2005; Petersen et al., 2001).

Additionally, Brennan and Smith (2005) and Dorn et al. (2015) suggest that rapid plant development after sowing is more important than the final CC biomass (Baraibar et al., 2018). For some examples, these results can be referred to the data presented. In late September 2017, the treatments *R. sativus*, *A. strigosa* and *P. tanacetifolia* showed the highest soil cover with 52-55%. Both, the *R. sativus* and the *A. strigosa* treatment achieved the highest WCE among the single sown CCs with 72% and 83%, respectively. In contrast, the *P. tanacetifolia* treatment, even though biomass and soil cover were well developed, performed as poorly as the very weak established treatments *A. graveolens* and *C. tinctorius* with less than 13% of soil cover.

The mixtures were not more efficient at suppressing weeds than the monocultures, which agrees with several studies (Baraibar et al., 2018; Brust, Weber et al., 2014; Finney et al., 2016; Smith et al., 2014). The most efficient single sown CCs showed a higher suppression ability than the most efficient mixture in both years, which is also shown by (Smith et al., 2014). According to Baraibar et al. (2018), CC mixtures containing grasses are more efficient to suppress weeds than monocultures with Brassicaceae species or legumes. Within both years, all mixtures were clearly more efficient at suppressing weeds than *V. sativa*. This can be inferred from the studies of Baraibar et al. (2018) and Hayden et al. (2012), who conclude that CCs with early canopy closing, to which vetch does not belong, generally show better weed suppression. In 2016, the *R. sativus* treatment reached the highest WCE with 60%, while in 2017 the Mixture 1 and the

R. sativus treatment showed a similar WCE of 75% and 72%, respectively. All other mixtures only reached a WCE between 42% and 62%. Finney et al. (2016) state as a reason that highly productive single sown CCs may produce as much biomass as diverse species mixtures. In October 2016 and 2017, particularly the single sown treatments like *R. sativus* and *P. tanacetifolia* were achieving higher dry matter yields than the mixtures. However, as discussed, the biomass of CC monocultures and mixtures is not, or only weakly, related to the weed suppression potential. Generally, species-specific mechanisms for weed suppression are still not well understood. How different mechanisms of weed suppression act or interact also need further investigation (Baraibar et al., 2018). Even though mixtures might not be an improved tool for weed management in cover cropping systems, many other benefits are attributed to CC mixtures. In consideration of the dry matter, soil cover and the reduction of weeds during the 2016 season, the mixtures showed the ability to withstand unfavorable weather conditions better than many of the single sown CCs. The resilience of mixtures towards severe weather conditions or management errors (Wortman et al., 2012), might compensate their less efficient weed control compared to monocultures. However, only high crop densities are an effective tool for weed suppression (Weiner et al., 2010). As species mixtures follow the idea to be able to buffer the failure of other species, increasing the sowing density of all species included in the mixture should be considered. This might be relevant in order to achieve similar crop stands under unfavorable conditions than within well-performing single sown treatments, resulting in an improved weed suppression potential.

The six species mixtures (Mixture 3-5) did not show a more efficient weed suppression potential than the three species mixtures (Mixture 1-2). As demonstrated by Kunz et al. (2017), a five species mixture was not better than a mixture with seven species in terms of weed control. This leads to the conclusion that the quantity of plant species within a mixture is less relevant than the mixture composition. Brassicaceae and Poaceae species, for example, respond well to dry conditions, while Fabaceae species do not (Tribouillois et al., 2016). Mixture 1, with *R. sativus*, *A. strigosa* and *A. graveolens* showed the best weed control performance and was able to significantly reduce the weed density in both years compared to the control. Baraibar et al. (2018) concluded that a high proportion of grass species achieves a large reduction of weed biomass, as grass species are also highly suppressive in monocultures. Mixtures with an increasing proportion of rye were able to decrease the weed biomass as observed by Akemo et al. (2000). This might be the reason why Mixture 1 with the highest proportion of *A. strigosa* performed best, while Mixture 2, as the only mixture without grass species, showed a comparably slow soil cover and weak WCE in 2017. Mixture 3-5 with different proportions of *A. strigosa* showed a reliable establishment and an adequate weed suppression ability. Sufficient weed control might already be provided by low proportions of grass species within mixtures, meanwhile other species may fulfill important ecosystem services (Baraibar et al., 2018).

4.5 Conclusions

Out of the two years of data presented, *R. sativus* and *A. strigosa* are the two most promising single sown CCs, because they showed a fast establishment along with the highest weed suppression potential. In order to fulfill the requirements of diverse ecosystem services and weed control, CC mixtures like Mixture 1 seem to be suitable for cover cropping. In general, mixtures need to be composed reasonably in order to avoid weed problems caused by poorly competitive species (McLaren et al., 2019). Combing CC species with physical and chemical weed suppression mechanisms may increase the weed control success. Species with chemical mechanisms thereby, for example, contribute to an efficient weed control under unfavorable circumstances when CC development and biomass yield is low. CC mixtures might substantially contribute to the success of biological weed control if the weed suppression mechanisms of different plant species and their ideal composition within mixtures can be identified.

Author Contributions: Conceptualization, A.S. and M.S.; Formal analysis, A.S.; Investigation, A.S.; Methodology, A.S.; Supervision, R.G.; Visualization, A.S.; Writing-original draft, A.S. and M.S.; Writing-review & editing, R.G.

Funding: This research was financially supported by the “Ministerium für Ländlichen Raum, Ernährung und Verbraucherschutz Baden-Württemberg (MLR)” within the project “Conservation Agriculture” and the Research Training Group “Water-People-Agriculture” at the University of Hohenheim funded by the Anton & Petra-Ehrmann foundation.

Acknowledgments: Thanks to the support from the research station “Ihinger Hof” and the Weed Science group of the University of Hohenheim. Thanks to Jacob Weiner for his constructive comments concerning the analysis and visualization of the data. Additionally, we thank Gerassimos G. Peteinatos for manuscript revision and Charlotte Hein for data acquisition.

Conflicts of Interest: The authors declare no conflict of interest.

Chapter 5

Weed suppressive ability of cover crops under water-limited conditions

Alexandra Schappert[1], Alexander I. Linn[1], Dominic J. Sturm[1] and Roland Gerhards[1]

[1] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany

Published in: *Plant, Soil and Environment* (2019), 65, 541-548

The original publication is available at:
https://doi.org/10.17221/516/2019-PSE

5 Weed suppressive ability of cover crops under water-limited conditions

Alexandra Schappert[1], Alexander I. Linn[1], Dominic J. Sturm[1] and Roland Gerhards[1]

[1] Department of Weed Science, Institute of Phytomedicine, University of Hohenheim, 70599 Stuttgart, Germany

Abstract

The water demand of cover crops (CC) should be considered in order to achieve competitive crop stands for weed control also under unfavorable conditions. This study aims to estimate the weed suppressive ability of winter CC, as *Sinapis alba L.*, *Phacelia tanacetifolia* Benth., *Vicia sativa* L. and *Avena strigosa* Schreb., under a water-limited regime. The water deficit tolerance of different CC was determined in a greenhouse experiment by measuring the maximum quantum efficiency of photosystem II. Moreover, soil moisture, CC, and weed establishment were measured within field experiments in Southwest-Germany during two contrasting growing seasons in 2016 and 2017. *A. strigosa* showed a higher water deficit tolerance than *S. alba* in the greenhouse. In the field, *A. strigosa* showed the highest weed cover reduction (98%) in the field, along with an increasing effect on the soil moisture compared to the untreated control. *S. alba* performed most sensitive to water deficit in the greenhouse but reached the significantly highest weed control efficacy (94%) during the dry field season in 2016. Even though the selected CC showed differing sensitivities to water deficit in the greenhouse, their weed suppression ability was independent of the water supply under field conditions.

Keywords: abiotic stress; catch crop; chlorophyll fluorescence; weed management; water balance

5.1 Introduction

The increasing interest on cover crops (CCs) is caused by their associated benefits (Snapp et al., 2005) like weed suppression (Teasdale and Mohler, 2000), nutrient recycling efficiency, soil erosion reduction (Snapp et al., 2005) and cash crop productivity (Abdin et al., 2000). However, CCs may change the water balance significantly (Ward et al., 2012). In water-limited regions, producers do not opt integrating winter CCs between two cash crops, as CCs might decrease the restoration of soil water resources, which may lead to a lower soil water content for the following spring crop (Wortman et al., 2012).

If negative effects on the following cash crop are not expected, single CCs or cover crop (CC) mixtures are a suitable weed control measure during the fallow period from fall to spring. CCs suppress weeds during cultivation by competition for resources and by releasing biochemical compounds (Gfeller et al., 2018). To increase the weed control ability of CCs, an early CC establishment in fall, in combination with high biomass production and complete soil coverage, are targeted (Brennan and Smith, 2005; Finney et al., 2016). To achieve appropriate CC stands, CCs need to be resilient to abiotic stresses, including water deficits, as the probability of extreme weather events seems to rise due to climate change (IPCC, 2014).

This study aims to estimate the water demand of some commonly used winter CCs in Germany and their weed suppressive ability under moist and water-limited conditions. *Vicia sativa* L. (Fabaceae) has quite low habitat requirements and even increases water infiltration rates (Decker et al., 1994) but seem to respond sensitively to dry conditions (Tribouillois et al., 2016). *Phacelia tanacetifolia* Benth., which belongs to the family of Hydrophylaceae, requires higher water potentials for germination and prefers, as *V. sativa*, mild temperatures (below 30 °C) for germination (Tribouillois et al., 2016). In comparison, *Raphanus sativus* var. *oleiformis* Pers. and *Sinapis alba* L., which belong to the family of Brassicaceae and *Avena strigosa* Schreb. (Poaceae) seem to be more tolerant to water deficits during germination (Tribouillois et al., 2016). This study evaluates how these CCs are affected by water deficit and if themselves contribute to lower soil moisture contents compared to the control without CCs. Thereby, the following questions were addressed: (i) Do *P. tancacetifolia*, *S. alba* and *A. strigosa* show differing sensitivities to water deficit in greenhouse and field experiments; (ii) is the water stress tolerance of CCs determining their weed suppression ability, and (iii) is the soil moisture content from fall to winter affected by cover cropping.

5.2 Material and methods

Greenhouse experiment: Experimental set-up

A greenhouse pot trial was conducted twice to assess the tolerance to water deficit of *S. alba, P. tanacetifolia*, and *A. strigosa*. A randomized complete block design with 4 repetitions per treatment was used. The greenhouse temperature was set to 20/14°C day/night at a 12 h photoperiod. To receive a unique set of plants, plants were pre-grown in vermiculite until the second leaf was unfolded. At this time, three seedlings of one species were transplanted to one plastic pot (7 x 7 x 8 cm), which was filled with 350 g of soil (60% sand, 28.7% silt, and 11.3% clay). One pot served as one repetition. After transplanting, plants were grown 7 days with full water supply. The trial consisted of 15 treatments of different periods without irrigation. The durations without irrigation ranged from 1 to 14 consecutive days without water supply. Whereby, e.g., treatment 2 and 14 were not irrigated for 2 and 14 days, respectively. A control, which was irrigated throughout the whole trial period, was included. Each pot of the respective treatment was irrigated with 30 mL of water until field capacity after reaching the first day of irrigation and every second day afterward.

Before the first time of irrigation, the maximum quantum efficiency of photosystem II (Fv/Fm) was determined with an Imaging PAM M-Series chlorophyll fluorometer (Heinz Walz GmbH, Effeltrich, Germany) to receive information on the physiological plant status at the end of the water-limited period. Before the measurements, plants were dark acclimated for 30 min. Afterward, the ground fluorescence (Fo) and the maximum fluorescence (Fm) were determined. The variable fluorescence (Fv) was calculated by subtracting Fo from Fm. The Fv/Fm value was calculated as:

$$\mathrm{Fv/Fm} = (\mathrm{Fm} - \mathrm{Fo})\ \mathrm{Fm}^{-1} \tag{4}$$

The Fv/Fm value is a commonly used parameter to receive information on the photosynthetic efficiency (Baker, 2008). It can be used to quantify plant stress in plants of diverse origin (Rosenqvist and van Kooten, 2003). In healthy conditions, the Fv/Fm value is ~ 0.8 (Björkman and Demmig, 1987), while lower values indicate plant stress.

Field experiments: Experimental and meteorological conditions

Two field experiments were conducted in Southwest-Germany at the research station of the University of Hohenheim (48.74°N, 8.92°E, 475 m a.s.l.) near Renningen from August until December in 2016 and 2017. The soil at Experiments 1 and 2 in 2016 was classified as a silty clay (6% sand, 53% silt, and 41% clay). Soil texture of 6% sand, 65% silt and 29% clay was indicated at Experiment 1 in 2017. In 2017, the soil type at Experiment 2 was a silty loam (27% sand, 48% silt and 25% clay). The monthly weather details and the water balance are shown in Table 18. The daily water balance (D, mm) was calculated as:

$$D = P - ET_o \tag{5}$$

While P is the precipitation (mm) and ET_o the crop reference evapotranspiration (mm). ET_o was calculated using the ET_o calculator version 3.2 (FAO 2012). The soil textures, crop rotations, and field preparations for Experiments 1 and 2 are shown in Table 19.

Table 18. Mean temperature, total precipitation, water balance and total crop reference evapotranspiration (ET_o).

Year	**Month**	**Temperature** (C°)	**Precipitation** (mm)	**ET_o** (mm)	**Water Balance** (mm)
2016	July	18.1	64.8	115.7	-50.9
	August	17.8	29.3	107.9	-78.6
	September	16.4	50.6	76.7	-26.1
	October	8.1	53.3	26.9	26.4
	November	3.6	48.7	11.7	37.0
	Total	**12.8**	**246.7**	**338.9**	**-92.2**
2017	July	18.1	109.9	109.9	0.0
	August	18.1	69.3	94.5	-25.2
	September	12.1	52.2	52.7	-0.5
	October	10.8	51.1	37.2	13.9
	November	4.2	63.0	11.9	51.1
	Total	**12.7**	**345.5**	**306.2**	**39.3**

Table 19. Experimental set-up and conditions of the field trials.

	2016		2017	
	Experiment 1	**Experiment 2**	**Experiment 1**	**Experiment 2**
Crop rotation	winter wheat - cover crop		winter wheat – cover crop	winter barley – cover crop
Cereal harvest date	08/08/2016		10/08/2017	05/08/17
Soil preparation (depth)	stubble cultivator + deep tillage (15 cm) + power harrow (6 - 8 cm)		stubble cultivator + deep tillage (15 cm) + power harrow (6 - 8 cm)	
Sowing date	19/08/2016		25/08/2017	
Sowing depth (cm)	2		2	
Soil texture	silty clay		silty clay loam	silty loam

Set-up and data acquisition of Experiment 1

Experiment 1 was conducted with 3 treatments and 8 replications within a randomized complete block design. In 2016 and 2017, *S. alba*, *P. tanacetifolia*, and *A. strigosa* (Deutsche Saatveredelung AG (DSV), Lippstadt, Germany) were sown in pure stands with seed densities of 25, 10 and 120 kg ha^{-1}, respectively within 30 m^2 plots. A control treatment without CCs was included. The weed flora was determined 7 weeks after sowing (WAS). CC and weed dry matter were measured by harvesting, washing, and drying 0.25 m^2 fresh material 7 WAS.
According to Rasmussen (1991), weed control efficacy (WCE) was calculated as:

$$\text{WCE (\%)} = 100 - wt\,(0.01 \text{ x } wc)^{-1} \tag{6}$$

Where: *wt* - weed dry matter (kg ha^{-1}) of the CC treatments; *wc* - weed dry matter (kg ha^{-1}) of the control without CCs.

Set-up and data acquisition of Experiment 2

R. sativus, *V. sativa*, *P. tanacetifolia,* and *A. strigosa* were sown, in 2016 and 2017, in 60 m^2 plots with seed densities of 25, 100, 10 and 120 kg ha^{-1}, respectively. Experiment 2 was set up as a randomized complete block design with four replications. Within the control treatment, no CC was sown. Soil moisture contents were measured within one tube per plot by a frequency domain reflectometry device called PR2 probe (Profile Probe; Delta-T Devices Ltd., Burwell, UK). The soil cover of CCs and weeds were estimated four times per plot with a metal frame, covering an area of 0.25 m^2, 7 WAS. The weed community was also determined 7 WAS.

Data analysis (field and greenhouse experiments)

The software R (version 3.5.1, R Foundation for Statistical Computing, Vienna, Austria) was used for data analysis. The data were visually checked for normal distribution and homogeneity of variance. Based on the Fv/Fm values, dose-response curves were calculated with a three parametric log-logistic model and checked for fit with a lack-of-fit test (Ritz et al., 2015). To receive differences in the resilience to water deficit of the different CCs, the duration for a reduction of 50% in the Fv/Fm value (TE_{50}) was calculated. An analysis of variance (ANOVA) was performed for the TE_{50} and the ground truth field data collected for the field Experiments 1 and 2. Differences, of the treatment means, were obtained using a Tukey-HSD (honestly significant difference) test with $p \leq 0.05$.

5.3 Results and discussion

Within the greenhouse experiment, *S. alba* showed the highest sensitivity to water scarcity (Figure 15) and reached TE_{50} already after 12.3 days without irrigation, whereas *A. strigosa* reached TE_{50} after 14.6 days. *P. tanacetifolia* showed the significantly highest tolerance to water deficit and exhibited a TE_{50} to 15.9 days without irrigation.

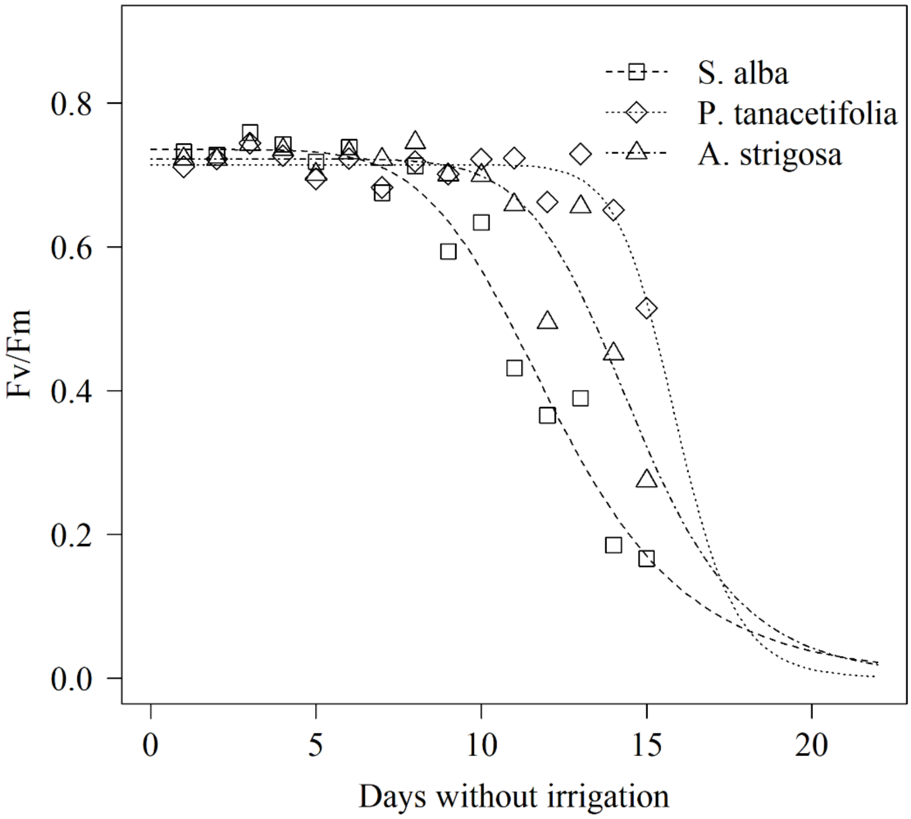


Figure 15. Dose-response curves of the maximum quantum efficiency of the photosystem II (Fv/Fm) response of *Sinapis alba* L., *Phacelia tanacetifolia* Benth. and *Avena strigosa* Schreb. to days without irrigation.

A similar weed community composition was noticed in the experimental field for both the experiments. In 2016, volunteer crops (Experiment 1 and 2: winter wheat) and annual broad-leaved weeds like *Capsella bursa-pastoris* M., *Chenopodium album* L., *Galium aparine* L. and *Lamium purpureum* L dominated the weed community. In 2017 at Experiment 1, *C. album*, *G. aparine*, *Stellaria media* L. and volunteer crops (winter wheat) were dominating. *C. bursa-pastoris*, *L. purpureum*, M*atricaria spp.* and volunteer crops (winter barley) were predominant in the weed flora of Experiment 2 in 2017. The field sites showed a water equilibrium of -92.2 mm in 2016 (from July until November) and a positive water equilibrium in 2017 with 39.3 mm within the same months (Table 18). The amount of water, which was lost by ET_o in 2016, exceeded the amount of precipitation throughout the whole season (Figure 16). Due to the water deficit in 2016, the maximum amount of dry matter with 1002 kg ha^{-1} (*S. alba*) in Experiment 1 was almost 60% lower than the maximum amount of dry matter in 2017 (*S. alba*) (Figure 17).

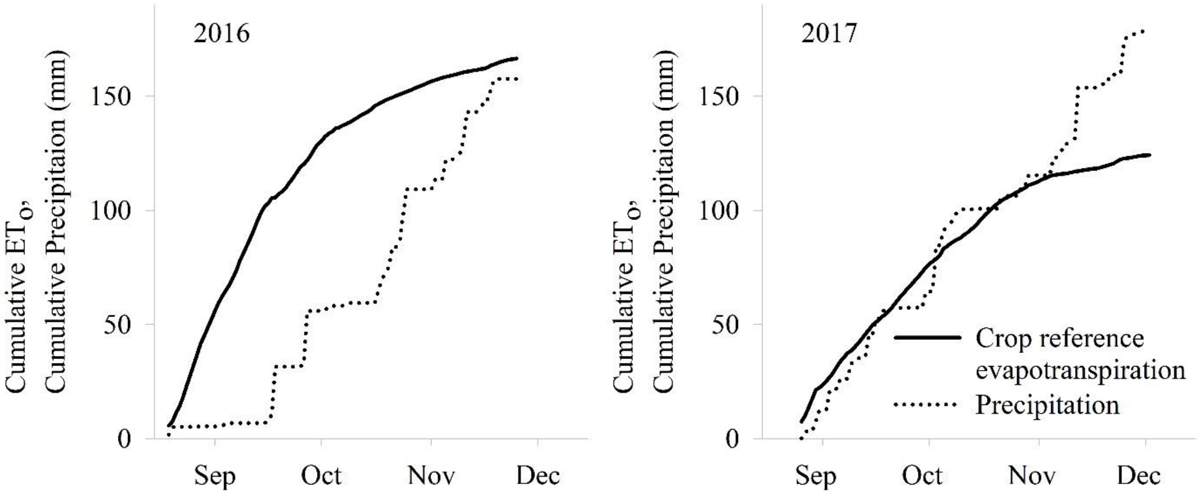


Figure 16. Cumulative reference crop evapotranspiration (ET$_o$) and precipitation from August until December 2016 and 2017.

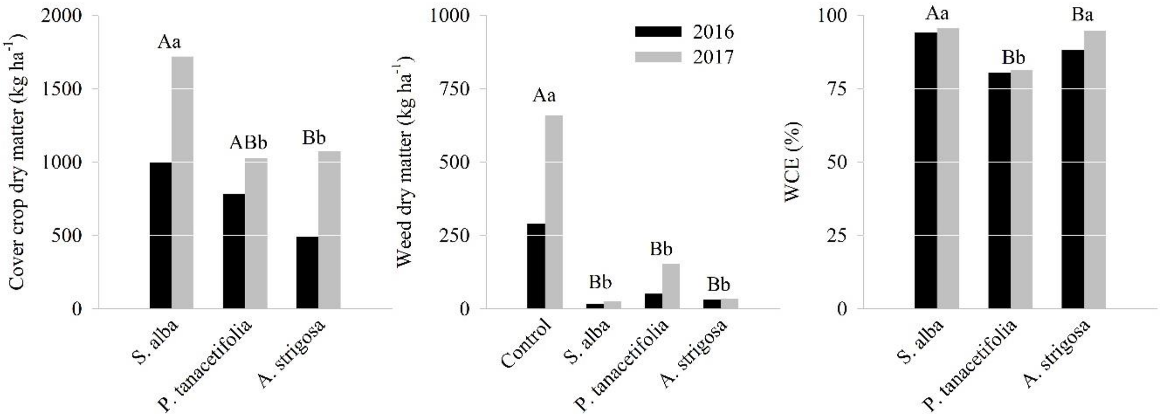


Figure 17. Cover crop dry matter, weed dry matter, and weed control efficacy (WCE) 7 weeks after sowing (Experiment 1). Capital letters within one graph show significant differences in 2016, according to Tukey-HSD (honestly significant difference) test ($p \leq 0.05$). Small letters within one graph show significant differences in 2017, according to Tukey-HSD test ($p \leq 0.05$).

Even though the highest sensitivity to water scarcity was measured for *S. alba* in the greenhouse, *S. alba* was unimpaired by water deficits in the field. This is consistent with literature where mustard is described as drought-tolerant (Brown et al., 2005; Tian et al., 2014). Bodner et al. (2007) found that *S. alba*, when used as a CC, shows high evapotranspiration losses compared to CCs like vetch and phacelia. However, according to their study, *S. alba* compensates for these water loss with a high biomass production, which increased the competitions with weeds. the field, *S. alba* showed the lowest weed dry matter and highest WCE with ~96% in both years (Experiment 1). This result agrees with other studies that also suggest *S. alba* as being suitable as an efficient weed control measure. Brust, Claupein et al. (2014) and Kunz et al. (2016) showed a weed density reduction between 57–59% compared to the no-CC control. Björkman et al. (2015) showed a reduction of more than 50% in 9 of 10 study cases with weed biomass reductions by up to 99% by *S. alba* as compared to the untreated control. *A. strigosa* reached a similar WCE with 95% (Experiment 1 in 2017) and the highest reduction of weed coverage as compared to the control with 98% (Experiment 2 in 2017 (Figure 18)).

V. sativa was also able to significantly reduce the weed coverage as compared to the control in 2017. Nevertheless, following Baraibar et al. (2018), *V. sativa* showed a weaker weed suppression potential than the Brassicaceae or Poaceae species. Also, Nielsen et al. (2015) indicated that grasses are more competitive than legumes. Additionally, *V. sativa* is being expected to be more sensitive to drought during germination (Constantin, Dürr et al., 2015). *P. tanacetifolia* showed the highest tolerance to water deficit in the greenhouse. While producing a similar amount of dry matter per unit area as *A. strigosa* (Experiment 1 in 2017), *P. tanacetifolia* demonstrated a significantly weaker WCE than *S. alba* and *A. strigosa*. Additionally, *P. tanacetifolia* exhibited a great level of coverage ability (62%) in 2016 and decreased weed coverage by 67%. However, it was only as efficient as *R. sativus*, with only 42% of soil coverage (Figure 18). In conclusion, CCs are attributed to an efficient weed suppression potential if they are strong resource competitors, show an early CC canopy development (Brennan and Smith, 2005) and produce a certain biomass amount (Finney et al., 2016; Gfeller et al., 2018). However, biochemical weed suppression mechanisms of CCs, as attributed to, e.g., the family of Brassicaceae or Poaceae (Belz, 2007), seem to contribute substantially to the weed suppression success. The weed suppressive effects of *A. strigosa* are reported to be considerably during cultivation and afterward (Brust and Gerhards, 2012; Price et al., 2006; Schappert et al., 2019). *A. strigosa* showed a great weed suppression potential during the dry season, even though the dry matter production of *A. strigosa* was quite low. Plant stress, as, e.g., induced by water deficits, may enhance the allelopathic potential (Einhellig, 1996), which might have contributed to efficient weed control by *A. strigosa* during the dry season in 2016.

Although allelopathy seems to contribute to weed control during CC cultivation, its effects on the subsequent cash crop should not be neglected. It is reported by Sturm and Gerhards (2016) that mulch of *R. sativus* is inhibiting crop germination and root length, which was attributed to the allelopathic potential of Brassicaceae. However, allelopathic compounds, like isothiocyanates emitted by *Brassica napus*, were described to disappear quickly as compared to the decomposition of the CC residue mulch layer, which functions as a physical barrier to weeds (Petersen et al., 2001; Yenish et al., 1995). This might explain why maize emergence was unaffected after growing winter cereals as CCs within a study from Dhima et al. (2006) and after growing Poaceae and Brassicaceae CCs within this study (data not shown). In contrast, *A. strigosa* is very popular in Brazil as a preceding crop to soybean. In this specific combination, *A. strigosa* was reported to increase crop yield as compared to other CC treatments and a winter fallow (Derpsch et al., 1986; Price et al., 2006).

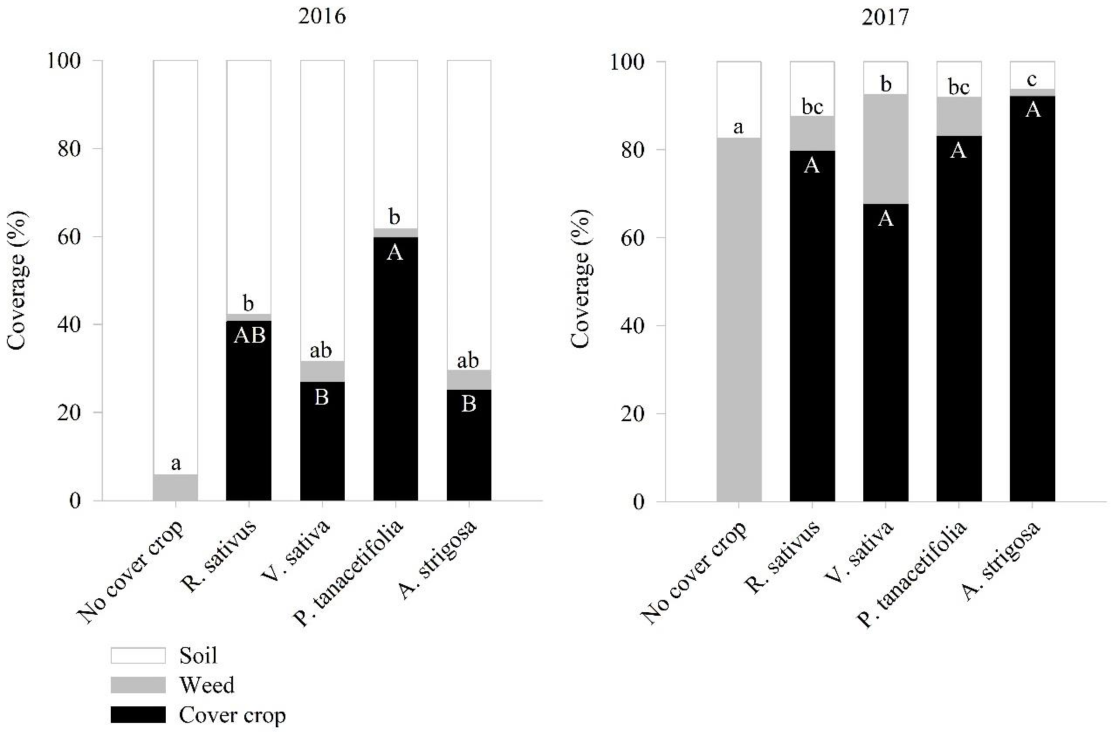


Figure 18. Weed and cover crop coverage in 2016 and 2017 (Experiment 2). Capital letters within one graph show significant differences in cover crop coverage, according to Tukey-HSD (honestly significant difference) test ($p \leq 0.05$). Small letters within one graph show significant differences in weed coverage, according to Tukey-HSD test ($p \leq 0.05$).

In 2016, when CCs generally developed poorly, *V. sativa* and *A. strigosa* increased the soil moisture content compared to the *P. tanacetifolia*, *R. sativus* var. *oleiformis*, and the control treatments (Figure 19). Mitchell et al. (1999), in contrast, showed that *V. sativa* was reducing the soil moisture compared to treatments without CCs. The different observations can be explained as the water use of different CCs varies according to the degree of water stress, climate, and soil fertility (Meisinger et al., 1991).

The soil moisture in 2017 was generally higher than in the previous years, with subtle differences between the CC treatments, but relative differences between years were similar. This leads to the conclusion that the impact of CCs on the soil moisture increases under dry conditions, an effect which was noticed by Mitchell et al. (1999).

Information about the water deficit tolerance (Figure 15), the soil moisture values (Figure 19), the weed biomass, and coverage (Figure 17 and 18), it is necessary to choose appropriate CCs to combine their advantages. *A. strigosa*, thereby, seems to condense several benefits. From the results of the greenhouse experiment, it was observed that *A. strigosa* showed greater water deficit tolerance as compared to *S. alba*. Although this could not be proven under field conditions. However, *A. strigosa* did not develop sufficiently under dry conditions in both field experiments, also concerning other CC treatments. Nevertheless, it was still able to reduce the weed cover and biomass compared to the control and increased the soil moisture. In the wet season 2017, *A. strigosa* showed the highest soil cover with 92% resulting in the highest weed suppression and minor effects on soil water content. *S. alba* showed a similar high weed suppression potential but simultaneously exhibited the highest sensitivity to drought in the greenhouse.

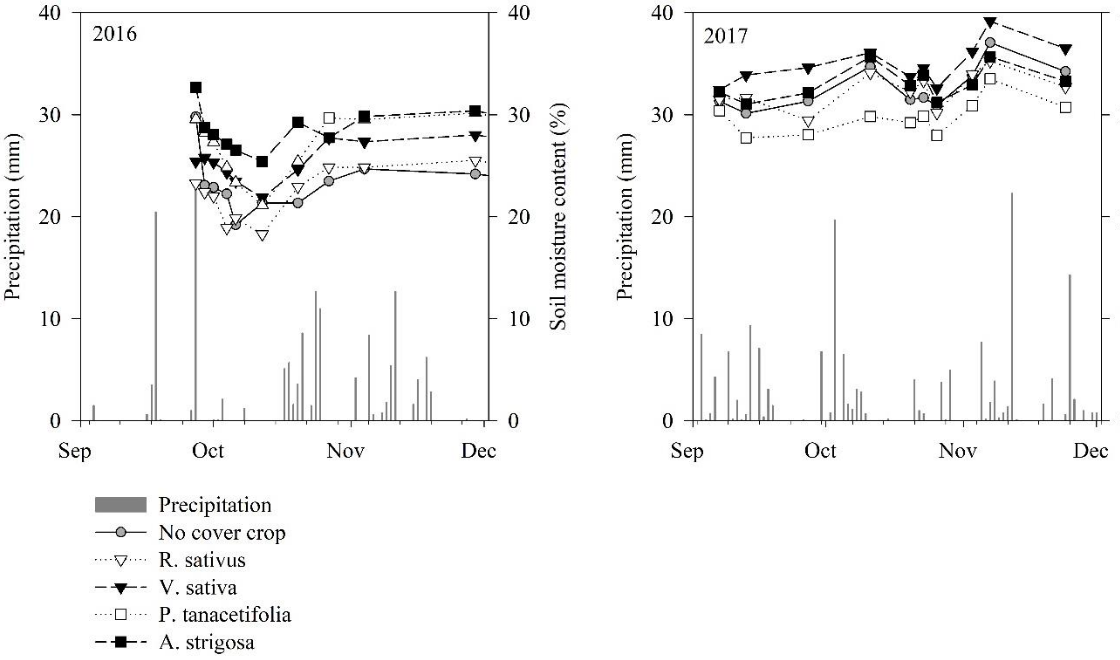


Figure 19. Precipitation and average soil moisture content in 10-30 cm depth of different cover crops from September until December in the years 2016 and 2017 (Experiment 2).

In conclusion, in the greenhouse under controlled conditions, CCs showed different water stress tolerances. CC biomass production under dry field conditions could not be attributed to CC water stress tolerance, as CCs with a low water deficit tolerance in the greenhouse produced the highest dry matter in the field. In the field, interrelations seem to be more complex and CC germination and establishment, important factors of the weed suppression potential, depend on several abiotic and biotic factors as well as management practices (as, e.g., seed density and depth).

Generally, when CCs produce a low amount of biomass, as e.g., in water-limited areas or within years of low precipitation in fall, their benefits like weed suppression are a lot smaller than in humid areas or seasons (Nielsen et al., 2015). Taking into account the water demand and the specific weed suppression mechanisms of CCs, therefore, may contribute to reducing the depletion of soil moisture and improves the success of weed control by CCs also under water-limited circumstances. Still, further research is needed to gather more information on CC species for specific requirements related to different soil types and climate conditions.

Acknowledgment: Thanks to the support from the research station Ihinger Hof and the Weed Science group at the University of Hohenheim. Additionally, we thank Matthias Schumacher, Constanze Heck, Matthias Haep, Stefanie Krauter, Charlotte Hein, Paula Ott, Lena Deutsch, Frans von Hutten, and Oscar Metzger for data acquisition.

Funding acknowledgment statement: Supported by the Ministerium für Ländlichen Raum, Ernährung und Verbraucherschutz Baden-Württemberg within the Project Conservation Agriculture and by the Anton & Petra-Ehrmann-Stiftung Research Training Group ‘Water-People-Agriculture’ at the University of Hohenheim.

Conflicts of Interest: The authors declare no conflict of interest.

Chapter 6

General discussion

6 General discussion

Winter cover crops can be implemented during the fallow season prior to spring cropping and provide weed control during and after cultivation. However, the weed control ability of cover crops is highly variable. To enhance the relevance of cover cropping substituting a weedy fall-to-spring fallow, the weed control reliability of cover crops also needs to increase under unfavorable circumstances. Improved cover cropping strategies may contribute to reduced herbicide inputs and soil tillage within integrated agricultural production systems. Therefore, this study investigated how cover crop sowing techniques, species selection, and species mixture compositions may improve the cover crop establishment and development and, therefore, the weed suppression success during the fall-to-winter period and the following cash crop season.

Within a field experiment, which was conducted at two locations near Hirrlingen, Germany, from 2017 and 2018, the weed control efficacy of cover crops was compared with diverse stubble management practices, including glyphosate application(s), non-inversion, and inversion tillage practices. Furthermore, four field experiments were performed from 2015-2018 at a research station of the University of Hohenheim near Renningen, Germany, whereby different pure cover crop stands and mixtures were tested and cover crop residue management in spring was evaluated with a focus on the overall weed suppression ability of cover crops. Additionally, it was investigated how species selection and species diversity within cover crop mixtures may alter the weed suppression success. The capability to cope with water limitations was evaluated for selected species on the basis of the collected field data and further examined within a greenhouse experiment conducted in 2018.

6.1 Weed suppression ability of cover crops during the fall-to-winter season

With an overall weed and volunteer crop suppression during the fall-to-winter season up to 98%, cover crops have proven to be an efficient weed control measure within this study (Chapters 2-5). In particular, single sown *Avena strigosa* Schreb. has shown the greatest potential for weed control across the experiments shown in Chapters 3-5, reaching significant weed density and weed cover reductions up to 83-98% compared to the untreated control. The mixture used within Chapters 2 and 3 (Experiment 1) showed a similar weed control potential compared to the implemented mechanical and chemical weed control measures. Notably, *Alopecurus myosuroides* Huds. was controlled by this mixture by 100%, which was more efficient than any tillage practice or glyphosate treatments. However, the mixtures used in Chapter 3 (Experiments 2 and 3) and 4 showed a weaker weed suppression potential than the most efficient pure cover crop stands.

The weed control efficacy of cover crops had a wide range, according to the selected species, the location and the season, which was also observed by Dorn et al. (2013; 2015). Water deficits in 2016 reduced the weed control ability among the cover crops tested in Chapters 3 and 4, to a maximum of 61%. How species selection and mixing strategies may increase the weed suppression stability will be evaluated in the following chapters.

6.1.1 Cover crop species consideration

Pure stands of *A. strigosa* with a soil cover of 92%, and *Sinapis alba* L. with 1.7 t ha^{-1} dry matter reached the highest weed cover and dry matter reduction of more than 95% (Chapters 4, 5). *A. strigosa* achieved a weed dry matter reduction of 92% (Chapter 4) and 95% (Chapter 3) with differing dry matter amounts of 2.2 and 1.1 t ha^{-1}, respectively. Water-limitations in 2016 caused low dry matter amounts of *A. strigosa* but may have enhanced the concentration of released allelochemicals (Einhellig, 1996). This might have contributed to the weed control success of *A. strigosa* although the dry matter production was certainly low. This is in agreement with Baraibar et al. (2018) and Kunz et al. (2016) who also concluded that biomass production is not necessarily predicting the weed control success of cover crops. But when high dry matter yields of *A. strigosa* came along with soil coverage of more than 90%, the weed control efficacy was highly improved. This relation cannot be transferred to *Phacelia tanacetifolia* Benth.. Because *P. tanacetifolia* showed a similar or even higher dry matter production and soil cover in pure stand than *Raphanus sativus* var. *oleiformis* Pers. and *A. strigosa* but showed a weaker weed suppression ability. Although *P. tanacetifolia* did not show the greatest weed suppression among the cover crops tested, it might be worth considering, as it provides additional ecosystem benefits. *P. tanacetifolia* is, for example, an ideal preceding crop because it is not related to any of the cash crops commonly used in Germany. Additionally, *P. tanacetifolia* is popular as a bee pasture (Williams and Christian, 1991).

In the end, there were no correlations between weed suppression and cover crop biomass or soil cover. The assumption that allelopathy is contributing to weed control has been shown by several studies (Gfeller et al., 2018; Kunz et al., 2016; Sturm et al., 2018) and is assumed to have contributed to the weed control success of *R. sativus* and *A. strigosa*. However, allelopathy is highly related to the cultivars, their development stage and the environment (Belz, 2007) and was not further evaluated within this study.

It can be summarized that the weed control success was most likely improved by growing species which are reported as having highly competitive and allelopathic properties, which agrees with Tribouillois et al. (2015) and Baraibar et al. (2018). Therefore, species like *Anethum graveolens* L., *Carthamus tinctorius* L., *Vicia sativa* L., *Fagopyrum esculentum* Moench, and *Trifolium subterraneum* L. cannot be recommended for weed control as pure stands or as a main component within mixtures, as they established weak or have been winter-killed early in our recent study.

Although certain characteristics of single species or species groups increase the weed suppression ability, weather and management define additional limitations. Weed suppression in 2015 and 2017 was much higher than during the dry season in 2016 where cover crop cover and dry matter were low. Growing drought-tolerant species might improve weed control, as only well-established cover crops contribute to weed plant and weed seed dispersal reductions. Assuming from Chapters 3-5, *A. strigosa*, *R. sativus*, and *S. alba* showed the highest weed suppression ability under water-limited conditions among the species tested. However, their weed control potential was quite different. While *S. alba* achieved an almost complete weed control (Chapter 5) during the dry season in 2016, *R. sativus* reached a maximum weed dry matter and density reduction of 39-61% only (Chapters 3 and 4).

The majority of the experiments revealed that weed control within dry seasons is non-sufficient and requires more attention. Therefore, further investigations on the water needs of *S. alba*, *A. strigosa*, and *P. tanacetifolia* were conducted in the greenhouse (Chapter 5). Clear differences among the species occurred in reaction to low water availabilities. A comparison between these cover crops within the field, however, showed that the weed suppression ability, cover crop dry matter, and soil cover formation of cover crops cannot be explained by the water supply alone. *S. alba* and *A. strigosa* showed a high weed suppression potential of 94% and 88%, respectively, during the water-limited season in 2016, although *S. alba* was most sensitive to water deficit in the greenhouse. In conclusion, the competitiveness of cover crops against weeds relies, in additions to a low susceptibility to dry conditions, on a number of factors as e.g. sowing density and species-specific resource allocation (Brennan and Boyd, 2012; Lambers and Poorter, 1992; Tribouillois et al., 2016).

Although the greenhouse experiment did not explain the cover crop weed suppression performance in the field, further greenhouse experiments might be helpful for species screening, in order to predict cover crop performances under a water-limited regime. Experiments might include variations of the water stress level under different soil, temperature, and humidity conditions. To reflect farming practices, species should be directly sown in pots at commonly used sowing depths and densities. Weed suppression might be directly evaluated by sowing the weed and cover crop seeds simultaneously within the same pots. Additionally, cover crop response to water stress needs to be further tested under changing management and field conditions in order to guarantee the relevance of the results to implemented cover cropping systems.

6.1.2 Cover crop species mixtures

In several experiments presented, pure stands of *R. sativus* and *A. strigosa* had shown the highest weed suppression ability among the pure cover crop stands. Also, Mixture 1 with high ratios of *R. sativus* and *A. strigosa* reached the highest weed control efficacy among the mixtures used within Chapter 4. This agrees with the results from Florence et al. (2019) who argued that species, which perform well in pure stands, are also productive in mixtures. Within a direct comparison, none of the species mixtures achieved higher weed control than the most efficient pure stands. Species that performed poorly in pure stands probably did not contribute to the weed suppression in mixtures. Additionally, mixtures, in terms of seed density, contained only a portion of the most efficient cover crops in pure stands. This resulted in a weaker performance of the mixture compared to species components sown in pure stands.

According to Dukes (2001), resource-rich conditions promote highly productive mixtures, as dominant species are not able to fully acquire all available resources from which other species then profit. This might be the reason for the highly competitive cover crop mixture in Hirrlingen, which caused complete suppression of volunteer wheat and *A. myosuroides* (Chapter 2). In 2016, when water was limited, resource partitioning was most likely reduced, as the dominant and competitive species shift their resource allocation to acquire more water. Subsequently, competition with other species increased (Dukes, 2001). This means that weed control by cover crop mixtures is increased by high yielding, competitive cover crop stands under favorable conditions and high resource allocation by cover crops if conditions are unfavorable. These findings cannot be attributed to all of the experiments presented, as the weed control success is more complex than the cover crop yield formation alone (see Chapters 1.2. and 6.1.1).

While the dry matter production of the mixtures used within Chapter 4 was greater in the water-limited 2016 season compared to the 2017 season, the weed control ability was higher in 2017. The mixture used within Chapter 3, in two different field experiments, showed two very contrasting results concerning weed control during the dry season in 2016. Weed biomass reduction varied from 10% (Experiment 2) to 98% (Experiment 3). Experimental conditions for both experiments, like soil type and weather, cannot be named as reasons, as they were similar and equal, respectively. Low weed biomass reduction is rather expected to be caused by the 75% higher weed biomass in the control treatments in Experiment 2 compared to Experiment 3 with only 264 kg ha^{-1} weed dry matter. However, Mixture 1, which was used within Chapter 4, was able to achieve a weed control efficacy of 75% when weed biomass in the control treatment reached values above 1 t ha^{-1}. What was different between both experimental trials was the high number of volunteer crops (data not shown). In conclusion, the mixture used in Experiments 2 and 3 (Chapter 3) was not able to combat high numbers of volunteer crops. From these results, it should not be derived that cover crops have a generally weak ability to control volunteer crops.

Brust, Claupein et al. (2014) and the results from the experiment in Hirrlingen (Chapter 2) agree that CCs are well suited to control volunteer crops. Several agronomic reasons might have contributed to the improved cover crop establishment and weed control ability of the cover crop mixture sown in Hirrlingen compared to those at Ihinger Hof. Experimental conditions, including soil type and precipitation, were similar. Sturm et al. (2017) reported that sowing cover crops one week after cereal harvest significantly improved the suppression of volunteer wheat compared to later sowing dates. Cover crops were sown six days earlier within the mulch-till treatment and 18 days earlier within the no-till treatment in Hirrlingen compared to Ihinger Hof. There, cover crops were sown on the 25th of August in 2017.

The mixture used at Hirrlingen, furthermore, contained the highest amount of *A. strigosa* with 45%, while the mixtures at Ihinger Hof only contained between 33-35% *A. strigosa* at most. As evaluated by Akemo et al. (2000), Baraibar et al. (2018) and McLaren et al. (2019) an increasing proportion of Poaceae within mixtures is improving the weed control. This suits to another example within this study. Mixture 2 (Chapter 4), as the only mixture without *A. strigosa*, produced the highest amount of dry matter in 2016, while simultaneously showing a generally weak weed suppression ability compared to mixtures where *A. strigosa* was included.

Generally, *A. strigosa* is worth considering within mixtures for several reasons: 1.) allelopathic characteristics are an additional factor for niche differentiation (Zuppinger-Dingley et al., 2014); 2.) reliable weed control also under dry conditions (Chapters 3-5) and 3.) the ability to compensate for less productive species (Dukes, 2001). However, as crop rotations in Europe are commonly dominated by cereals, *A. strigosa* cannot be frequently included in these cropping systems because it forms a potential infection bridge for pathogens and fungi, which induces cereal diseases.

Focusing on single, potent species is one possibility to improve the weed suppression ability of mixtures. Species composition and richness should also be considered (Finney and Kaye, 2017). Although Kunz et al. (2016) demonstrated that species richness among mixtures is not improving weed control, several studies indicate that diversity and thus productivity of mixtures is more complex than the number of species included (Dukes, 2001; Hector et al., 1999; Zuppinger-Dingley et al., 2014). The nine species mixture used in Hirrlingen (Chapter 2) showed the highest weed suppression potential among the mixtures tested within this study. The factors that might have contributed to the weed suppression success, in this case, were discussed previously. The six species mixtures in 2016 at Ihinger Hof, showed a higher average weed control ability with 36% than the three species mixtures with 17% (Chapter 4). However, under favorable conditions in 2017, the three species mixture (Mixture 1) performed best among the mixtures tested in Chapter 4. This suits the findings from Hector et al. (1999) and Dukes (2001), who stated that poorly productive mixtures profit from increasing species richness. As species richness, in general, is named to increase productivity (Balvanera et al., 2006), adding more species in the cover crop mixtures may increase cover crop performance and thus weed suppression potential. Species-rich mixtures, including well-performing, even ‘selfish’ species, also increase productivity (Wacker et al., 2009), whereby species-rich mixtures, with only low competitive species, may contribute to weed problems (McLaren et al., 2019). Considering species richness, species composition, and functional group richness increased the productivity in grassland experiments (Dukes, 2001; Hector et al., 1999), and are therefore expected to improve the weed suppression by cover crops as well (Baraibar et al., 2018). Unfortunately, depending on the composition, seed mixtures might be more expensive and the N return, in comparison to pure cover crops stands, is more difficult to estimate by producers. However, in addition to increased reliability on weed control, mixtures show a greater ability to combine multiple ecosystem services like nitrogen retention, disease resistance, and habitat provision for beneficial insects (Finckh et al., 2000; Finney and Kaye, 2017; Snapp et al., 2005). In order to increase the multifunctionality of cover crop mixtures, functional diversity among components might be more important than species richness (Finney and Kaye, 2017).

In narrow crop rotations, including high numbers of cereals and oilseed rape, two of the most promising functional cover crops named in this study (Poaceae and Brassicaceae), can only be sparsely included in crop rotations. However, sufficient weed control can be realized by increasing the number of species and functional groups, considering allelopathic cover crops and productive species that are able to compensate for poor-performing cover crops. However, weed suppression mechanisms of cover crops sown in pure stands or in mixtures are still not sufficiently understood and require extensive research. Further knowledge would contribute to greatly simplify the composition of mixtures. Meanwhile, developing mixtures with reliable establishment and development is, therefore, the main priority to improve the general weed suppression ability of cover crops.

6.2 Contribution of cover crops to weed control after cultivation

In order to counteract the development of herbicide resistance and to control herbicide-resistant weeds, alternative weed control measures need to be implemented. *A. myosuroides*, as the currently most challenging grass weed in Europe, was efficiently controlled by cover crops. The experiments have shown that an efficient *A. myosuroides* suppression during cover crop cultivation also resulted in low densities after cultivation (Chapters 2 and 3 (Experiment 1)). The fall-to-winter weed control measures, like cover crops (direct-sown) and plowing, achieved an *A. myosuroides* control efficacy of more than 86% during the spring barley season (Chapter 3). Chemical treatments and non-inversion tillage showed an *A. myosuroides* control of less than 50%. In conclusion, *A. myosuroides* control is improved by either retaining the seeds at the soil surface and inhibiting germination or burying them by plowing. Whereas plowing was expected to be important to control *A. myosuroides*, no-till systems are rather attributed to increase its densities (Lutman et al., 2013; Moss, 1985). However, combining the no-till system with highly productive cover crop stands effectively controlled *A. myosuroides*. CCs sown within the no-till system resulted in greater *A. myosuroides* control during the spring barley season and suppressed weeds only slightly less than cover crops sown with the mulch-till system during cultivation. Concluding that direct sowing of CCs is appropriate to control weeds in general and *A. myosuroides* in particular, cover cropping might help to support herbicide-resistance strategies.

Further experiments should target direct-sowing of cover crops to reduce tillage operations. This would reduce labor and costs. Additionally, reducing chemical and mechanical stubble management practices would enable to select earlier sowing dates of cover crops that could improve their productivity (Chapter 6.3).

The productivity of the CCs used in another two experiments (Chapter 3, Experiment 2 and 3) was probably too low to impact the weed control during the corn cropping season. Therefore, weed densities and dry matter at the cover crop treatments did not differ from those at the control treatments.

6.2.1 Management strategies and crop yield

Well-established cover crops are able to control herbicide-resistant and problematic weeds as *A. myosuroides* and *Cyperus esculentus* L. and weeds in general (Mirsky et al., 2010; Zhou et al., 2016). Low competitive cover crop stands are reported to result in increased weed seed soil entries (Mirsky et al., 2010). The short-term and long-term success of weed control mostly relies on a combination of different measures. Weed suppression seems to be improved when resource competition and allelopathic interference by cover crops is combined with mechanical weed damage and soil disturbance (Gerowitt, 2003; Liebman and Dyck, 1993; Mirsky et al., 2010).

Moonen and Barberi (2004) reported from a long-term experiment that plowing, after growing rye as a cover crop, had reduced the weed seed bank density by 25% compared to the crop residue control. In the same study, rye failed the seed reduction effect in the no-till system while subterranean clover did. The weed suppression during the corn cropping seasons, as presented in Chapter 3 (Experiments 2 and 3), was solely related to the tillage implemented in spring rather than the cover crops sown in fall. As the weed suppressive effects of cover crops were expected to be greatest within the no-till system (Kruidhof et al., 2009), the cover crops chosen had apparently not produced sufficient mulch biomass (Chapter 3, Experiment 2). Also, the early distribution of cover crop residues at the soil surface did not impact the weed control success by cover crops after cultivation (Chapter 3, Experiment 3). Weed suppression early after mulching depends on the presence and concentration level of allelochemicals and/or physical barriers. Both effects are expected to disappear faster after growing non-frost tolerating winter cover crops in contrast to winter-hardy cover crops, as they are starting to decompose already after a natural termination by frost. The termination date and method of overwintering cover crops are well reported to reduce the weed density before and during the cash cropping season (Dorn et al., 2013; Kruidhof et al., 2009; Mirsky et al., 2011). Therefore, selecting more frost-tolerant species, which are late maturing or even overwintering cover crops may increase the amount of cover crop residues and thus the weed control ability.

If the cover crop performance is weak during the fall-to-winter season and a mechanical termination of cover crops and weeds prior to cash crop sowing is not sufficient, non-selective herbicides are commonly sprayed. In order to reduce these herbicide applications, inversion tillage may be considered (Gerowitt, 2003), which is unfortunately not targeting the idea of conservation agriculture and soil protection. However, the results from Experiment 2 presented in Chapter 3 show that the application of non-selective herbicides at the no-till treatments in spring was significantly more effective to reduce the weed dry matter during the corn season than plowing, regardless if cover crops were grown or not. To which extent cover cropping goes along with a reduction of soil tillage and herbicide applications is still not sufficiently examined. If site-specific cover crop strategies, including resilient cover crops, are identified, stability and productivity increases and the necessity to implement inversion tillage or non-selective herbicide applications in spring might decrease.

In order to justify the reduction of mechanical or chemical weed management measures by cover cropping, cover crops need to maximize creating unfavorable conditions for weeds while minimizing the negative impacts on the subsequent spring crop (Liebman et al., 1997). The soil water content in cover cropping systems is affected by increased water infiltration (Gulick et al., 1994) and species-specific induced water losses by evapotranspiration (Bodner et al., 2007). Cash crops might benefit from increased soil water contents after cover cropping compared to a fallow season (Blanco-Canqui et al., 2011; Fageria et al., 2005). On the other hand, if cover crops establish successfully under water-limited conditions, concerns about the water supply of the cash crop may arise. Because in water-limited areas or within below-average dry seasons, cover cropping is reported to deplete soil water resources in comparison to a weedy-fallow (Bodner et al., 2007). This interferes with the water availability for the subsequent cash crops and their yield formation (Nielsen and Vigil, 2005; Unger and Vigil, 1998; Wortman et al., 2012). When cover crops negatively affect the cash crop productivity, producers will refrain from implementing cover crops into their crop rotations. In order to avoid water depletion within generally warm regions with a long-lasting vegetation period and limited rainfall, cover crop sowing delay or cover crop termination prior to winter kill can be considered (Probst and Probst, 1982; Unger and Vigil, 1998).

There are some approaches for cover crop termination methods to avoid water depletion within usually humid but within below-average precipitation seasons (Kornecki et al., 2009; Wortman et al., 2012). Many more studies dealt with the evaluation of cover crops grown in semi-arid areas (Bodner et al., 2007; Mitchell et al., 1999; Unger and Vigil, 1998). Applying the findings from semi-arid areas to usually humid areas with seasons without sufficient rainfall would expand the possibilities to improve cover cropping under a generally water-limited regime. But the transferability from one case to another has not been sufficiently evaluated. However, results from water-limited areas seem to be in agreement with the data presented.

In addition to an adjusted cover crop management, the cover crop species selection also affects the soil moisture content. That cover crops reduce soil moisture contents compared to a weedy-fallow during dry seasons, as previously mentioned, might not hold true in many cases. According to Bodner et al. (2007) and shown in Chapter 5, cover cropping had rather neutral or positive effects on the soil moisture contents during cultivation. Increasing soil water contents, for example, were shown within this study for *V. sativa* and for *Vicia villosa* L. cv. Beta within experiments from Bodner et al. (2007). Therefore, it is worth considering cover crops that combine a positive impact on the water balance and efficient weed control. *A. strigosa* showed reliable weed control under unfavorable conditions while increasing the soil moisture content. *S. alba*, with a high tolerance to dry conditions and fast soil coverage, was also beneficial for weed control (Chapter 5) and has the ability to compensate evapotranspiration losses by productivity (Bodner et al., 2007). Out of the data presented, growing cover crops at usually humid regions but in exceptional dry seasons is throughout suitable to control weeds. Additionally, the yields of spring barley and corn of the cover crop treatments were similar to those of the control treatments.

6.3 Conclusions and further adjustments to improve the weed control ability of cover crops

The experimental results showed that cover crops are worth integrating into the crop rotation as they provided efficient weed, volunteer crop, and *A. myosuroides* control during cultivation in particular and partly after cultivation. A negative impact on weed density and yield in the subsequent spring crop was not determined. Nevertheless, cover crop performance is strongly related to environmental conditions, wherefore weed control may show high variability within different years. However, it should always be considered that weed control is only part of the

manifold advantages provided by cover crops. Regardless of cover crops that are not compensating their sowing costs with measurable benefits in certain years, replacing a weedy fallow by cover cropping should be considered. Applying more diverse crop rotations may not increase crop yield and weed suppression but reduces external inputs (Davis et al., 2012). Keeping the field fallow may require labor as intense stubble tillage practices and/or herbicide applications to control weeds without achieving ecological benefits.
The monetary value of ecological effects caused by cover crops is sometimes difficult to estimate by producers, as some benefits are not obviously visible and only measurable after a certain time and frequency of cover cropping. As some environmental impacts (as run-off and nitrate discharge to surface water) go beyond the production areas, the state might create incentives for cover cropping (Snapp et al. 2005) as realized in the European Union with subsidies. Those incentives would become negligible or redundant if reliable cover cropping strategies would be identified.

Many studies agree that the weed suppression success is linked to the establishment and the development of competitive cover crop stands (Brust, Claupein et al., 2014; Finney et al., 2016; Gfeller et al., 2018). Identifying cover crop requirements would help to increase the development of selected species for specific sites. However, experimental results revealed that the weed suppression ability of some species tested, was independent of the water availability (Chapter 5). *S. alba* and *A. strigosa*, for example, produced much less dry matter within the seasons with water deficit compared to the season with sufficient precipitation, but they showed similar effective weed control within both seasons. In conclusion, the selection of cover crop species which combine physical and chemical weed suppression mechanisms may increase the weed control effectiveness (Chapter 6.1.1).

Species mixtures were named as an opportunity to improve the reliability of the cover crop performance by increased resilience against management errors and severe weather conditions (Wortman et al., 2012). In order to increase their stability within a long-term perspective and their absolute weed suppressive ability, cover crop mixing strategies (as mentioned in Chapter 6.1.2) need further investigations. *A. strigosa*, *R. sativus* and *S. alba* as the most promising cover crops (Chapter 6.1.1) within this study concerning weed control, could be tested together with changing ratios and seed densities. To refer to the idea of increasing species diversity and functional richness to improve the weed control ability of cover crop mixtures (Chapter 6.1.2), single, highly competitive species could be tested in increasing proportions in order to increase weed control. Supplementary components, which fulfill other ecosystem services, should also be included with differing numbers, ratios, and densities. It is expected that at a certain mixing ratio, the competitive species are so dominant within the mixture that weed control is increased, but on the other hand ecosystem services are decreased because additional components cannot develop properly. Meeting several expectations within one mixture, therefore, is difficult but might increase the likelihood of cover crops being integrated into crop rotations.

Transferring the performance of single sown species directly to species mixtures would simplify the species selection process. However, when considering different species to be included in mixtures, their performance should be directly tested in mixtures rather than in pure stands. According to Zuppinger-Dingley et al. (2014) species tested in pure stands performed differently from those tested within diverse mixtures, as complementarity and differentiation are, thereby, promoted. In conclusion, the development of mixing strategies will remain challenging, particularly when management strategies are included as an additional factor.

Management adjustments might include fertilizer consideration, higher sowing densities, adjusted sowing techniques and sowing dates (Dukes, 2001; Marín and Weiner, 2014; Sturm et al., 2017; Thomsen and Hansen, 2014; Vos and van der Putten, 1997). When comparable crop stands in mixtures as in monocultures are targeted, sowing densities of single components need to be increased to improve their capability to compensate for weak performing species (Dukes, 2001). Decreased row distance and uniform sowing patterns might improve cover crop weed suppression by increased competitiveness (Marín and Weiner, 2014). During sowing, all mixture components are usually placed in a single seed tank. Differing seed sizes induce dissociation in the seed tank, resulting in heterogeneous crop stands. The usual sowing depth of cover crop mixtures is chosen according to the average required placement depth. A drilling machine combining several tanks and possibilities to deposit cover crop seeds according to their optimal seed depth requirements might improve cover crop germination and establishment. If the technical equipment is not available, coarse-grained seeds may be seeded first, in a deeper layer, and fine-seeded seeds within an additional working step in an upper soil layer. However, this would result in increased costs and labor, albeit split sowing creates the opportunity to seed slow emerging seeds, like legumes, prior to fast-emerging seeds, which would support the legumes. In order to avoid supplementary drilling, cover crop seeds may be placed simultaneously while harvesting when the harvester is combined with a sowing appliance. A green bridge might be realized by broadcast sowing already before cash crop harvest. This might induce cover crop stands which suppress weeds more efficiently than postharvest sown cover crops and promote seed predation (Sturm et al., 2017; Thomsen and Hansen, 2014; Westerman et al., 2003).

Even if multifunctional, site-adapted mixtures are identified and the management is adapted to their requirements, the success of cover crops in weed suppression still relies on the environmental conditions during germination and establishment. If the weed control efficacy by cover crops within a specific season is poor, producers can easily complement additional weed control measures, such as tillage in spring (Chapter 6.2.1), in order to avoid increased weed infestations in the subsequent cash crop.

Chapter 7

Summary

Zusammenfassung

7 Summary

Weed control in agricultural production systems is indispensable to achieve stable crop yields. Integrated cropping systems are demanding for preventive and ecologically harmless weed control measures in order to protect soil and water resources and to retard the selection of herbicide-resistant weeds. Well-established winter cover crops provide nutrient retention and soil protection and may effectively suppress weeds. This contributes to reduce chemical and mechanical fall- and spring-applied weed control practices. However, producers are cautious towards integrating cover crops in crop rotations, as their performance is related to environmental conditions and varies, therefore, significantly from season to season. To increase their integration into cropping systems, reliability on weed control by cover crops needs to improve. In the current study, management strategies such as i) the cover crop sowing method, ii) the selection of water deficit tolerating cover crop species, iii) cover crop species combinations, iv) the adjustment of the mulching date and v) tillage practices after cover crop cultivation were considered as possibilities to improve the effectiveness of cover crops to control weeds during cultivation and in the subsequent cash crop. Five field experiments and one greenhouse experiment were conducted from 2015-2018 to investigate the following objectives:

- to assess if cover crops are as effective to control weeds and volunteer crops during the fall-to-winter season as chemical and mechanical weed control measures;
- to test if cover crops are an adequate weed control measure within *Alopecurus myosuroides* Huds. infested fields;
- to explore the effects of cover crops on weed control and yield during the cash crop season and to identify if the tillage system and the mulching date can, thereby, expand the weed suppressive effects of cover crop residues;
- to evaluate how species selection and species diversity are stabilizing productivity and therefore the weed suppression efficacy of cover crop mixtures compared to pure cover crop stands;
- to identify if the water requirements during cover crop establishment and water limitations are determining the weed control success of selected cover crops.

The current thesis resulted in four scientific articles. Within the first and the second publication, the general weed and *A. myosuroides* control ability of a cover crops mixture during and after cultivation were compared in the field with various fall-applied tillage methods and glyphosate

treatments. Due to the development of highly competitive cover crop stands, weeds were suppressed by 98% and *A. myosuroides* by 100% during cultivation. Therefore, cover crops were more efficient compared to glyphosate application(s), non-inversion and inversion tillage and revealed a great potential to reduce or even replace chemical and mechanical fall-applied weed control measures. The efficient *A. myosuroides* control during the cover crop cultivation remained until spring barley harvest. This quantifies cover crops to complement herbicide resistance management strategies. In contrast, due to the weak cover crop performance during fall-to-winter within another two experiments included in the second article, weed suppressive effects of cover crops disappeared after the cultivation of cover crops. This might have been the reason why reduced tillage and adjusted mulching dates in spring failed in contributing to expand weed suppressive effects of cover crops in these experiments.

Cover crop mixtures are attributed to show a greater resilience against unfavorable conditions than pure cover crop stands which is expected to result in an increased weed suppression ability. Within article three, the weed control efficacy of pure cover crop stands was compared with species mixtures. Pure stands of *Avena strigosa* Schreb. and *Raphanus sativus* var. *oleiformis* Pers. provided the most efficient weed control with 83% and 72%, respectively. Cover crop species mixtures showed a weaker weed suppression ability than the most efficient pure stand. In order to improve the weed control ability of cover crop mixtures, it was evaluated that the species selection is more relevant than the species diversity. Thereby, environmental requirements, such as water and temperature demand, and weed suppression mechanisms should be considered. Weed suppression of mixtures was improved by increasing the proportions of *A. strigosa* and *R. sativus* var. *oleiformis*, as they were showing a susceptibility for dry conditions and combine a strong competition for resources and allelopathic interference with weeds.

Within the fourth article, it was explored whether a low susceptibility of single cover crop species to water-limitations accompanies an improved weed suppression ability. *A. strigosa* and *Sinapis alba* L. showed differing suitabilities to cope with water-deficit in the greenhouse. A relation between weed suppression and water demand of cover crops at the field was not identified. Although the weed control ability of cover crops is generally narrowed under water-limited conditions, the weed suppression potential of individual species seems to be independent of their water supply.

The adjustment of the cover crop sowing method, the consideration of species-specific requirements and the mixing strategies, were evaluated as being important to improve the

resilience of cover crops against severe environmental conditions and their weed control ability. Investigations of cover crop mixtures with respect to single component species, their mixing ratios and seed densities, might further increase the absolute and average effectiveness of cover crops as an integrated weed management practice.

7.1 Zusammenfassung

Unkrautkontrolle in landwirtschaftlichen Produktionssystemen ist unerlässlich, um stabile Erträge zu erzielen. Integrierte Anbausysteme zielen darauf ab, verstärkt präventive und ökologisch unbedenkliche Unkrautkontrollmaßnahmen einzusetzen, um Boden- und Wasserressourcen zu schützen und die Selektion herbizidresistenter Unkräuter zu verzögern. Gut etablierte Winterzwischenfruchtbestände sorgen für einen Nährstoffrückhalt und schützen den Boden vor Erosion. Eine effiziente Unkrautunterdrückung durch Zwischenfrüchte kann den Einsatz von chemischen und mechanischen Stoppelbearbeitungsmaßnahmen reduzieren. Winterzwischenfrüchte sind allerdings bisher noch kein fester Bestandteil in Fruchtfolgen, da deren Entwicklung, von Jahr zu Jahr, stark variieren kann. Dadurch schwankt auch die Zuverlässigkeit der Unkrautunterdrückung. Kann diese dauerhaft gewährleistet werden, könnte der Anbau von Zwischenfrüchten zunehmend interessanter werden. In dieser Studie wurden Bewirtschaftungsstrategien wie i) die Aussaatmethode von Zwischenfrüchten, ii) die Berücksichtigung trockentoleranter Zwischenfrüchte, iii) Zwischenfruchtmischungen, iv) unterschiedliche Mulchtermine und v) die Bodenbearbeitung nach dem Zwischenfruchtanbau als Möglichkeiten zur Verbesserung der Unkrautkontrolle durch Zwischenfrüchte evaluiert. Mit den folgenden Zielsetzungen wurden von 2015-2018 fünf Feldversuche und ein Gewächshausversuch durchgeführt:

- Bewertung des Unkrautunterdrückungspotentials von Zwischenfrüchten während der Herbst/Winter-Saison, im Vergleich zu chemischen und mechanischen Unkrautkontrollmaßnahmen;
- Eignung von Zwischenfrüchten zur Kontrolle von *Alopecurus myosuroides* Huds;
- Bewertung des Einflusses von Zwischenfrüchten auf die Unkrautkontrolle und den Ertrag in den darauffolgenden Sommerungen. Des Weiteren wurden der Einfluss der Bodenbearbeitung und des Mulchdatums im Frühjahr auf die unkrautunterdrückende Wirkung des Zwischenfruchtmulchs untersucht;
- Entwicklung verschiedener Ansätze das Unkrautunterdrückungspotential von Zwischenfruchtmischungen, im Vergleich zu Reinsaaten, unter Berücksichtigung der Artenauswahl und Artenvielfalt, zu steigern;
- Prüfung des Zusammenhangs zwischen dem Wasserbedarf von ausgewählten Zwischenfruchtarten und deren Unkrautunterdrückungserfolg.

Aus den Ergebnissen entstanden vier wissenschaftliche Artikel. In der ersten und zweiten Veröffentlichung wurde die Unterdrückung von Unkräutern und *A. myosuroides* durch

Zwischenfrüchte, im Vergleich zu verschiedenen im Herbst durchgeführten Bodenbearbeitungsvarianten und Glyphosatbehandlungen, beurteilt. Durch die Etablierung von konkurrenzfähigen Zwischenfruchtbeständen konnten Unkräuter und *A. myosuroides* während der Zwischenfruchtsaison um 98% bzw. 100% reduziert werden. Behandlungen, bei denen Glyphosat appliziert oder (wende und nicht-wendende) Bodenbearbeitung durchgeführt worden war, wiesen eine schlechtere Unkrautkontrolle auf, als Behandlungen mit Zwischenfrüchten. Der Einfluss des Zwischenfruchtanbaus auf *A. myosuroides* war auch noch während des Anbaus der Sommergerste erheblich. Dies bestätigt die Annahme, dass der Zwischenfruchtanbau als Maßnahme im Herbizidresistenzmanagement eingesetzt werden kann. Im Gegensatz dazu, konnten die Zwischenfrüchte, die in zwei weiteren Versuchen verwendet wurden, keine unkrautunterdrückende Wirkung in der Sommerung erzielen. Reduzierte Bodenbearbeitung und angepasste Mulchtermine im Frühjahr konnten ebenfalls nicht dazu beigetragen, die unkrautunterdrückende Wirkung des Zwischenfruchtmulchs zu verbessern.

Im dritten Artikel wurde überprüft, ob Zwischenfruchtmischungen, im Vergleich zu Zwischenfruchtreinsaaten, durch ihre höhere Widerstandsfähigkeit gegenüber ungünstigen Witterungsbedingungen, eine effizientere Unkrautunterdrückung aufweisen. Reinbestände von *Avena strigosa* Schreb. und *Raphanus sativus* var. *oleiformis* Pers. erzielten mit 83% bzw. 72% die effizienteste Unkrautunterdrückung. Mischungen zeigten eine schwächere Unkrautunterdrückung als der effizienteste Reinbestand. Um das Unkrautunterdrückungspotential von Mischungen zu verbessern, wurde evaluiert, dass die Berücksichtigung der Artenauswahl bedeutender ist, als die Artenvielfalt. Mit zunehmenden Anteilen von *A. strigosa* und *R. sativus* var. *oleiformis* in der Mischung, stieg die unkrautunterdrückende Wirkung. Beide Arten zeigten eine Toleranz gegenüber Trockenheit und unterdrücken Unkräuter durch physikalische und chemische Mechanismen.

Im vierten Artikel wurde untersucht, ob eine geringe Sensibilität ausgewählter Zwischenfruchtarten gegenüber Wassermangel mit einer verbesserten Unkrautunterdrückung bei Trockenheit einhergeht. Dabei wurden unterschiedliche Sensibilitäten für *A. strigosa* und *Sinapis alba* L. im Gewächshaus ermittelt. Obwohl die Unkrautkontrollfähigkeit von Zwischenfrüchten unter wasserlimitierten Bedingungen generell eingeschränkt ist, korrelierte das Unkrautunterdrückungspotenzial einzelner Arten im Feldversuch nicht mit der Wasserverfügbarkeit.

Die Anpassung der Zwischenfruchtaussaat, die Berücksichtigung art-spezifischer Anforderungen und die Herangehensweise Zwischenfruchtarten zu kombinieren, stellen potentielle Ansatzpunkte dar, um die Widerstandsfähigkeit von Zwischenfrüchten gegenüber ungünstigen Bedingungen zu verbessern. Damit einhergehend, kann das Unkrautunterdrückungspotential von Zwischenfrüchten gesteigert werden. Um die absolute sowie durchschnittliche Wirksamkeit von Zwischenfrüchten als integrierte Unkrautkontrollmaßnahme zu steigern, sollten Zwischenfruchtmischungen, unter Beachtung von Einzelkomponenten sowie deren Mischungsverhältnissen und Saatstärken, weiter untersucht werden.

8 Bibliography

Abdin, O. A., Zhou, X. M., Cloutier, D., Coulman, D. C., Faris, M. A. and Smith, D. L. (2000) ‘Cover crops and interrow tillage for weed control in short season maize (*Zea mays*)’, *European Journal of Agronomy*, vol. 12, no. 2, pp. 93–102.

Abraham, C. T. and Singh, S. P. (1984) ‘Weed management in sorghum-legume intercropping systems’, *The Journal of Agricultural Science*, vol. 103, no. 1, pp. 103–115.

Akemo, M. C., Regnier, E. E. and Bennett, M. A. (2000) ‘Weed suppression in spring-sown rye (*Secale cereale*)–pea (*Pisum sativum*) cover crop mixes’, *Weed Technology*, vol. 14, no. 3, pp. 545–549.

Baker, N. R. (2008) ‘Chlorophyll fluorescence: a probe of photosynthesis in vivo’, *Annual review of plant biology*, vol. 59, pp. 89–113.

Balvanera, P., Pfisterer, A. B., Buchmann, N., He, J. ‐ S., Nakashizuka, T., Raffaelli, D. and Schmid, B. (2006) ‘Quantifying the evidence for biodiversity effects on ecosystem functioning and services’, *Ecology letters*, vol. 9, no. 10, pp. 1146–1156.

Baraibar, B., Hunter, M. C., Schipanski, M. E., Hamilton, A. and Mortensen, D. A. (2018) ‘Weed suppression in cover crop monocultures and mixtures’, *Weed Science*, vol. 66, no. 1, pp. 121–133.

Bàrberi, P. (2002) ‘Weed management in organic agriculture: are we addressing the right issues?’, *Weed Research*, vol. 42, no. 3, pp. 177–193.

Bàrberi, P. and Mazzoncini, M. (2001) ‘Changes in weed community composition as influenced by cover crop and management system in continuous corn’, *Weed Science*, vol. 49, no. 4, pp. 491–499.

Belz, R. G. (2007) ‘Allelopathy in crop/weed interactions–an update’, *Pest Management Science*, vol. 63, no. 4, pp. 308–326.

Bilalis, D., Sidiras, N., Economou, G. and Vakali, C. (2003) ‘Effect of different levels of wheat straw soil surface coverage on weed flora in *Vicia faba* crops’, *Journal of Agronomy and Crop Science*, vol. 189, no. 4, pp. 233–241.

Björkman, O. and Demmig, B. (1987) ‘Photon yield of O_2 evolution and chlorophyll fluorescence characteristics at 77 K among vascular plants of diverse origins’, *Planta*, vol. 170, no. 4, pp. 489–504.

Björkman, T., Lowry, C., Shail, J. W., Brainard, D. C., Anderson, D. S. and Masiunas, J. B. (2015) ‘Mustard cover crops for biomass production and weed suppression in the Great Lakes region’, *Agronomy Journal*, vol. 107, no. 4, pp. 1235–1249.

Blanco-Canqui, H., Mikha, M. M., Presley, D. R. and Claassen, M. M. (2011) ‘Addition of cover crops enhances no-till potential for improving soil physical properties’, *Soil Science Society of America Journal*, vol. 75, no. 4, pp. 1471–1482.

Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A. and Hergert, G. W. (2015) ‘Cover crops and ecosystem services: Insights from studies in temperate soils’, *Agronomy Journal*, vol. 107, no. 6, pp. 2449–2474.

Blesh, J. (2018) ‘Functional traits in cover crop mixtures: Biological nitrogen fixation and multifunctionality’, *Journal of Applied Ecology*, vol. 55, no. 1, pp. 38–48.

Blevins, R. L., Cook, D., Phillips, S. H. and Phillips, R. E. (1971) ‘Influence of No-tillage on Soil Moisture 1’, *Agronomy Journal*, vol. 63, no. 4, pp. 593–596.

Blubaugh, C. K., Hagler, J. R., Machtley, S. A. and Kaplan, I. (2016) ‘Cover crops increase foraging activity of omnivorous predators in seed patches and facilitate weed biological control’, *Agriculture, Ecosystems & Environment*, vol. 231, pp. 264–270.

Bodner, G., Loiskandl, W. and Kaul, H.-P. (2007) ‘Cover crop evapotranspiration under semi-arid conditions using FAO dual crop coefficient method with water stress compensation’, *Agricultural Water Management*, vol. 93, no. 3, pp. 85–98.

Boström, U. (1999) ‘Type and time of autumn tillage with and without herbicides at reduced rates in southern Sweden: 1. Yields and weed quantity’, *Soil and tillage research*, vol. 50, 3-4, pp. 271–281.

Boydston, R. A. and Hang, A. (1995) ‘Rapeseed (*Brassica napus*) green manure crop suppresses weeds in potato (*Solanum tuberosum*)’, *Weed Technology*, vol. 9, no. 4, pp. 669–675.

Brainard, D. C., Bellinder, R. R. and Kumar, V. (2011) ‘Grass legume mixtures and soil fertility affect cover crop performance and weed seed production’, *Weed Technology*, vol. 25, no. 3, pp. 473–479.

Brennan, E. B. and Boyd, N. S. (2012) ‘Winter cover crop seeding rate and variety affects during eight years of organic vegetables: I. Cover crop biomass production’, *Agronomy Journal*, vol. 104, no. 3, pp. 684–698.

Brennan, E. B. and Smith, R. F. (2005) ‘Winter cover crop growth and weed suppression on the central coast of California’, *Weed Technology*, vol. 19, no. 4, pp. 1017–1024.

Brown, J., Davis, J. B. and Esser, A. (2005) *Pacific Northwest Condiment Yellow Mustard (Sinapis alba L.) Grower Guide: 2000-2002,* National Renewable Energy Lab., Golden, CO (US).

Brown, P. D. and Morra, M. J. (1995) ‘Glucosinolate-containing plant tissues as bioherbicides’, *Journal of Agricultural and food Chemistry*, vol. 43, no. 12, pp. 3070–3074.

Brust, J., Claupein, W. and Gerhards, R. (2014) ‘Growth and weed suppression ability of common and new cover crops in Germany’, *Crop Protection*, vol. 63, pp. 1–8.

Brust, J. and Gerhards, R. (2012) ‘Lopsided oat (*Avena strigosa*) as a new summer annual cover crop for weed suppression in Central Europe’, *Julius-Kühn-Archiv*, vol. 1, no. 434, pp. 257–264.

Brust, J., Gerhards, R., Karanisa, T., Ruff, L. and Kipp, A. (2011) ‘Why undersown and cover crops become important again for weed suppression in european cropping systems’, *Gesunde Pflanzen*, vol. 63, no. 4, pp. 191–198.

Brust, J., Weber, J. and Gerhards, R. (2014) ‘Do cover crop mixtures have the same ability to suppress weeds as competitive monoculture cover crops?’, *Julius-Kühn-Archiv*, no. 443, pp. 422–430.

Cassman, K. G., Grassini, P. and van Wart, J. (2010) ‘Crop yield potential, yield trends, and global food security in a changing climate’, *Handbook of climate change and agroecosystems. Imperial College Press, London*, pp. 37–51.

Chauvel, B., Guillemin, J. P., Colbach, N. and Gasquez, J. (2001) ‘Evaluation of cropping systems for management of herbicide-resistant populations of blackgrass (*Alopecurus myosuroides* Huds.)’, *Crop Protection*, vol. 20, no. 2, pp. 127–137.

Cirujeda, A. and Taberner, A. (2006) ‘Relating weed size, crop soil cover and soil moisture with weed harrowing efficacy on *Papaver rhoeas* and other dicotyledoneous weeds in Mediterranean conditions’, *Biological agriculture & horticulture*, vol. 24, no. 2, pp. 181–195.

Clements, R. O., Martyn, T. M., Donaldson, G. and Wolfe, M. (2000) ‘Clover: cereal bi-cropping for organic farms’, *Aspects of Applied Biology*, no. 62, pp. 181–185.

Colbach, N., Busset, H., Roger-Estrade, J. and Caneill, J. (2014) ‘Predictive modelling of weed seed movement in response to superficial tillage tools’, *Soil and tillage research*, vol. 138, pp. 1–8.

Colbach, N., Dürr, C., Roger-Estrade, J., Chauvel, B. and Caneill, J. (2006) ‘AlomySys: Modelling black-grass (*Alopecurus myosuroides* Huds.) germination and emergence, in interaction with seed characteristics, tillage and soil climate: I. Construction’, *European Journal of Agronomy*, vol. 24, no. 2, pp. 95–112.

Constantin, J., Dürr, C., Tribouillois, H. and Justes, E. (2015) ‘Catch crop emergence success depends on weather and soil seedbed conditions in interaction with sowing date: A simulation study using the SIMPLE emergence model’, *Field Crops Research*, vol. 176, pp. 22–33.

Constantin, J., Le Bas, C. and Justes, E. (2015) ‘Large-scale assessment of optimal emergence and destruction dates for cover crops to reduce nitrate leaching in temperate conditions using the STICS soil-crop model’, *European Journal of Agronomy*, vol. 69, pp. 75–87.

Cousens, R. and Mortimer, M. (1995) *Dynamics of weed populations*, Cambridge University Press.

Cousens, R. and Moss, S. R. (1990) ‘A model of the effects of cultivation on the vertical distribution of weed seeds within the soil’, *Weed Research*, vol. 30, no. 1, pp. 61–70.

Creamer, N. G., Bennett, M. A., Stinner, B. R., Cardina, J. and Regnier, E. E. (1996) ‘Mechanisms of weed suppression in cover crop-based production systems’, *HortScience*, vol. 31, no. 3, pp. 410–413.

Dao, T. H. (1991) ‘Field decay of wheat straw and its effects on metribuzin and S-ethyl metribuzin sorption and elution from crop residues’, *Journal of environmental quality*, vol. 20, no. 1, pp. 203–208.

Davies, L. R. and Neve, P. (2017) ‘Interpopulation variability and adaptive potential for reduced glyphosate sensitivity in *Alopecurus myosuroides*’, *Weed Research*, vol. 57, no. 5, pp. 323–332.

Davis, A. S., Hill, J. D., Chase, C. A., Johanns, A. M. and Liebman, M. (2012) ‘Increasing cropping system diversity balances productivity, profitability and environmental health’, *PLoS One*, vol. 7, no. 10, e47149.

Decker, A. M., Clark, A. J., Meisinger, J. J., Mulford, F. R. and McIntosh, M. S. (1994) ‘Legume cover crop contributions to no-tillage corn production’, *Agronomy Journal*, vol. 86, no. 1, pp. 126–135.

Derpsch, R., Sidiras, N. and Roth, C. H. (1986) ‘Results of studies made from 1977 to 1984 to control erosion by cover crops and no-tillage techniques in Paraná, Brazil’, *Soil and tillage research*, vol. 8, pp. 253–263.

Deutsche Saatveredelung AG (2018) *Zwischenfrüchte* [Online]. Available at www.dsv-saaten.de (Accessed 8 August 2018).

Dhima, K. V., Vasilakoglou, I. B., Eleftherohorinos, I. G. and Lithourgidis, A. S. (2006) ‘Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development’, *Crop Science*, vol. 46, no. 1, pp. 345–352.

Dorn, B., Jossi, W. and van der Heijden, M. (2015) ‘Weed suppression by cover crops: comparative on‐farm experiments under integrated and organic conservation tillage’, *Weed Research*, vol. 55, no. 6, pp. 586–597.

Dorn, B., Stadler, M., van der Heijden, M. and Streit, B. (2013) ‘Regulation of cover crops and weeds using a roll-chopper for herbicide reduction in no-tillage winter wheat’, *Soil and tillage research*, vol. 134, pp. 121–132.

Dukes, J. S. (2001) ‘Productivity and complementarity in grassland microcosms of varying diversity’, *Oikos*, vol. 94, no. 3, pp. 468–480.

Dunbar, M. W., Gassmann, A. J. and O'Neal, M. E. (2017) ‘Limited impact of a fall-seeded, spring-terminated rye cover crop on beneficial arthropods’, *Environmental Entomology*, vol. 46, no. 2, pp. 284–290.

Einhellig, F. A. (1996) ‘Interactions involving allelopathy in cropping systems’, *Agronomy Journal*, vol. 88, no. 6, pp. 886–893.

Ellis, K. E. and Barbercheck, M. E. (2015) ‘Management of overwintering cover crops influences floral resources and visitation by native bees’, *Environmental Entomology*, vol. 44, no. 4, pp. 999–1010.

Evans, J. A., Tranel, P. J., Hager, A. G., Schutte, B., Wu, C., Chatham, L. A. and Davis, A. S. (2016) ‘Managing the evolution of herbicide resistance’, *Pest Management Science*, vol. 72, no. 1, pp. 74–80.

Fageria, N. K., Baligar, V. C. and Bailey, B. A. (2005) ‘Role of cover crops in improving soil and row crop productivity’, *Communications in soil science and plant analysis*, vol. 36, 19-20, pp. 2733–2757.

Falquet, B., Gfeller, A., Pourcelot, M., Tschuy, F. and Wirth, J. (2015) ‘Weed suppression by common buckwheat: A review’, *Environmental Control in Biology*, vol. 53, no. 1, pp. 1–6.

FAO (2012) Eto Calculator. Land and Water Digital Media Series No. 36. Rome, Food and Agriculture Organization.

Farooq, M., Jabran, K., Cheema, Z. A., Wahid, A. and Siddique, K. H. M. (2011) ‘The role of allelopathy in agricultural pest management’, *Pest Management Science*, vol. 67, no. 5, pp. 493–506.

Finckh, M., Gacek, E., Goyeau, H., Lannou, C., Merz, U., Mundt, C., Munk, L., Nadziak, J., Newton, A. and Vallavieille-Pope, C. de (2000) ‘Cereal variety and species mixtures in practice, with emphasis on disease resistance’, *Agronomie*, vol. 20, no. 7, pp. 913–937.

Finney, D. M. and Kaye, J. P. (2017) ‘Functional diversity in cover crop polycultures increases multifunctionality of an agricultural system’, *Journal of Applied Ecology*, vol. 54, no. 2, pp. 509–517.

Finney, D. M., White, C. M. and Kaye, J. P. (2016) ‘Biomass production and carbon/nitrogen ratio influence ecosystem services from cover crop mixtures’, *Agronomy Journal*, vol. 108, no. 1, pp. 39–52.

Florence, A. M., Higley, L. G., Drijber, R. A., Francis, C. A. and Lindquist, J. L. (2019) ‘Cover crop mixture diversity, biomass productivity, weed suppression, and stability’, *PLoS One*, vol. 14, no. 3, e0206195.

Fourie, H., Ahuja, P., Lammers, J. and Daneel, M. (2016) ‘Brassicacea-based management strategies as an alternative to combat nematode pests: A synopsis’, *Crop Protection*, vol. 80, pp. 21–41.

Froud-Williams, R. J., Chancellor, R. J. and Drennan, D. S.H. (1984) ‘The effects of seed burial and soil disturbance on emergence and survival of arable weeds in relation to minimal cultivation’, *Journal of Applied Ecology*, pp. 629–641.

Gallandt, E. R., Molloy, T., Lynch, R. P. and Drummond, F. A. (2005) ‘Effect of cover-cropping systems on invertebrate seed predation’, *Weed Science*, vol. 53, no. 1, pp. 69–76.

Gerowitt, B. (2003) ‘Development and control of weeds in arable farming systems’, *Agriculture, Ecosystems & Environment*, vol. 98, 1-3, pp. 247–254.

Gfeller, A., Herrera, J. M., Tschuy, F. and Wirth, J. (2018) ‘Explanations for *Amaranthus retroflexus* growth suppression by cover crops’, *Crop Protection*, vol. 104, pp. 11–20.

Gliessman, S. R. (1986) *Plant interactions in multiple cropping systems*, New York, MacMillan.

Gruber, S. and Claupein, W. (2009) ‘Effect of tillage intensity on weed infestation in organic farming’, *Soil and tillage research*, vol. 105, no. 1, pp. 104–111.

Gruber, S., Pekrun, C., Möhring, J. and Claupein, W. (2012) ‘Long-term yield and weed response to conservation and stubble tillage in SW Germany’, *Soil and tillage research*, vol. 121, pp. 49–56.

Gulick, S. H., Grimes, D. W., Goldhamer, D. A. and Munk, D. S. (1994) ‘Cover-crop-enhanced water infiltration of a slowly permeable fine sandy loam’, *Soil Science Society of America Journal*, vol. 58, no. 5, pp. 1539–1546.

Hajjar, R., Jarvis, D. I. and Gemmill-Herren, B. (2008) ‘The utility of crop genetic diversity in maintaining ecosystem services’, *Agriculture, Ecosystems and Environment*, vol. 123, no. 4, pp. 261–270.

Haramoto, E. R. and Gallandt, E. R. (2005) ‘Brassica cover cropping: I. Effects on weed and crop establishment’, *Weed Science*, vol. 53, no. 5, pp. 695–701.

Hartwig, N. L. and Ammon, H. U. (2002) ‘Cover crops and living mulches’, *Weed Science*, vol. 50, no. 6, pp. 688–699.

Hashemi, M., Farsad, A., Sadeghpour, A., Weis, S. A. and Herbert, S. J. (2013) ‘Cover‐crop seeding‐date influence on fall nitrogen recovery’, *Journal of Plant Nutrition and Soil Science*, vol. 176, no. 1, pp. 69–75.

Hayden, Z. D., Brainard, D. C., Henshaw, B. and Ngouajio, M. (2012) ‘Winter annual weed suppression in rye–vetch cover crop mixtures’, *Weed Technology*, vol. 26, no. 4, pp. 818–825.

Heap, I. (2017) ‘The International Survey of Herbicide Resistant Weeds’ [Online]. Available at www.weedscience.org (Accessed 30 April 2019).

Hector, A., Schmid, B., Beierkuhnlein, C., Caldeira, M. C., Diemer, M., Dimitrakopoulos, P. G., Finn, J. A., Freitas, H., Giller, P. S. and Good, J. (1999) ‘Plant diversity and productivity experiments in European grasslands', *Science,* vol. 286, no. 5442, pp. 1123–1127.

Hernanz, J. L., López, R., Navarrete, L. and Sanchez-Giron, V. (2002) 'Long-term effects of tillage systems and rotations on soil structural stability and organic carbon stratification in semiarid central Spain', *Soil and tillage research,* vol. 66, no. 2, pp. 129–141.

Hill, R. L. (1990) 'Long-term conventional and no-tillage effects on selected soil physical properties', *Soil Science Society of America Journal,* vol. 54, no. 1, pp. 161–166.

Hiltbrunner, J., Liedgens, M., Bloch, L., Stamp, P. and Streit, B. (2007) 'Legume cover crops as living mulches for winter wheat: Components of biomass and the control of weeds', *European Journal of Agronomy,* vol. 26, no. 1, pp. 21–29.

Holmes, A. A., Thompson, A. A. and Wortman, S. E. (2017) 'Species-specific contributions to productivity and weed suppression in cover crop mixtures', *Agronomy Journal,* vol. 109, no. 6, pp. 2808–2819.

Hooker, K. V., Coxon, C. E., Hackett, R., Le Kirwan, O'Keeffe, E. and Richards, K. G. (2008) 'Evaluation of cover crop and reduced cultivation for reducing nitrate leaching in Ireland', *Journal of environmental quality,* vol. 37, no. 1, pp. 138–145.

Hooper, D. U., Chapin, F. S., Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D. M., Loreau, M. and Naeem, S. (2005) 'Effects of biodiversity on ecosystem functioning: a consensus of current knowledge', *Ecological monographs,* vol. 75, no. 1, pp. 3–35.

House, G. J., Stinner, B. R., Crossley, D. A., Odum, E. P. and Langdale, G. W. (1984) 'Nitrogen cycling in conventional and no-tillage agroecosystems in the Southern Piedmont', *Journal of Soil and Water Conservation,* vol. 39, no. 3, pp. 194–200.

Hussain, I., Olson, K. R. and Ebelhar, S. A. (1999) 'Impacts of tillage and no-till on production of maize and soybean on an eroded Illinois silt loam soil', *Soil and tillage research,* vol. 52, 1-2, pp. 37–49.

Huston, M. A. (1997) 'Hidden treatments in ecological experiments: re-evaluating the ecosystem function of biodiversity', *Oecologia,* vol. 110, no. 4, pp. 449–460.

Inderjit and Asakawa, C. (2001) 'Nature of interference potential of hairy vetch (*Vicia villosa* Roth) to radish (*Raphanus sativus* L.): Does allelopathy play any role?', *Crop Protection,* vol. 20, no. 3, pp. 261–265.

IPCC (2014) *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]*, IPCC, Geneva, Switzerland, 151 pp.

Isermann, K. (1990) 'Share of agriculture in nitrogen and phosphorus emissions into the surface waters of Western Europe against the background of their eutrophication', *Fertilizer Research*, vol. 26, 1-3, pp. 253–269.

Kahnt, G. (1983) *Gründüngung*, 2nd edn, Frankfurt a. M, Germany, Verlagsunion Agrar.

Kornecki, T. S., Price, A. J., Raper, R. L. and Arriaga, F. J. (2009) 'New roller crimper concepts for mechanical termination of cover crops in conservation agriculture', *Renewable Agriculture and Food Systems*, vol. 24, no. 3, pp. 165–173.

Kravchenko, A. N., Robertson, G. P., Thelen, K. D. and Harwood, R. R. (2005) 'Management, topographical, and weather effects on spatial variability of crop grain yields', *Agronomy Journal*, vol. 97, no. 2, pp. 514–523.

Kruidhof, H. M., Bastiaans, L. and Kropff, M. J. (2009) 'Cover crop residue management for optimizing weed control', *Plant and soil*, vol. 318, 1-2, pp. 169–184.

Kunz, C., Sturm, D. J., Sökefeld, M. and Gerhards, R. (2017) 'Weed suppression and early sugar beet development under different cover crop mulches', *Plant Protection Science*, vol. 53, no. 3, pp. 187–193.

Kunz, C., Sturm, D. J., Varnholt, D., Walker, F. and Gerhards, R. (2016) 'Allelopathic effects and weed suppressive ability of cover crops', *Plant, Soil and Environment*, vol. 62, no. 2, pp. 60–66.

Kuo, S. and Jellum, E. J. (2000) 'Long-term winter cover cropping effects on corn (*Zea mays* L.) production and soil nitrogen availability', *Biology and fertility of soils*, vol. 31, no. 6, pp. 470–477.

Lambers, H. and Poorter, H. (1992) 'Inherent variation in growth rate between higher plants: a search for physiological causes and ecological consequences', in *Advances in ecological research*, Elsevier, pp. 187–261.

Langdale, G. W., Blevins, R. L., Karlen, D. L., McCool, D. K., Nearing, M. A., Skidmore, E. L., Thomas, A. W., Tyler, D. D. and Williams, JR (1991) 'Cover crop effects on soil erosion by wind and water', *Cover crops for clean water*, pp. 15–22.

Liebman, M. and Dyck, E. (1993) ‘Crop rotation and intercropping strategies for weed management’, *Ecological applications*, vol. 3, no. 1, pp. 92–122.

Liebman, M., Gallandt, E. R. and Le Jackson (1997) ‘Many little hammers: ecological management of crop-weed interactions’, *Ecology in agriculture*, vol. 1, pp. 291–343.

Liebman, M., Mohler, C. L. and Staver, C. P. (2001) *Ecological management of agricultural weeds*, Cambridge University Press.

Lutman, P. J.W., Moss, SR, Cook, S. and Welham, S. J. (2013) ‘A review of the effects of crop agronomy on the management of *Alopecurus myosuroides*’, *Weed Research*, vol. 53, no. 5, pp. 299–313.

MacArthur, R. and Levins, R. (1967) ‘The limiting similarity, convergence, and divergence of coexisting species’, *The American Naturalist*, vol. 101, no. 921, pp. 377–385.

Machleb, J., Kollenda, B. L., Peteinatos, G. G. and Gerhards, R. (2018) ‘Adjustment of Weed Hoeing to Narrowly Spaced Cereals’, *Agriculture*, vol. 8, no. 4, p. 54.

Malézieux, E., Crozat, Y., Dupraz, C., Laurans, M., Makowski, D., Ozier-Lafontaine, H., Rapidel, B., Tourdonnet, S. de and Valantin-Morison, M. (2009) ‘Mixing plant species in cropping systems: concepts, tools and models: a review’, in *Sustainable agriculture*, Springer, pp. 329–353.

Mantle, P. G. and Shaw, S. (1976) ‘Role of ascospore production by *Claviceps purpurea* in aetiology of ergot disease in male sterile wheat’, *Transactions of the British Mycological Society*, vol. 67, no. 1, pp. 17–22.

Marcillo, G. S. and Miguez, F. E. (2017) ‘Corn yield response to winter cover crops: An updated meta-analysis’, *Journal of Soil and Water Conservation*, vol. 72, no. 3, pp. 226–239.

Marín, C. and Weiner, J. (2014) ‘Effects of density and sowing pattern on weed suppression and grain yield in three varieties of maize under high weed pressure’, *Weed Research*, vol. 54, no. 5, pp. 467–474.

McLaren, C., Swanwpoel, P. A. and Bennet, J. E. (2019) ‘Cover crop biomass production is more important than diversity for weed suppression’, *Crop Protection*, vol. 59, no. 2, pp. 733–748.

Meisinger, J. J., Hargrove, W. L., Mikkelsen, R. L., Williams, J. R. and Benson, V. W. (1991) ‘Effects of cover crops on groundwater quality’, *Cover Crops for Clean Water. Soil and Water Conservation Society. Ankeny, Iowa*, pp. 57–68.

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

Melander, B., Liebman, M., Davis, A. S., Gallandt, E. R., Bàrberi, P., Moon, A., Rasmussen, J., van der Weide, R. and Vidotto, F. (2017) 'Non-chemical weed management', *Weed Research: Expanding Horizons, 1st ed.; Hatcher, PE, Froud-Williams, RJ, Eds*, pp. 245–270.

Melander, B., Munier-Jolain, N., Charles, R., Wirth, J., Schwarz, J., van der Weide, R., Bonin, L., Jensen, P. K. and Kudsk, P. (2013) 'European perspectives on the adoption of nonchemical weed management in reduced-tillage systems for arable crops', *Weed Technology*, vol. 27, no. 1, pp. 231–240.

Mirsky, S. B., Curran, W. S., Mortenseny, D. M., Ryany and Shumway, D. L. (2011) 'Timing of cover-crop management effects on weed suppression in no-till planted soybean using a roller-crimper', *Weed Science*, vol. 59, no. 3, pp. 380–389.

Mirsky, S. B., Gallandt, E. R., Mortensen, D. A., Curran, W. S. and Shumway, D. L. (2010) 'Reducing the germinable weed seedbank with soil disturbance and cover crops', *Weed Research*, vol. 50, no. 4, pp. 341–352.

Mitchell, J. P., Peters, D. W. and Shennan, C. (1999) 'Changes in soil water storage in winter fallowed and cover cropped soils', *Journal of Sustainable Agriculture*, vol. 15, 2-3, pp. 19–31.

Mohler, C. L. and Galford, A. E. (1997) 'Weed seedling emergence and seed survival: separating the effects of seed position and soil modification by tillage', *Weed Research*, vol. 37, no. 3, pp. 147–155.

Mohler, C. L., Liebman, M. and Staver, C. P. (2001) 'Enhancing the competitive ability of crops', *Ecological management of agricultural weeds*, pp. 269–321.

Moonen, A. C. and Barberi, P. (2004) ʻSize and composition of the weed seedbank after 7 years of different cover‐crop‐maize management systemsʼ, *Weed Research*, vol. 44, no. 3, pp. 163–177.

Moss, S. (2017) 'Black-grass (*Alopecurus myosuroides*): Why has this Weed become such a Problem in Western Europe and what are the Solutions?', *Outlooks on Pest Management*, vol. 28, no. 5, pp. 207–212.

Moss, S. R. (1979) ‘The influence of tillage and method of straw disposal on the survival and growth of black‐grass, *Alopecurus myosuroides*, and its control by chlortoluron and isoproturon’, *Annals of Applied Biology*, vol. 91, no. 1, pp. 91–100.

Moss, S. R. (1985) ‘The survival of *Alopecurus myosuroides* Huds. seeds in soil’, *Weed Research*, vol. 25, no. 3, pp. 201–211.

Moss, S. R., Am Perryman, S. and Tatnell, L. V. (2007) ‘Managing herbicide-resistant blackgrass (*Alopecurus myosuroides*): theory and practice’, *Weed Technology*, vol. 21, no. 2, pp. 300–309.

Moss, S. R. and Hull, R. (2012) ‘Quantifying the benefits of spring cropping for control of *Alopecurus myosuroides* (black-grass)’, *Aspects of Applied Biology*, no. 117, pp. 1–6.

Moss, S. R. and Rubin, B. (1993) ‘Herbicide-resistant weeds: a worldwide perspective’, *The Journal of Agricultural Science*, vol. 120, no. 2, pp. 141–148.

Nielsen, D. C., Lyon, D. J., Hergert, G. W., Higgins, R. K. and Holman, J. D. (2015) ‘Cover crop biomass production and water use in the Central Great Plains’, *Agronomy Journal*, vol. 107, no. 6, pp. 2047–2058.

Nielsen, D. C. and Vigil, M. F. (2005) ‘Legume green fallow effect on soil water content at wheat planting and wheat yield’, *Agronomy Journal*, vol. 97, no. 3, pp. 684–689.

Norris, R. F. and Kogan, M. (2000) ‘Interactions between weeds, arthropod pests, and their natural enemies in managed ecosystems’, *Weed Science*, vol. 48, no. 1, pp. 94–158.

Ofori, F. and Stern, W. R. (1987) ‘Cereal–legume intercropping systems’, *Advances in Agronomy*, vol. 41, pp. 41–90.

Parr, M., Grossman, J. M., Reberg-Horton, S. C., Brinton, C. and Crozier, C. (2011) ‘Nitrogen delivery from legume cover crops in no-till organic corn production’, *Agronomy Journal*, vol. 103, no. 6, pp. 1578–1590.

Pekrun, C. and Claupein, W. (2006) ‘The implication of stubble tillage for weed population dynamics in organic farming’, *Weed Research*, vol. 46, no. 5, pp. 414–423.

Petersen, J., Belz, R., Walker, F. and Hurle, K. (2001) ‘Weed suppression by release of isothiocyanates from turnip-rape mulch’, *Agronomy Journal*, vol. 93, no. 1, pp. 37–43.

Petit, S., Trichard, A., Biju-Duval, L., McLaughlin, Ó. B. and Bohan, D. A. (2017) ‘Interactions between conservation agricultural practice and landscape composition promote weed seed predation by invertebrates’, *Agriculture, Ecosystems & Environment*, vol. 240, pp. 45–53.

Potts, S. G., Biesmeijer, J. C., Kremen, C., Neumann, P., Schweiger, O. and Kunin, W. E. (2010) ‘Global pollinator declines: trends, impacts and drivers’, *Trends in ecology & evolution*, vol. 25, no. 6, pp. 345–353.

Powles, S. B. and Yu, Q. (2010) ‘Evolution in action: plants resistant to herbicides’, *Annual review of plant biology*, vol. 61, pp. 317–347.

Price, A. J., Reeves, D. W. and Patterson, M. G. (2006) ‘Evaluation of weed control provided by three winter cereals in conservation-tillage soybean’, *Renewable Agriculture and Food Systems,* vol. 21, no. 3, pp. 159–164.

Prieto, I., Violle, C., Barre, P., Durand, J.-L., Ghesquiere, M. and Litrico, I. (2015) ‘Complementary effects of species and genetic diversity on productivity and stability of sown grasslands’, *Nature Plants,* vol. 1.

Probst, G. and Probst, M. (1982) *Praktische Gründüngung für Landwirtschaft, Gartenbau, Sonderkulturen Medizin für den Boden,* München, Ed. Siebeneicher, Volkwirtschaftlicher Verlag.

Putnam, A. R., Defrank, J. and Barnes, J. P. (1983) ‘Exploitation of allelopathy for weed control in annual and perennial cropping systems’, *Journal of chemical ecology*, vol. 9, no. 8, pp. 1001–1010.

Rasmussen, J. (1991) ‘A model for prediction of yield response in weed harrowing’, *Weed Research*, vol. 31, no. 6, pp. 401–408.

Regulation (EU) No 1307/2013 of the European Parliament of the Council of 17 December 2013 ‘Establishing rules for direct payments to farmers under support schemes within the framework of the common agricultural policy and repealing Council Regulation (EC) No 637/2008 and Council Regulation (EC) No 73/2009. 63’.

Rice, C. W., Smith, M. S. and Blevins, R. L. (1986) ‘Soil Nitrogen Availability after Long-term Continuous No-tillage and Conventional Tillage Corn Production 1’, *Soil Science Society of America Journal*, vol. 50, no. 5, pp. 1206–1210.

Ritz, C., Baty, F., Streibig, J. C. and Gerhard, D. (2015) ‘Dose-response analysis using R’, *PLoS One*, vol. 10, no. 12, e0146021.

Rosenqvist, E. and van Kooten, O. (2003) *Chlorophyll fluorescence: a general description and nomenclature. In: DeEll J.R., Toivonen P.M.A. (eds) Practical Applications of Chlorophyll Fluorescence in Plant Biology,* Springer, Boston, MA.

Rueda-Ayala, V., Jaeck, O. and Gerhards, R. (2015) ‘Investigation of biochemical and competitive effects of cover crops on crops and weeds’, *Crop Protection,* vol. 71, pp. 79–87.

Sainju, U. M. and Singh, B. P. (2001) ‘Tillage, cover crop, and kill-planting date effects on corn yield and soil nitrogen’, *Agronomy Journal,* vol. 93, no. 4, pp. 878–886.

Sánchez-Moreiras, A. M., Weiss, O. A. and Reigosa-Roger, M. J. (2003) ‘Allelopathic evidence in the Poaceae’, *The Botanical Review,* vol. 69, no. 3, pp. 300–319.

Schappert, A., Messelhäuser, M., Saile, M., Peteinatos, G. and Gerhards, R. (2018) ‘Weed Suppressive Ability of Cover Crop Mixtures Compared to Repeated Stubble Tillage and Glyphosate Treatments’, *Agriculture,* vol. 8, no. 9, p. 144.

Schappert, A., Schumacher, M. and Gerhards, R. (2019) ‘Weed Control Ability of Single Sown Cover Crops Compared to Species Mixtures’, *Agronomy,* vol. 9, no. 6, p. 294.

Schulz, M., Marocco, A., Tabaglio, V., Macias, F. A. and Molinillo, J. M. G. (2013) ‘Benzoxazinoids in rye allelopathy-from discovery to application in sustainable weed control and organic farming’, *Journal of chemical ecology,* vol. 39, no. 2, pp. 154–174.

Smith, R. G., Atwood, L. W. and Warren, N. D. (2014) ‘Increased productivity of a cover crop mixture is not associated with enhanced agroecosystem services’, *PLoS One,* vol. 9, no. 5, pp. e97351.

Snapp, S. S., Swinton, S. M., Labarta, R., Mutch, D., Black, JR, Leep, R., Nyiraneza, J. and O'neil, K. (2005) ‘Evaluating cover crops for benefits, costs and performance within cropping system niches’, *Agronomy Journal,* vol. 97, no. 1, pp. 322–332.

Stott, P. A., Stone, D. A. and Allen, M. R. (2004) ‘Human contribution to the European heatwave of 2003’, *Nature,* vol. 432, no. 7017, p. 610.

Sturm, D. J. and Gerhards, R. (2016) ‘Comparison of different cover crop mulches and extracts on inhibition of crop and weed growth’, *Julius-Kühn-Archiv,* no. 452, p. 424.

Sturm, D. J., Kunz, C. and Gerhards, R. (2016) ‘Inhibitory effects of cover crop mulch on germination and growth of *Stellaria media* (L.) Vill., *Chenopodium album* L. and *Matricaria chamomilla* L’, *Crop Protection,* vol. 90, pp. 125–131.

Sturm, D. J., Kunz, C., Peteinatos, G. and Gerhards, R. (2017) ‘Do cover crop sowing date and fertilization affect field weed suppression?’, *Plant, Soil and Environment*, vol. 63, no. 2, pp. 82–88.

Sturm, D. J., Peteinatos, G. and Gerhards, R. (2018) ‘Contribution of allelopathic effects to the overall weed suppression by different cover crops’, *Weed Research*, vol. 58, no. 5, pp. 331–337.

Tabaglio, V., Marocco, A. and Schulz, M. (2013) ‘Allelopathic cover crop of rye for integrated weed control in sustainable agroecosystems’, *Italian Journal of Agronomy*, vol. 8, no. 1, p. 5.

Teasdale, J. R. (1996) ‘Contribution of cover crops to weed management in sustainable agricultural systems’, *Journal of Production Agriculture*, vol. 9, no. 4, pp. 475–479.

Teasdale, J. R., Beste, C. E. and Potts, W. E. (1991) ‘Response of weeds to tillage and cover crop residue’, *Weed Science*, vol. 39, no. 2, pp. 195–199.

Teasdale, J. R. and Mohler, C. L. (1993) ‘Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye’, *Agronomy Journal*, vol. 85, no. 3, pp. 673–680.

Teasdale, J. R. and Mohler, C. L. (2000) ‘The quantitative relationship between weed emergence and the physical properties of mulches’, *Weed Science*, vol. 48, no. 3, pp. 385–392.

Thomsen, I. K. and Hansen, E. M. (2014) ‘Cover crop growth and impact on N leaching as affected by pre‐ and postharvest sowing and time of incorporation’, *Soil use and management*, vol. 30, no. 1, pp. 48–57.

Thorup-Kristensen, K. (1994) ‘The effect of nitrogen catch crop species on the nitrogen nutrition of succeeding crops’, *Fertilizer Research*, vol. 37, no. 3, pp. 227–234.

Tian, E., Zeng, F., MacKay, K., Roslinsky, V. and Cheng, B. (2014) ‘Detection and molecular characterization of two FAD3 genes controlling linolenic acid content and development of allele-specific markers in yellow mustard (Sinapis alba)’, *PLoS One*, vol. 9, no. 5, e97430.

Tilman, D. (1999) ‘The ecological consequences of changes in biodiversity: A search for general principles’, *Ecology*, vol. 80, no. 5, pp. 1455–1474.

Tilman, D., Lehman, C. L. and Thomson, K. T. (1997) ‘Plant diversity and ecosystem productivity: theoretical considerations’, *Proceedings of the national academy of sciences*, vol. 94, no. 5, pp. 1857–1861.

Tilman, D., Reich, P. B., Knops, J., Wedin, D., Mielke, T. and Lehman, C. (2001) ‘Diversity and productivity in a long-term grassland experiment’, *Science*, vol. 294, no. 5543, pp. 843–845.

Tilman, D., Reich, P. B. and Knops, J. M. H. (2006) ‘Biodiversity and ecosystem stability in a decade-long grassland experiment’, *Nature*, vol. 441, no. 7093, p. 629.

Tribouillois, H., Dürr, C., Demilly, D., Wagner, M.-H. and Justes, E. (2016) ‘Determination of germination response to temperature and water potential for a wide range of cover crop species and related functional groups’, *PLoS One*, vol. 11, no. 8.

Tribouillois, H., Fort, F., Cruz, P., Charles, R., Flores, O., Garnier, E. and Justes, E. (2015) ‘A functional characterisation of a wide range of cover crop species: Growth and nitrogen acquisition rates, leaf traits and ecological strategies’, *PLoS One*, vol. 10, no. 3.

Tschuy, F., Gfeller, A., Azevedo, R., Khamissé, C., Henriet, L. and Wirth, J. (2014) ‘Weed suppression by cover crops: Analyzing different factors’, *Agrarforschung Schweiz*, vol. 5, 7-8, pp. 292–299.

Unger, P. W. and Vigil, M. F. (1998) ‘Cover crop effects on soil water relationships’, *Journal of Soil and Water Conservation*, vol. 53, no. 3, pp. 200–207.

van Wart, J., Kersebaum, K. C., Peng, S., Milner, M. and Cassman, K. G. (2013) ‘Estimating crop yield potential at regional to national scales’, *Field Crops Research*, vol. 143, pp. 34–43.

Vita, P. de, Di Paolo, E., Fecondo, G., Di Fonzo, N. and Pisante, M. (2007) ‘No-tillage and conventional tillage effects on durum wheat yield, grain quality and soil moisture content in southern Italy’, *Soil and tillage research*, vol. 92, no. 1, pp. 69–78.

Vos, J. and van der Putten, P. E.L. (1997) ‘Field observations on nitrogen catch crops. I. Potential and actual growth and nitrogen accumulation in relation to sowing date and crop species’, *Plant and soil*, vol. 195, no. 2, pp. 299–309.

Wacker, L., Baudois, O., Eichenberger-Glinz, S. and Schmid, B. (2009) ‘Effects of plant species richness on stand structure and productivity’, *Journal of Plant Ecology*, vol. 2, no. 2, pp. 95–106.

Ward, P. R., Flower, K. C., Cordingley, N., Weeks, C. and Micin, S. F. (2012) ‘Soil water balance with cover crops and conservation agriculture in a Mediterranean climate’, *Field Crops Research*, vol. 132, pp. 33–39.

Wayman, S., Cogger, C., Benedict, C., Collins, D., Burke, I. and Bary, A. (2015) ‘Cover crop effects on light, nitrogen, and weeds in organic reduced tillage’, *Agroecology and Sustainable Food Systems*, vol. 39, no. 6, pp. 647–665.

Weber, J., Kunz, C., Peteinatos, G., Zikeli, S. and Gerhards, R. (2017) ‘Weed control using conventional tillage, reduced tillage, no-tillage, and cover crops in organic soybean’, *Agriculture*, vol. 7, no. 5, p. 43.

Weiner, J., Andersen, S. B., Wille, W. K.‐M., Griepentrog, H. W. and Olsen, J. M. (2010) ‘Evolutionary Agroecology: the potential for cooperative, high density, weed‐suppressing cereals’, *Evolutionary Applications*, vol. 3, 5‐6, pp. 473‐479.

Westerman, P. R., Hofman, A., Vet, L. E.M. and van der Werf, W. (2003) ‘Relative importance of vertebrates and invertebrates in epigeaic weed seed predation in organic cereal fields’, *Agriculture, Ecosystems & Environment*, vol. 95, 2-3, pp. 417–425.

Williams, I. H. and Christian, D. G. (1991) ‘Observations on *Phacelia tanacetifolia* Bentham (Hydrophyllaceae) as a food plant for honey bees and bumble bees’, *Journal of Apicultural Research*, vol. 30, no. 1, pp. 3–12.

Wortman, S. E., Francis, C. A., Bernards, M. L., Drijber, R. A. and Lindquist, J. L. (2012) ‘Optimizing cover crop benefits with diverse mixtures and an alternative termination method’, *Agronomy Journal*, vol. 104, no. 5, pp. 1425–1435.

Wrucke, M. A. and Arnold, W. E. (1985) ‘Weed species distribution as influenced by tillage and herbicides’, *Weed Science*, vol. 33, no. 6, pp. 853–856.

Yenish, J. P., Worsham, A. D. and Chilton, W. S. (1995) ‘Disappearance of DIBOA-glucoside, DIBOA, and BOA from rye (*Secale cereale* L.) cover crop residue’, *Weed Science*, vol. 43, no. 1, pp. 18–20.

Zhou, X., Roberts, R. K., Larson, J. A., Lambert, D. M., English, B. C., Mishra, A. K., Falconer, L. L., Hogan, R. J., Johnson, J. L. and Reeves, J. M. (2016) ‘Differences in glyphosate-resistant weed management practices over time and regions’, *Weed Technology*, vol. 30, no. 1, pp. 1–12.

Zuppinger-Dingley, D., Schmid, B., Petermann, J. S., Yadav, V., Deyn, G. B. de and Flynn, D. F. B. (2014) ‘Selection for niche differentiation in plant communities increases biodiversity effects’, *Nature*, vol. 515, no. 7525, p. 108.

Curriculum vitae

Personal Data

Name: Alexandra Schappert

Date and Place of Birth: 23rd of April 1991, Meisenheim

University Education

April 2016 – to date	Doctoral Candidate at the Department of Weed Science, Institute of Phytomedicine, University of Hohenheim
April 2016 – to date	PhD School ‘Water for life’, Anton & Petra Ehrmann-Stiftung Research Training Group, University of Hohenheim
Oct. 2013 – March 2016	Studies in Biobased Products and Bioenergy, University of Hohenheim *Master of Science (M.Sc.)*
Oct. 2010 – Oct. 2013	Studies in Biobased Products and Bioenergy, University of Hohenheim *Bachelor of Science (B.Sc.)*

Work Experience

2019 – to date	Research Assistant at the Department of Management of Crop Water Stress in the Tropics and Subtropics and at the Anton & Petra Ehrmann-Stiftung Research Training Group, University of Hohenheim

2016 – 2019	Academic Assistant at the Department of Management of Crop Water Stress in the Tropics and Subtropics and at the Anton & Petra Ehrmann-Stiftung Research Training Group, University of Hohenheim
2011 – 2015	Student Assistant at the Department of Management of Crop Water Stress in the Tropics and Subtropics and at the Anton & Petra Ehrmann-Stiftung Research Training Group, University of Hohenheim

School Education

2001 – 2010	Paul-Schneider Gymnasium, Meisenheim *Abitur*

Stuttgart-Hohenheim, 23. September 2019

Danksagung

An dieser Stelle, sei all denen gedankt, die zur Entstehung dieser Arbeit beigetragen haben. Ein besonderer Dank geht an Prof. Dr. Roland Gerhards für die Möglichkeit zur Promotion. Ich möchte mich bei Dr. Dominic J. Sturm bedanken, der vor allem zu Beginn, aber auch während der gesamten Promotionsphase ein willkommener Berater war und dessen Versuche zum Gelingen dieser Arbeit beigetragen haben.

Bei Kevin Leitenberger, Aline Huber, Sebastian Bökle und dem gesamten Team der Versuchsstation Ihinger Hof möchte ich mich für die Unterstützung und Durchführung der Feldversuche bedanken. Danke an die Studierenden Charlotte Hein, Constanze Heck, Lena Nicolai, Matthias Haep und Sarah Kalmbach, die mich bei Hitze sowie Kälte auf dem Feld unterstützt haben. Besondere Erwähnung findet hierbei Stefanie Krauter, durch die einige meiner Fragestellungen einen anderen Schwerpunkt bekommen haben. Ein großes Dankeschön geht an Marcus Saile, der das große Potential von Zwischenfrüchten zur Kontrolle von Ackerfuchsschwanz aufgezeigt hat. Danke an alle Kolleginnen, Kollegen und Freunde im Fachgebiet Herbologie, die mir bei den Versuchen geholfen haben. Danke an Robin Mink und Alexander I. Linn für die Installation der Bodenfeuchte-Messrohre. Weiter danke ich Alexander I. Linn, Dr. Gerassimos P. Peteinatos und Matthias Schumacher für ihre Begeisterungsfähigkeit und die (statistische) Beratung. Jeffrey Thimm danke ich für das ‘proofreading’.

Dr. Marcus Giese und Prof. Dr. Folkard Asch danke ich für das Vertrauen und den Zuspruch, der dazu beigetragen hat, dass ich mich persönlich und wissenschaftlich in dieser Weise entwickeln und einbringen konnte. Ganz besondere Erwähnung findet hier auch das ‘Ministerium für Ländlichen Raum, Ernährung und Verbraucherschutz Baden-Württemberg (MLR)’ mit dem Projekt ‘Konservierende Bodenbearbeitung’ und das Graduierten Kolleg ‘Water-People-Agriculture’ von der Anton & Petra-Ehrmann Stiftung, die mich sowohl fachlich, als auch finanziell unterstützt haben.

Ich möchte meiner Familie danken, die mir das Studium sowie die Promotion ermöglicht haben. Ein besonderer Dank geht an Sören Wansel, der immer mein stärkster Befürworter war und ohne den vieles anders gekommen wäre.

Eidesstattliche Versicherung über die eigenständig erbrachte Leistung gemäß § 18 Absatz 3 Satz 5 der Promotionsordnung der Universität Hohenheim für die Fakultäten Agrar-, Natur- sowie Wirtschafts- und Sozialwissenschaften

1. Bei der eingereichten Dissertation zum Thema

Evaluating different Management Strategies to Increase the Effectiveness of Winter Cover Crops as an Integrated Weed Management Measure

handelt es sich um meine eigenständig erbrachte Leistung.

2. Ich habe nur die angegebenen Quellen und Hilfsmittel benutzt und mich keiner unzulässigen Hilfe Dritter bedient. Insbesondere habe ich wörtlich oder sinngemäß aus anderen Werken übernommene Inhalte als solche kenntlich gemacht.

3. Ich habe nicht die Hilfe einer kommerziellen Promotionsvermittlung oder -beratung in Anspruch genommen.

4. Die Bedeutung der eidesstattlichen Versicherung und der strafrechtlichen Folgen einer unrichtigen oder unvollständigen eidesstattlichen Versicherung sind mir bekannt.

Die Richtigkeit der vorstehenden Erklärung bestätige ich. Ich versichere an Eides Statt, dass ich nach bestem Wissen die reine Wahrheit erklärt und nichts verschwiegen habe.

Stuttgart-Hohenheim, 23.09.2019 A. Schappert