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Institute for Phytomedicine
Department of Weed Science (360b)

Weed Suppression with Cover Crops and Undersown Crops in Modern Cropping Systems

Dissertation

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Für Angeliki

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Abbreviations and Acronyms

%	Percent
=	Equality sign
$\leq$	Less than or equal to
°C	Degrees Celsius
°E	Degree east/longitude
°N	Degree north/latitude
Benth.	Bentham
C_4	Plants with C_4 carbon fixation
Cass.	de Cassini
cm	Centimetre
DAP	Days after planting
dt.	Decitonne
e.g.	For example
et al.	Et alii (and others)
Fig.	Figure
g	Gram
Gaertn.	Gärtner
ha	Hectar
HH	Hohenheim
IHO	Ihinger Hof

kg	Kilogramm
L.	Linné
Lam.	Lamarck
L.f.	Linnaeus the Younger
ltm.	Longtime monthly
m	Metre
m^2	Square metre
mg	milligram
MV	Mean value
N	Nitrogen
N_{min}	Soil available mineral nitrogen
NO_3^-	Nitrate
Poir.	Poiret
Schreb.	von Schreber
scop.	Scopoli
SD	Standard deviation
STD	Standard deviation
t	Ton
T_{50}	Time until 50 percent emergence
Tab.	Table
TR	Trossin
USA	United States of America
Vill.	Villars
WAP	Weeks after planting
α	Probability

1 General Introduction

1.1 Actual situation in German agricultural systems

Sustainability and the production of high yields are the most important purposes of every cropping system. However, the resilience and yield stability of cropping systems decreases if crop diversity within the cropping system is reduced (Smith et al., 2008). In the last decade, only a small number of cash crop species were grown in German agricultural systems due to economic constraints and regional circumstances. In 2011, the fall seeded crops winter wheat, winter barley and winter rape were grown on 47.7 % of the entire arable land in Germany. Considering additionally the cultivation of silage corn, four different crop species were cultivated on 65 % of German fields (Statistisches Bundesamt, 2013). However, the proportion of these crops in crop rotations is not uniformly distributed across Germany due to different soil and climatic conditions. Therefore, in many cropping systems only one spring seeded crop occurs within a period of three or even four years. Especially in low diverse cropping systems with no periodically change between spring and fall seeded crops become pests, diseases and especially weeds more and more an important problem (Blackshaw et al., 1994; Brust and King, 1994; Guo et al., 2005).

To minimize crop injury by pests, diseases and weeds in those cropping systems, increased application of pesticides and intensive tillage with the moldboard plow are required (Kegode et al., 1999; Légère et al., 1997). However, tillage with the moldboard plow is cost expensive, time consuming, damages the soil structure, reduces the water infiltration, increases the risk of soil erosion and harms the soil biology (Gebhardt et al., 1985). Therefore, farmers changed their cultivation management and used less intensive tillage equipment like chisels plows and disc harrows or they even omitted soil tillage. Although reduced tillage and conservation agriculture improve the stability of cropping systems against environmental factors, the combination with a monotonous crop diversity results in increased occurrence of pests, diseases and weeds (Anderson et al., 1998).

Reasons for the increasing weed population in those cropping systems are the stay of weed seeds in soil layers from which they can emergence and furthermore the absence of alternating growth conditions which preserves the repeated propagation of weed species with a well adapted life cycle to the occurring agronomic practice (Benvenuti et al., 2001; Liebman and Dyck, 1993). To control the increasing weed population frequent application of herbicides during vegetation of the cash crop but also during fallow periods are necessary to prevent weeds from seed dispersal (Ghosheh and Al-Hajaj, 2005). Especially the seed dispersal of weeds during fallow periods increases the weed seedbank and results in higher weed emergence in the following years (Cardina et al., 2002; Mulugeta and Stoltenberg, 1997). Even if fallow periods are too short for seed dispersion or if reduced weed growth occurs like in winter months, the application of a burn down herbicide is common practice prior seeding of the following cash crop, especially in cropping systems with reduced tillage. Reason therefore is the fact that most herbicides are not able to control mature weeds without damaging growth or yield formation of the crop. However, also with a frequently application of herbicides, weed density is still high in such agricultural systems. Furthermore, an increased development of herbicide resistances can be observed due to the repeated application of herbicides with identical mode of action (Chauvel et al., 2009; Price et al., 2011). To avoid or at least reduce these problems of conservation tillage and low cash crop diversity, cultivation of cover crops and undersown crops can can be a possible solution to increase the sustainability of those cropping systems.

1.2 Benefits of cover crops

Cover crops are plants which grow between two cash crops and provide multiple benefits to the agroecosystem (Hartwig and Ammon, 2002). Among others, cover crops are able to prevent soil erosion by wind and water, reduce leaching of water soluble nutrients, improve the soil structure and build vertical macro pores which increase water infiltration (De Baets et al., 2011; Hooker et al., 2008; Parlak and Özaslan Parlak, 2010; Stirzaker and White, 1995). Due to shading of the soil surface in summer months, cover crops are able to reduce the temperature of the upper soil layer, which is beneficial for the microbial community (Levy et al., 2007).

Cultivated in fall instead of fallow, cover crops are also able to suppress growth of weeds and volunteer crops by competition for light water and nutrients or through the release of allelopathic substances (Bezuidenhout et al., 2012; Creamer et al., 1996). If summer annual cover crops suppress weeds and volunteer crops during their vegetation in fall and freeze in frosty winter nights, they may provide a seedbed without living plants in spring. Therefore, successful cultivation of cover crops can avoid tillage or the application of a burn down herbicide like glyphosate in fall and prior to cash crop seeding in spring.

To achieve these beneficial effects, cover crop should offer the following growth characteristics:

- long period of possible seeding dates in fall.
- fast germination and emergence even under dry and unfavorable soil conditions.
- fast soil coverage within few weeks after sowing.
- long time of vegetative growth to produce a high amount of shoot and also root dry matter.
- no development of fertile seeds to prevent growth of “weedy” cover crops in the next cash crop.
- enough frost tolerance to avoid early frost kill before the end of the vegetation period in fall.

In the last years, only few summer annual cover crop species were cultivated in Germany (Statistisches Bundesamt, 2007). Mainly yellow mustard, oilseed radish and phacelia were cultivated, because there are easy to manage and well adapted to growth conditions in fall. Seeded before mid of August, yellow mustard, oilseed radish and phacelia offer only a short period of vegetative growth due to long-day photoperiodism, which highly reduces their beneficial effects. However, compared to seeding dates at end of August, cover crops provide in general more benefits if there were planted in summer immediately after harvest of the previous cash crops. Due to an early seeding date, cover crops achieve longer time for vegetation during warm and sunny days at the end of summer, which results in higher above and below ground dry matter production (Fourie et al., 2001). Therefore new cover crops species are required which get along with early seeding dates immediately after harvest but also with cool and rainy growth conditions in fall.

One of those potential new cover crop species could be tartary buckwheat (*Fagopyrum tataricum* (L.) Gaertn.) because it has a fast youth growth and the ability of rapid soil coverage due to its broad leaves (Campbell, 1997). Another potential new cover crop species for Central Europe is forage radish (*Raphanus sativus* L. var. longipinnatus), which is already cultivated as cover crop in in the Mid-Atlantic region of the USA (White and Weil, 2010). Forage radish is able to cover the soil surface within a few weeks after sowing. Furthermore it has the ability to penetrate even through compacted soil layers with its vigorous taproot (Lawley et al., 2011). Lopsided oat (*Avena strigosa* Schreb.) and red oat (*Avena byzantina* K. Koch) are also potential cover crop species for Central Europe. Lopsided oat is a popular cover crop in no-till cropping systems in south America (Derpsch et al., 1986). It is characterized by a rapid growth and high biomass production, which are suitable characteristics for a cover crop. Red oat is mainly cultivated for forage and grain production in south Brazil and is also used as cover crop in no-till systems (Martinez et al., 2010). The suitability of red oat as cover crop has only been examined in a reduced extend. However, due to its close relation to common oat (*Avena sativa* L.), which is also a suitable cover crop successful cultivation as summer annual cover crop could be possible.

A further potential cover crop species is niger (*Guizotia abyssinica* (L.f.) Cass.), an annual herbaceous plant from the *Asteraceae* family. Niger has broad leaves, a fast growth within the first few weeks after sowing and the ability to build up a huge amount of dry matter. Its origin is Ethiopia, where it is cultivated as an oilseed crop (Yadav et al., 2012). Niger grows on a wide range of soil types but needs temperatures between 15 °C and 23 °C for good growth (Getinet and Sharma, 1996). Sorghum (*Sorghum bicolor* L. Moench) is a summer annual C_4 grass which offers best growth in warm and sunny environments (Snapp et al., 2005). It is able to close the soil surface rapidly and produces a large amount of dry matter (Ngouajio et al., 2003). Sorghum has a high ability for weed suppression by competition for main growth factors and also due to the release of allelochemicals from living and decomposing plant tissue (Bicksler and Masiunas, 2009). The last potential new cover crop species is grain amaranth (*Amaranthus cruentus* L.) which was only tested as cover crop in few studies until now. But due to its broad and shallow angled leaves and fast growth it could be well suited as cover crop (Boer et al., 2008; Mennan et al., 2009). If successful cultivation of those new cover crop species in Central Europe is possible, farmers get more opportunity for cover crop cultivation, which may result in a more stable cropping system and reduced application of pesticides.

1.3 Benefits of undersown crops

Undersown crops are plants which are seeded either together with, or shortly after cash crops, which are called main crops if they are cultivated together with undersown crops. Undersown crops are grown as living ground cover during and also after the growing season of the main crop (Hartwig and Ammon, 2002). Like summer or fall seeded cover crops, undersown crops are able to reduce erosion, enhance the soil microbial activity, and could increase the soil organic matter, which improves the storage of plant nutrients and water (Brandsæter et al., 2012; Breland, 1995; Känkänen and Eriksson, 2007; Nakamoto and Tsukamoto, 2006). Furthermore, undersown crops have the ability to suppress or prevent the germination and growth of weeds during and after the vegetation of the main crop (Ballaré and Casal, 2000; Kruk et al., 2006).

However, not all plants have the ability to handle the previous mentioned aims. For a usage as undersown crop, a plant species should be easy to broadcast in already growing plant stocks, germinate even under dry and unfavorable seedbed conditions and should offer an adequate growth under limited light conditions. After establishment, no negative interference on yield formation of the main crop should occur neither by competition about limited growth factors nor due to release of allelopathic substances (Bezuidenhout et al., 2012; Carof et al., 2007; den Hollander et al., 2007; Liedgens et al., 2004; Putnam and DeFrank, 1983). Also a small shoot growth is beneficial to prevent competition about space and light or interruption at harvest (Hively and Cox, 2001). Furthermore, the undersown crop should not be a host for pests and diseases or become a weed in the subsequent crop due to seed propagation or regrowth. Especially forage and grassland plants achieve these requirements in most cases. Therefore, members of the *Poaceae* and *Fabaceae* plant family are mainly used as undersown crops. In Germany many undersown crop species are available which are well adapted to local conditions.

Beside others, perennial ryegrass (*Lolium perenne* L.), Italian ryegrass (*Lolium multiflorum* Lam.) and red fescue (*Festuca rubra* L.) are commonly used grass species (Kunelius et al., 1992). From the fabacea family, primarily white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.) and subterranean clover (*Trifolium subterraneum* L.) are popular undersown crops (Deguchi et al., 2007; Echtenkamp and Moomaw, 1989; Ilnicki and Enache, 1992). The main advantage of legume undersown crops is their ability to fix atmospheric nitrogen, due to a symbiosis with Rhizobium bacteria, which can be transferred to the main crop or is available in the subsequent crop (Boller and Nösberger, 1987; Burity et al., 1989; Jensen, 1996; Mallarino et al., 1990). Due to their shallow angled leaves, legumes have faster soil coverage than grasses, which is an important factor for the suppression of weeds. While legumes have a taproot with a relatively small amount of fine roots, grass species offer a fibrous root system, which allows an enhancement of the soil structure and intensive depletion of water and nitrogen(Breland, 1995; Craine et al., 2003).

Undersown crops are mainly cultivated in cereals and corn, because in those crops no growth and yield decrease or interference during the harvest process occurs if adapted management strategies are realized. To prevent the main crop from yield reduction, while adequate growth of undersown crops (e.g. for weed suppression) is still possible, it is important to harmonize the undersown crop and the main crop either by selecting suitable plant species or by cultural practice. By the variation of cultural practice farmers can adapt a certain undersown crop to an otherwise unsuitable main crop by adjusting plant density, irrigation, fertilization and the time of undersown crop establishment. Especially, the sowing date has a huge influence on the growth and competition ability of undersown crops. The possible period of undersown crop establishment depends on the growth and competition ability of the undersown crop species and the main crop. Due to adapted combination of undersown crop species, main crop and sowing date it can be possible to cultivate even highly competitive undersown crop species in sensitive main crop stands without yield decrease. On the other hand it is also possible to reach good growth of low competitive undersown crop species in fast growing main crops.

With a harmonized management strategy it can be possible to achieve good growth of different undersown crop species under many environmental situations, which is required for a sustainable weed suppression. Due to weed suppression with undersown crops it could be possible to reduce the amount of applied herbicides especially in cropping systems with an reduced amount of tillage.

1.4 Objectives of this thesis

The objectives of this thesis were:

- to evaluate the suitability of new cover crop species for cultivation in Central Europe.
- to evaluate the ability of common and new cover crop species for suppression of weeds and volunteer grain under German growing conditions after harvest of grain cereals in fall.
- to determine if cultivation of cover crops in previous fall can reduce the weed density in spring prior seeding next crop.
- to asses if management of undersown crops influences the growth and yield formation of the main crop.
- to asses if management of undersown crops influences their ability to suppress weeds.

2 Publications

The publications related to this work are listed as follows:

- Reviewed publications:
  - Warum Untersaaten und Zwischenfrüchte wieder Bedeutung zur Unkrautregulierung in Europäischen Ackerbausystemen bekommen
  - Growth and weed suppression ability of common and new cover crops in Germany
- Conference proceedings:
  - Lopsided oat (*Avena strigosa*) as a new summer annual cover crop for weed suppression in Central Europe
- Submitted (in review):
  - Evaluation of Three Potential Cover Crops for Weed Suppression in Central Europe
  - Management of undersown crops influences their competitiveness with cereals and weeds

A briefly description of the paper content is given in the front of every section.
Please note that only the abstracts of the publications are included due to the coprights of the publishers, except where submitted versions were not yet published.

2.1 Warum Untersaaten und Zwischenfrüchte wieder Bedeutung zur Unkrautregulierung in Europäischen Ackerbausystemen bekommen

Section 2.1 gives an overview about reasons why cover crops and undersown crops are important for weed suppression in European cropping systems. The section includes three field experiments which show the successful suppression of weeds by cover crops and undersown crops. The cover crop section of the paper describes the suppression of weeds and volunteer grain in fall by different cover crop species and gives a brief introduction about the underlying mechanisms. The undersown crop section of the paper describes the growth of different undersown crop species during vegetation and after harvest of the main crop. Furthermore, the undersown crop section shows that growth and yield formation of the main crop not necessarily were influenced by the different undersown crop species.

Warum Untersaaten und Zwischenfrüchte wieder Bedeutung zur Unkrautregulierung in Europäischen Ackerbausystemen bekommen / Why Undersown and Cover Crops Become Important Again for Weed Suppression in European Cropping Systems

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Zusammenfassung

Die positiven Wirkungen von Zwischenfrüchten und Untersaaten auf das Agrarökosystem sind bereits vielfach belegt. In europäischen Ackerbausystemen hat sich der Anteil an Winterungen stark erhöht, weshalb Zwischenvegetationszeiten für den Anbau von Zwischenfrüchten verkürzt sind. In dieser Studie wurde untersucht, ob Zwischenfrüchte und Untersaaten auch Unkräuter in solchen Anbausystemen effektiv unterdrücken können. Hierzu wurden in den Jahren 2008 bis 2010 an der Universität Hohenheim drei Feldversuche durchgeführt. Weißklee (*Trifolium repens*) und Deutsches Weidelgras (*Lolium perenne*) konnten als Untersaat in Weizen und Dinkel die Dichte und Trockenmasse der Unkräuter verringern ohne die Bestandesdichte oder den Kornertrag des Getreides negativ zu beeinflusst. Nach der Getreideernte bildete sich innerhalb von zwei Wochen aus der Untersaat ein dichter Pflanzenbestand. Im dritten Feldversuch wurden Gelbsenf (*Sinapis alba*), Phacelia (*Phacelia tanacetifolia*), Sandhafer (*Avena strigosa*) und eine Gemenge aus Alexandrinerklee (*Trifolium alexandrinum*), Saatwicke (*Vicia sativa*), Tatarischer Buchweizen (*Fagopyrum tataricum*) und Ramtillkraut (*Guizotia abyssinica*) unmittelbar nach der Weizenernte etabliert. Die Zwischenfrüchte liefen schnell auf und verringerten die Anzahl und Biomasse der auflaufenden Unkräuter. Gelbsenf verringerte die Sprossmasse der Unkräuter um 93 %. Sandhafer reduzierte die Wurzelmasse der Unkräuter um 97 % und die Unkrautdichte um 90 %. Voraussetzung hierfür ist jedoch ein rasches ober- sowie unterirdisches Wachstum der Zwischenfrüchte, verbunden mit einer intensiven Beschattung der Unkräuter. Die Untersuchungen belegen dass Zwischenfrüchte und Untersaaten, auch in intensiven Ackerbausystemen, einen Beitrag zur nachhaltigen und umweltschonenden Bewirtschaftung leisten können.

Schlüsselwörter: Untersaaten, Zwischenfrüchte, Unkrautregulierung

Abstract

Cover crops and under-sown crops influence the agroecosystem in many positive ways and have the ability to suppress weeds. However, the proportion of winter annual cereals in European cropping system has strongly increased, which consequently reduced the time for cover crop cultivation. In this study, it was investigated if cover crops and under-sown crops have the ability to reduce weed infestations also in rotations with a high percentage of winter annual cereals. Therefore, three field experiments were conducted at the University of Hohenheim from 2008 until 2010. *Trifolium repens* and *Lolium perenne* reduced weed density and biomass in *Triticum aestivum* and *Triticum spelta*, when they were cultivated as under-sown crops. Both under-sown crops had no negative effect on yield of cereals. Until 14 days after harvest, under-sown crops established a dense plant canopy. In the third experiment, *Sinapis alba*, *Phacelia tanacetifolia*, *Avena strigosa* and a mixture of *Trifolium alexandrinum*, *Vicia sativa*, *Fagopyrum tataricum* and *Guizotia abyssinica* were cultivated directly after harvest of winter wheat. The cover crops emerged after few days and were able to reduce the density and biomass of weeds. *Sinapis alba* reduced above-ground weed biomass by 93 %. *Avena strigosa* suppressed root growth of weeds by 97 % and weed density by 90 %. To achieve a high weed suppression, it is necessary for cover crops to emerge quickly and grow rapidly until complete soil coverage. The results underline the capability of under-sown and cover-crops to promote a sustainable and environmental friendly cropping system.

Key words: Cover crops, Under-sown crops, Weed control, Weed suppression

2.2 Growth and weed suppression ability of common and new cover crops in Germany

Section 2.2 deals with the growth and weed suppression ability of common and new cover crop species in Germany. This study evaluates the suitability of tartary buckwheat, forage radish, red oat and grain amaranth for cultivation in Germany and compare it to the common cover crops yellow mustard, oilseed radish and phacelia. Results presented in this section were collected in four field experiments at three locations in south-west and eastern Germany during the years 2010, 2011 and 2012. Beside the growth characteristics of cover crops, which included emergence, soil coverage and dry matter accumulation, the weed suppression ability of cover crop species in fall and the weed density in spring were measured as well.

Growth and weed suppression ability of common and new cover crops in Germany

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Abstract

Cover crops are able to provide multiple benefits for the agroecosystem and farmers. Cover crops are able to suppress weeds during fall and winter, which is a main requirement for the reduction of tillage and herbicides. However, only a few cover crop species are currently grown in Germany. Therefore, four new cover crop species (tartary buckwheat, forage radish, red oat and grain amaranth) were compared with common cover crop species (white mustard, oilseed radish and phacelia) regarding their soil coverage, dry matter production and weed suppression ability. White mustard emerged faster than all other cover crops and build the most shoot dry matter at both locations in southwest Germany twelve weeks after planting (WAP). Only oilseed radish was able to reduce the weed dry matter at all locations eight WAP. Phacelia reduced weed density by 77 % at Meiereihof twelve WAP. Tartary buckwheat provided the highest soil coverage four WAP, offered the most shoot dry matter eight WAP and was able to reduced weed dry matter by more than 96 % at Meiereihof and Ihinger Hof twelve WAP. Forage radish showed best root growth and reduced the weed density in spring by more than 81 % at all location. Red oat and grain amaranth emerged slower, produced a reduced amount of biomass than the other cover crops and were not able to suppress weeds. The results suggest that tartary buckwheat and forage radish are well suited for cultivation as cover crops in Germany due to their fast growth and good suppression of weeds.

Keywords: Root growth, Weed suppression, Weed–crop interactions, Volunteer crops

2.3 Lopsided oat (*Avena strigosa*) as a new summer annual cover crop for weed suppression in Central Europe

Section 2.3 describes the growth and weed suppression ability of lopsided oat to evaluate its suitability for cultivation as new summer annual cover crop in Central Europe. Therefore, emergence, shoot and also root growth of lopsided oat were measured in a pot and field experiment and compared to common cover crop species. Additionally the ability of lopsided oat to suppress weeds in fall and spring was measured in the field experiment.

Lopsided oat (*Avena strigosa*) as a new summer annual cover crop for weed suppression in Central Europe / Rauhafer (*Avena strigosa*) als neue Zwischenfrucht zur Unkrautunterdrückung in Mitteleuropa

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Abstract

Lopsided oat (*Avena strigosa*) is a common summer annual cover crop in Brazil since many years. Two experiments were carried out in Stuttgart-Hohenheim in 2010 to compare the growth and weed suppression ability of lopsided oat with yellow mustard (*Sinapis alba*), phacelia (*Phacelia tanacetifolia*) and a cover crop mixture. The emergence and dry matter production of the cover crop species were analyzed in a pot experiment. Lopsided oat build 20.7 dt ha^{-1} of shoot- and 5.5 dt ha^{-1} of root dry matter twelve weeks after planting. A field experiment was established after harvest of winter wheat in summer. The soil was prepared with a disc harrow and cover crops were sown the next day. At four week intervals, dry matter and plant density of cover crops, weeds and volunteer wheat were measured. Twelve weeks after planting, 17.8 dt ha^{-1} of shoot- and 6.2 dt ha^{-1} of root dry matter was built by lopsided oat. Lopsided oat was able to reduce the shoot dry matter of weeds and volunteer wheat by 98 %, which was the best result of all cover crops. Cover crops were able to reduce the root dry matter of weeds and volunteer wheat by 55 % to 97 %. While a density of 54.5 plants m^{-2} was measured in the weedy control plots, only 5.5 plants m^{-2} were counted in plots of lopsided oat. The results suggest that lopsided oat could be well suited for the suppression of weeds and volunteer wheat in autumn. Furthermore, its cultivation would also increase the number of cover crops in Central Europe.

Keywords: Competition, Field experiment, Pot experiment, Root, Shoot, Volunteer wheat

Zusammenfassung

Rauhafer (*Avena strigosa*) wird vor allem in Brasilien als Zwischenfrucht angebaut. Um die Eignung von Rauhafer zur Unterdrückung von Unkräutern/Ausfallgetreide mit Gelbsenf (*Sinapis alba*), Phacelia (*Phacelia tanacetifolia*) sowie einer Zwischenfruchtmischung zu vergleichen wurden im Jahre 2010 zwei Versuche in Stuttgart Hohenheim durchgeführt. Auflaufen sowie Wachstum der Zwischenfrüchte wurden in einem Topfversuch bestimmt, bei welchem Rauhafer eine Spross- sowie Wurzel-Trockenmasse von 20,7 dt ha^{-1} und 5,5 dt ha^{-1} zwölf Wochen nach Aussaat bildete. Ein Feldversuch wurde nach Winterweizen etabliert um Anzahl und Trockenmasse der Zwischenfrüchte, der Unkräuter und des Ausfallgetreides zu messen. Die Aussaat erfolgte unmittelbar nach der Weizenernte im Anschluss an eine ca. 5 cm tiefe Bodenbearbeitung mit einer Kurzscheibenegge. Rauhafer konnte nach zwölf Wochen eine Spross- und Wurzel-Trockenmasse von 17,8 dt ha^{-1} und 6,2 dt ha^{-1} bilden. Das Spross-Wachstum der Unkräuter und des Ausfallgetreides konnte von Rauhafer um 98 % reduziert werden, der höchste gemessene Wert. Die Zwischenfrüchten konnten die Wurzel-Trockenmasse der Unkräuter und des Ausfallgetreides zwischen 55 % und 97 % reduziert. Während in den Kontrollparzellen 54,5 Unkräuter m^{-2} wuchsen wurden in den Rauhafer-Parzellen nur 5,5 Unkräuter m^{-2} gemessen. Die Ergebnisse der Versuche legen nahe dass Rauhafer sehr gut Unkräuter sowie Ausfallgetreide unterdrücken kann. Der Anbau von Rauhafer würde zu einer Bereicherung des bisherigen Spektrums an Zwischenfrüchten in Mitteleuropa führen.

Stichwörter: Ausfallgetreide, Feldversuch, Konkurrenz, Spross, Topfversuch, Wurzel

2.4 Evaluation of Three Potential Cover Crops for Weed Suppression in Central Europe

Section 2.4 includes the evaluation of the three potential cover crop species, namely niger, sorghum and lopsided oat, for cultivation and weed suppression in Central Europe. The section includes results from five field- and two pot experiments which were conducted in south-west and eastern Germany from 2010 to 2012. Different growth characteristics, which are important for the successful cultivation of cover crops like soil coverage, above and belowground dry matter accumulation were measured during the study. Furthermore, the ability of the three potential cover crops to suppress a common weed community in fall and particular the control of mono and dicotyledonous weeds were evaluated.

Evaluation of Three Potential Cover Crops for Weed Suppression in Central Europe

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Summary

Cover crop cultivation offers lots of advantages to agroecosystems. However, currently only a few cover crop species are cultivated in Central Europe. To enlarge this number, two experiments were conducted in 2010 and 2011 at four locations in southwestern and eastern Germany, to evaluate the growth and weed suppression ability of niger, lopsided oat and sorghum. In the cover crop evaluation experiment, niger and sorghum show comparable soil coverage and dry matter production as white mustard, a common cover crop in Central Europe. Lopsided oat offered variable results regarding its soil coverage and dry matter accumulation. Niger had a high competitive ability and was able to reduce shoot dry matter of weeds at all locations. Sorghum could reduce the shoot dry matter of weeds by 69 % at Meiereihof and 88 % at Ihinger Hof. Until spring, lopsided oat was able to reduce weed density by 97 % at Ihinger Hof and 99 % at Trossin. In the competition experiment, niger and sorghum were able to suppress growth of both weed species at Ihinger Hof, however, at Hohenheim, they were not able to suppress root growth of annual ryegrass. Lopsided oat had problems to reduce growth of annual ryegrass at both locations. The results suggest that all plant species may have the potential for suitable cultivation as cover crops in Central Europe.

Nomenclature: niger, *Guizotia abyssinica* (L.f.) Cass.; lopsided oat, *Avena strigosa* Schreb.; sorghum, *Sorghum bicolor* L. Moench; forage rape, *Brassica napus* L.; annual ryegrass, *Lolium multiflorum* Lam.

Key words: Niger, Sorghum, Lopseded oat, Weed dry matter, Weed density, Root growth

2.4.1 Introduction

Cover crops are an important part of agricultural systems to save and improve soil and crop quality. Cover crops are able to reduce soil erosion by wind and water (De Baets et al., 2011), enhance water infiltration (Gulick et al., 1994), increase soil organic carbon (Kuo et al., 1997), prevent the leaching of nitrate into groundwater (Logsdon et al., 2002), reduce soil compaction and build macro pores for the subsequent cash crop (Williams and Weil, 2004). Another important property of cover crops is the suppression of weeds and volunteer crops after harvest. Cover crops are able to suppress weeds by competition for main growth factors (light, water and nutrients) or the release of allelochemicals from living and decomposing plant tissue (Bezuidenhout et al., 2012; Creamer et al., 1996; Dhima et al., 2006). Today, only a small number of cover crop species are grown in Central Europe. Especially white mustard (*Sinapis alba* L.) is cultivated, because it is easy to manage and well adapted to fall growth conditions. However, white mustard requires relatively high amounts of soil water, moderate temperatures and a short day-length for high dry matter production and good weed suppression. Therefore, other cover crops are required, which rapidly cover the soil and produce a high amount of dry matter for good weed control, even under dry and unfavorable conditions directly after summer harvest.

In Central Europe, a successful cultivation of subtropical plant species as summer annual cover crops seems to be possible, because they only grow a short period of time during relatively warm months at the end of summer. In most years, this is enough time for good vegetative growth, but not for flowering and maturing of seeds. Another characteristic of subtropical plants, which could be a benefit for farmers, is their poor frost resistance. This ensures that cover crops are killed by frost over winter and do not grow as a weed in the following cash crop.

One of these potential new cover crops is niger (*Guizotia abyssinica* (L.f.) Cass.), an annual herbaceous plant which belongs to the *Asteraceae* family. Today, niger is cultivated as an oilseed crop in many parts of East Africa, India and Pakistan (Yadav et al., 2012). Depending on plant density, the shoot is moderately- to well- branched and could reach a height between

0.5 and 1.5 m. Its leaves are 10-20 cm long, 3-5 cm wide, and with a shallow leaf angle oppositely arranged at the shoot. Niger grows on a wide range of soil types, even at low pH-value. However, for good growth, temperatures between 15 °C and 23 °C and a moderate amount of rainfall are required (Getinet and Sharma, 1996). Lopsided oat (*Avena strigosa* Schreb.) is an important cover crop for conservation-tilled soybeans in southern Brazil and Paraguay. For a few years now, lopsided oat has also been grown in conservation agriculture systems in the southeastern USA and southwestern Australia (Bauer and Reeves, 1999; Flower et al., 2012). Lopsided oat seems to be well suited as cover crop, due to rapid growth and high biomass production. It is able to suppress weeds by direct competition and allelopathy (Price et al., 2008). Sorghum (*Sorghum bicolor* L. Moench) is a summer annual C_4 grass which is well adapted to dry, warm and sunny environments (Snapp et al., 2005). Commonly, it is cultivated for grain production or as forage crop. Used as a cover crop, sorghum rapidly closes canopy, produces a large amount of dry matter, immobilizes leachable nutrients and is able to reduce soil compaction (Ngouajio et al., 2003). Sorghum is a strong competitor and able to suppress even perennial weeds like Canada thistle (*Cirsium arvense* (L.) Scop.) due to physical interference and the release of allelochemicals (Bicksler and Masiunas, 2009).

The objectives of this study were to determine the growth characteristics and the weed suppression ability of niger, lopsided oat and sorghum to evaluate their suitability for cultivation as cover crops in Central Europe.

2.4.2 Materials and Methods

Experimental sites.

A cover crop evaluation- and a competition experiment were conducted at four locations in southwestern and eastern Germany. The cover crop evaluation was carried out in 2010 in pots at the University of Hohenheim (48°70′ N, 9°20′ E, 407 m altitude) to study growth of cover crops in fall. In 2011, the cover crop evaluation was conducted under field conditions at the experimental station Meiereihof (48°71′ N, 9°21′ E, 435 m altitude), Ihinger Hof (48°74′ N, 8°92′ E, 478 m altitude) and Trossin (51°61′ N, 12°81′ E, 120 m altitude) to measure additionally the weed suppression in fall and spring. The competition experiment was done in 2011, in pots at the University of Hohenheim and under field conditions at Ihinger Hof to study the interaction of cover crops with a dicotyledonous and a monocotyledonous "model weed". Soil used in pots at Hohenheim in 2010 was from Ihinger Hof, while in 2011, it was from the experimental station "Heidfeldhof" (48°71′ N, 9°20′ E, 430 m altitude). Climate and soil characteristics of the experimental sites are presented in Table 1.

Table 1: Average climatic conditions, soil properties and amount of soil mineral nitrogen (N_{min}) in both experiments.

	Cover crop evaluation				Competition experiment	
	Hohen-heim	**Meierei-hof**	**Ihinger Hof**	**Trossin**	**Hohen-heim**	**Ihinger Hof**
Av. Temp. (°C)	8.8	8.8	9.2	9.1	8.8	9.2
Av. Percep. (mm)	700	700	794	500	700	794
Soil texture	Clay Loam	Sandy Clay Loam	Clay Loam	Sandy Loam	Sandy Clay Loam	Clay Loam
Soil type	-	Haplic Luvisol	Haplic Luvisol	Cambisol	-	Haplic Luvisol
N_{min} (kg ha^{-1})	10.7	36.4	17.5	20.9	40.0	88.5

Experimental Design and Treatments.

The experimental design in both experiments was a randomized complete block with four replications. Plots at all locations had a size of 2 m by 10 m. The cover crop evaluation at Meiereihof and Ihinger Hof was conducted subsequent to winter wheat (*Triticum aestivum* L.), while at Trossin cover crops were cultivated after winter barley (*Hordeum vulgare* L.). Immediately after harvest of the previous crop, straw was removed and the soil was tilled with a disc at a depth of 5 cm. The field used in the competition experiment at Ihinger Hof was cultivated as grassland until 2010, and plowed in January 2011. Before sowing, the seedbed was prepared with a drill harrow. Cover crops were seeded using a plot seeder with double disk openers and a row spacing of 11 cm to a depth of 2 cm. At Hohenheim, pots were cultivated outdoors, to achieve comparable plant growth as under field conditions. Pots had a size of 20 cm by 20 cm, a height of 25 cm and were filled with crushed and sieved soil to allow adequate root growth. Cover crops were sown into pots by hand at a depth of 2 cm to ensure uniform plant arrangement. Every pot was irrigated using a dripper irrigation system to provide adequate water supply without encrusting the soil surface. No further fertilizer was applied neither in pots nor plots at any location, to see how cover crops respond to nutrient deficient soils. Used plant species in the cover crop evaluation at all locations were white mustard, niger, lopsided oat and sorghum with a seeding rate of 12.7 kg ha^{-1}, 11.1 kg ha^{-1}, 102.1 kg ha^{-1} and 44.9 kg ha^{-1}, respectively. White mustard was included as an additional treatment to compare the potential new cover crops with a common cover crop. To estimate the influence of cover crops on weed growth, a weedy control treatment additionally occurred in the cover crop evaluation experiment at Meiereihof, Ihinger Hof and Trossin. Cover crops were seeded on August 12^{th} 2010, August 10^{th} 2011, August 4^{th} 2011 and July 16^{th} 2011 at Hohenheim, Meiereihof, Ihinger Hof and Trossin, respectively. In the competition experiment, niger, lopsided oat and sorghum were seeded with the same seeding rate as in the cover crop evaluation. Used “model weeds” were annual ryegrass (*Lolium multiflorum* Lam.) and forage rape (*Brassica napus* L.), which were seeded together with cover crops and in single stand with a seeding rate of 21.6 kg ha^{-1} and 2.9 kg ha^{-1}, respectively. Cover crops and both weeds were seeded on July 7^{th} 2011 at Hohenheim and on July 6^{th} 2011 at Ihinger Hof. To determine only the interference between cover crops and both weeds, other plants were removed by hand.

Data Collection.

Soil coverage was measured in the cover crop evaluation at Hohenheim four and eight weeks after planting (WAP), at Meiereihof and Ihinger Hof four, six and eight WAP, and at Trossin eight WAP. To determine soil coverage, pictures were taken with a digital camera from an area of 12 m^2 in the field and from single pots at Hohenheim. Afterwards, images were analyzed using “ImageJ” Version 1.47a. Images were converted into

HSB-format and the green color of plants was separated from bare soil using the procedure "Color Threshold". If required, leaves of weeds were digitally masked by hand to separate them from cover crops. Finally, the masked green areas were estimated with the "Analyze Particles" procedure. Dry matter samplings were taken in the cover crop evaluation experiment four, eight and twelve WAP at Hohenheim, Meiereihof and Ihinger Hof and eight WAP at Trossin. Shoot and root dry matter samplings were collected from an area of $0.04\,m^2$, $0.25\,m^2$, $0.5\,m^2$ and $0.25\,m^2$, at Hohenheim, Meiereihof, Ihinger Hof and Trossin, respectively. In the competition experiment, plant samples were harvested twelve WAP from a samplings size of $0.04\,m^2$ at Hohenheim and $0.5\,m^2$ at Ihinger Hof. To measure the shoot and root dry matter of cover crops and weeds in pots and plots, the complete soil monolith was removed from the pot or plants were excavated until a depth of 30 cm. Roots of cover crops and weeds were cleaned from soil with water and then carefully separated by hand. Afterwards, roots were cut from shoots and dried for three days at 80 °C. To determine the weed density, the number of weeds was counted with a $0.1\,m^2$ frame at four randomly selected places in the plots at Meiereihof, Ihinger Hof and Trossin, eight WAP and at mid-March 2012.

Statistical Analysis.

For statistical analysis, the statistical language R version 2.15 was used (R Core Team, 2012). Analysis of variance was used to compare the statistical significance of soil coverage, dry matter of cover crops and weeds, as well as weed density. To verify the requirements for statistical analysis, the Shapiro-Wilk-test for normality and the Levene-test for homogeneity of variance were used. If required, data were transformed using square-root or log transformations to achieve the statistical assumptions. Afterwards, multiple comparison tests were conducted with the Tukey test at a significance level of $\alpha \leq 0.05$.

2.4.3 Results and Discussion

Weather Conditions.

In 2010, climatic conditions were characterized by cool and cloudy weather during September and October which was unfavorable for cover crop growth (Table2). The second growing season started with cool temperatures and high amounts of precipitation in July. However, from the beginning of August, good conditions for cover crop growth occurred. Especially September and October were dominated by warm and sunny weather in combination with adequate supply of rainfall at all locations. During November 2011, weather was warm at Meiereihof and Ihinger Hof, while almost no rainfall occurred at all locations.

Table 2: Air temperature and precipitation during the growing seasons and the 20-year monthly average at Hohenheim (Institute of Phytomedicine and Meiereihof), Ihinger Hof and Trossin.

Location	Air temperature (°C)					Precipitation (mm)				
	Jul.	Aug.	Sept.	Oct.	Nov.	Jul.	Aug.	Sept.	Oct.	Nov.
Hohenheim 2010	20.8	17.5	12.9	8.3	5.5	96.9	82.1	50.6	24.8	62.3
Hohenheim 2011	16.8	18.8	16.4	10.0	5.0	115.6	56.1	28.4	29.3	0.6
Hohenheim ltm.-average	17.7	17.1	14.0	9.3	3.9	69.9	79.3	56.5	43.4	54.9
Ihinger Hof 2011	15.8	18.4	15.4	9.2	5.0	61.6	54.4	60.8	58.5	0.6
Ihinger Hof ltm.-average	17.4	16.9	13.1	8.7	3.7	74.0	75.0	54.0	54.0	50.0
Trossin 2011	17.3	18.7	16.1	10.2	4.2	155.5	73.5	69.9	25.5	0.2
Trossin ltm.-average	19.3	18.9	14.4	9.6	4.8	77.4	66.1	55.3	31.3	46.8

Cover crop evaluation.

Soil Coverage. No difference between the soil coverage of white mustard, niger and sorghum could be measured at all locations eight WAP (Figure 1). Niger was able to cover the soil eight WAP by 88 % at Hohenheim and 93 % at Meiereihof. Lopsided oat showed eight WAP lower soil coverage than white mustard and niger at all locations expect Trossin. In contrast to the other cover crops, soil coverage of lopsided oat eight

WAP varied in a wide range between 38 % at Hohenheim and 85 % at Meiereihof. Sorghum covered the soil in a lower amount than white mustard at Meiereihof four WAP, however, at Hohenheim and Ihinger Hof, no difference could be measured.

The soil coverage of a plant is mainly influenced by the the growth rate and the leaf morphology, in particular by the angle and area of leaves. White mustard and niger are plant species with broad and shallow angled leaves, which allow them to completely cover the soil surface within a period of six WAP (De Baets et al., 2011). On the contrary, plant species like lopsided oat show reduced soil coverage, especially the first few WAP, due to their small and steeper angled leaves. As a result of this leaf morphology, it is necessary for such plant species to produce a high number of leaves or tillers for complete soil coverage in later growth stages. Similarly to lopsided oat, sorghum has a steeper leaf angle that causes delayed soil coverage. However, due to its broader leaves and a higher leaf area, sorghum is able to cover the soil like broadleaf cover crops.

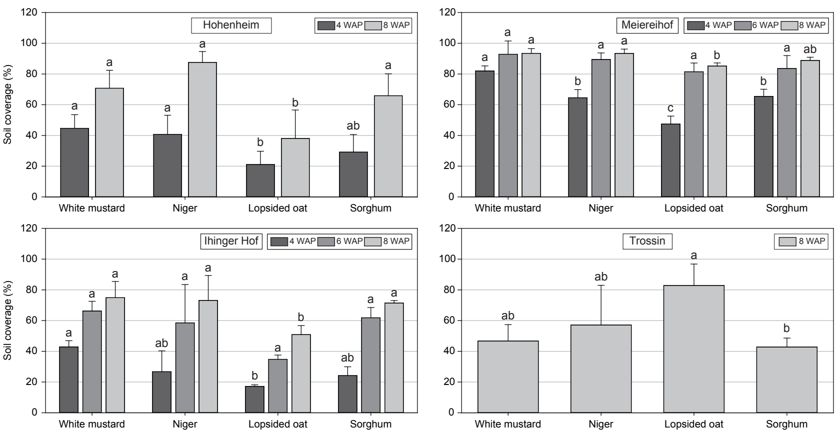

Figure 1: Soil coverage of cover crops. Bars represent mean values ± standard deviation. Within each location, and measurement dates, significant differences ($\alpha \leq 0.05$) are indicated by bars topped with different letters.

Cover Crop Dry Matter. At Meiereihof, dry matter of white mustard, niger and sorghum was more than two times greater than at the other locations which was mainly a result of a higher N_{min} content (Figure 2). Niger showed similar shoot and root dry matter as white mustard at all locations eight WAP. At this measurement date, lopsided oat produced the lowest shoot dry matter at Meiereihof and Ihinger Hof. However, at Trossin, lopsided oat offered the best shoot growth. This variable growth was also observed in the southern USA, where lopsided oat offered dry matter values between $132\,g\,m^{-2}$ and $625\,g\,m^{-2}$ (Price et al., 2006; Reeves et al., 2005). Lopsided oat had a better root growth than white mustard and niger at Hohenheim and Ihinger Hof four WAP. This fast initial root growth from members of the *Poaceae* family compared to other plant species was already known from previous studies (White and Weil, 2010). Sorghum offered similar shoot growth as white mustard at Hohenheim, Meiereihof and Trossin eight WAP while at Ihinger Hof a lower dry matter was measured. Sorghum produced a higher root dry matter than white mustard at Hohenheim and Ihinger Hof eight WAP. Shoot dry matter of sorghum, which ranged between $101\,g\,m^{-2}$ at Hohenheim and $405\,g\,m^{-2}$ at Meiereihof twelve WAP, was smaller than reported by other scientists, which observed values between $520\,g\,m^{-2}$ and $870\,g\,m^{-2}$ (Butler et al., 2012; Creamer and Baldwin, 2000; Ngouajio and Mennan, 2005). This was mainly a result of Central European growth conditions with shorter and cooler days in fall, which may have prevented a higher dry matter production of the C_4-species sorghum.

Niger was the plant species with the lowest frost tolerance of all cover crops and died due to slight frost at the end of October at Meiereihof, Ihinger Hof and Trossin, while sorghum grew until December at Meiereihof. Lopsided oat was able to survive short frost nights in fall, and provide growth and soil coverage up until long and heavy frost periods in winter. The higher frost tolerance of lopsided oat is beneficial for cover crop cultivation because frosty nights with temperatures slightly below 0 °C occur relatively often in Central Europe already from mid-September, while adequate growing conditions for cover crops are possible until mid-October.

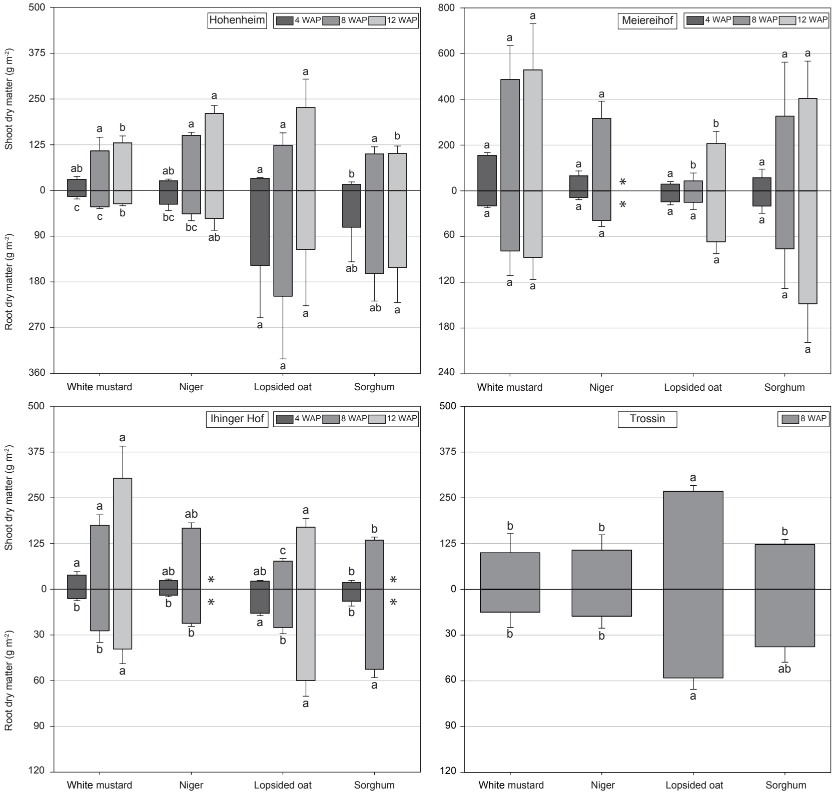

Figure 2: Shoot and root dry matter of cover crops. If no dry matter sampling was possible due to frost before harvest, columns are marked with an asterisk (*). Bars represent mean values ± standard deviation. Within each location, the shoot and root dry matters and measurement dates, significant differences ($\alpha \leq 0.05$) are indicated by bars topped with different letters.

Weed Dry Matter. The weed community was similar at Meiereihof, Ihinger Hof and Trossin and included primarily volunteer wheat or volunteer barley, common chickweed (*Stellaria media* (L.) Vill.), red deadnettle (*Lamium purpureum* L.), scented mayweed (*Matricaria chamomilla* L.) and Persian speedwell (*Veronica persica* Poir.). However, weed pressure differed widely among the three locations. Most weeds occurred at Meiereihof, followed by Trossin, while moderate weed pressure occurred at Ihinger Hof (Figure 3).

Niger showed similar weed suppression ability as white mustard and was able to reduce the shoot and root dry matter of weeds at all locations by up to 85 %. This was mainly a result of its good shoot growth and soil coverage due to its broad and shallow angled leaves, which resulted in a strong competitive ability for light just a few weeks after emergence (Brennan and Smith, 2005; Creamer and Baldwin, 2000). Lopsided oat was not able to reduce weed growth at Meiereihof, however, at Ihinger Hof and Trossin, it offered comparable results as niger and sorghum. At Trossin, lopsided oat showed the best weed suppression and was able to reduce shoot and root dry matter of weeds by 78 % and 79 %, respectively. Due to a reduced competitiveness for light that is mainly caused by its small and steeper angled leaves, lopsided oat needed for good weed suppression a well-developed root system and long vegetative growth which allows a high competitive ability for water and nutrients (Belcher et al., 1995). The well-developed root system of lopsided oat could be the main reason for its good weed suppression at Trossin, due to a high competitive ability for the small amount of nitrogen at this location. Sorghum reduced weed growth in the same amount as white mustard at all locations. The good reduction of weed shoot growth at Meiereihof (reduction of 69 %) and Ihinger Hof (reduction of 88 %) was in accordance with results from former studies where sorghum was able to reduce weed dry matter by more than 85 % (Creamer and Baldwin, 2000; Geneve and Weston, 1988).

Weed Density in fall and spring. Comparable to the weed dry matter, highest weed density was measured at Meiereihof, followed by Trossin, while a reduced weed density occurred at Ihinger Hof (Figure 3). Niger showed similar results to white mustard at all locations. At Meiereihof, niger and white mustard were able to reduce the weed density, whereas no reduction could be detected at Ihinger Hof and Trossin. Lopsided oat was the only plant species which could significantly reduce the weed density at Ihinger Hof and Trossin, however, no reduction was measured at Meiereihof. Sorghum was not able to reduce the weed density at any location.

Weed density decreased in the cover crop plots and the weedy control at all location until the measuring in spring (Table 3). In plots of niger, weed density was reduced at Ihinger Hof and Trossin. At both locations, no difference between niger and white mustard occurred, however, at Meiereihof, a reduced weed density was only counted in plots of white mustard. In plots of lopsided oat, weed density was reduced by 97 % at Ihinger Hof and 99 % at Trossin, while at Meiereihof no reduction was detected. At all locations, the highest weed density within the cover crops occurred in sorghum plots and it could only reduce weed density at Ihinger Hof.

Cover crops can reduce weed density by inhibiting germination through changes in light quality by photosynthetic active plant tissue (Batlla et al., 2000), diurnal soil temperature (Teasdale and Daughtry, 1993) or through release of allelochemicals (Bezuidenhout et al., 2012; Dhima et al., 2006). Cover crops may also increase post-germination mortality of weeds through competition (Teasdale and Abdul-Baki, 1998) or allelopathy. While white mustard and niger may reduce weed density mainly by shading of weeds and weed seeds, sorghum and lopsided oat may inhibit the germination and growth of weed seedlings mostly by competition for water and nutrients and the release of allelochemicals (Hoffman et al., 1996; Panasiuk et al., 1986; Price et al., 2008).

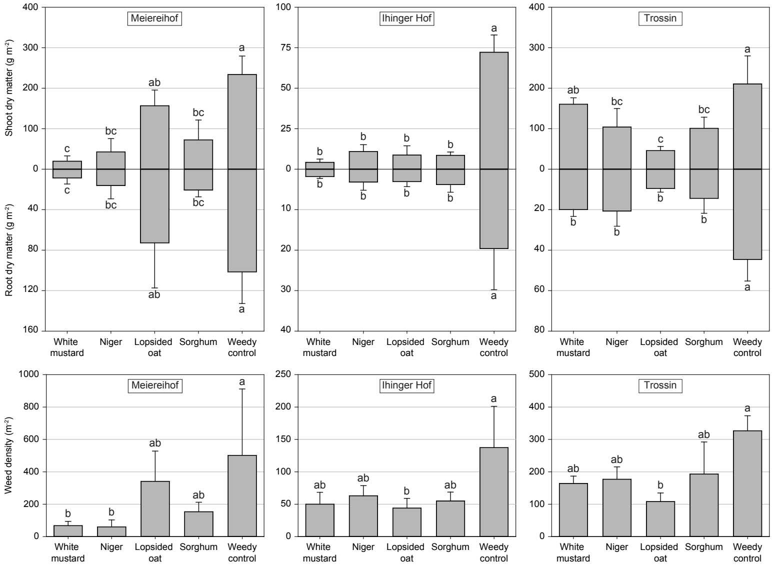

Figure 3: Shoot and root dry matter as well as the density of weeds in plots of cover crops and the weedy control. Bars represent mean values ± standard deviation. Within each location, the shoot and root dry matters and the weed density, significant differences ($\alpha \leq 0.05$) are indicated by bars topped with different letters.

Table 3: Mean value (MV) and standard deviation (STD) of weed density per square meter in plots of cover crops and the weedy control in spring at Meiereihof, Ihinger Hof and Trossin.

Treatment	Meiereihof		Ihinger Hof		Trossin	
	MV	STD	MV	STD	MV	STD
Yellow mustard	3.0 [z] b	6.0	1.5 c	3.0	11.0 bc	10.0
Niger seed	55.0 a	33.7	10.5 bc	7.2	11.0 bc	6.0
Lopsided oat	47.0 ab	51.9	2.5 c	2.5	1.0 c	2.0
Sorghum	69.0 a	33.4	26.0 b	14.0	28.0 ab	22.9
Weedy control	108.0 a	29.9	73.5 a	21.4	70.0 a	30.9

[z] Means within the same column followed by an identical letter do not differ statistically based on the Tukey test ($\alpha \leq 0.05$).

Competition experiment.

At Hohenheim, lopsided oat produced in pots with forage rape a higher shoot dry matter than niger and sorghum (Figure 4). Cover crops produce similar shoot dry matter regardless if they were cultivated in pots with forage rape or annual ryegrass. However, niger and lopsided oat show a smaller root growth in pots with annual ryegrass. At Ihinger Hof, niger and sorghum showed a higher shoot growth than lopsided oat. Sorghum offered a higher root growth than niger and lopsided oat. Cover crop growth was similar in plots with forage rape and annual ryegrass. All cover crops were able to reduce shoot growth of forage radish and annual ryegrass at Hohenheim. While all cover crops were able to reduce root growth of forage rape, no cover crop could reduce root dry matter of annual ryegrass. At Ihinger Hof, niger was able to reduce the shoot and root dry matter of forage rape and annual ryegrass. Lopsided oat did not reduce the shoot and root growth of annual ryegrass, and also the root growth of forage rape was not influenced. Sorghum was able to reduce the shoot and root dry matter of forage rape and annual ryegrass.

The smaller shoot growth of niger and sorghum compared to lopsided oat at Hohenheim have been mainly caused by their lower ability to absorb the small amount of nitrogen in pots. Due to the reduced growth of niger and sorghum at Hohenheim, they were not able to suppress root growth of annual ryegrass (Creamer and Baldwin, 2000). However, also lopsided oat was not able to reduce root growth of annual ryegrass. Especially under water and nutrient limited condition, as occurred in pots, annual ryegrass is a highly competitive plant species with the ability to reduce even the growth of competitive cover crops due to its well-developed root system (Stone et al., 1998). Niger and sorghum were able to reduce weed growth at Ihinger Hof mainly due to their good shoot growth and intensive shading (Brennan and Smith, 2005). Lopsided oat was not able to reduce growth of weeds at Ihinger Hof mainly due to its long-day characteristic which results in fast development, a reduced tillering, early grain formation and no further accumulation of dry matter. Therefore, competition for light, water and nutrients was reduced which resulted in a low suppression of weeds.

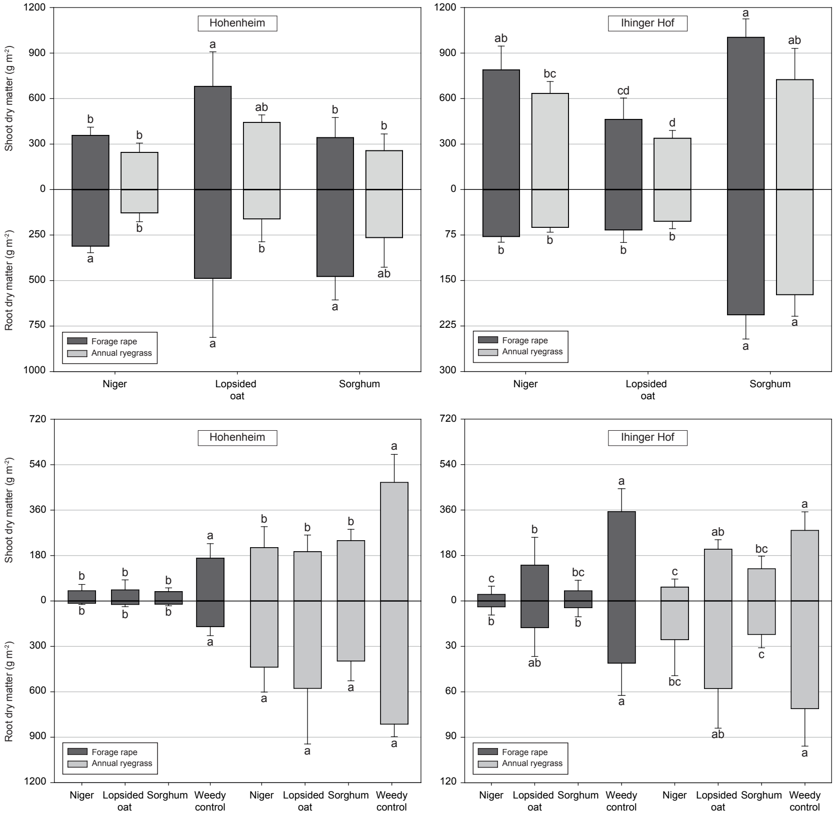

Figure 4: Shoot and root dry matter of cover crops in pots/plots of forage rape and annual ryegrass (1^{st} row) and shoot and root dry matter of forage rape and annual ryegrass in pots/plots of cover crops and the weedy control (2^{nd} row). Bars represent mean values ± standard deviation. Within each location, the shoot and root dry matters of cover crops and weeds, significant differences ($\alpha \leq 0.05$) are indicated by bars topped with different letters.

Conclusion

The results show that all plant species may have the potential for cultivation as cover crops in Central Europe. However, for successful cultivation and weed suppression it is important to match up cover crop species, environmental conditions and the sowing time. The results suggest that niger and sorghum grow better under sufficient nitrogen availability and early sowing times, best before mid-July for adequate growth and high competiveness against weeds. Lopsided oat seems to be better suited for locations with a reduced amount of nitrogen, because it mainly suppresses weeds by competition for water and nutrients with its well-developed root system. For successful weed suppression it is important to sow lopsided oat not too early because of its long-day characteristics, which otherwise reduce its competition ability due to decreased dry matter production. Lopsided oat is able to tolerate later sowing dates than niger and sorghum because it grows better at lower temperatures and has a higher frost tolerance.

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2.5 Management of undersown crops influences their competitiveness with cereals and weeds

Section 2.5 deals with the management of undersown crops and its influence on competitiveness to cereal crops and weeds. The results presented in this section were measured in four field and one pot experiment that were conducted from 2009 until 2012 in south-west Germany. Within this section, the influence of fertilization, seeding date and selection of undersown crop species on the growth and yield formation of cereal main crops was discussed. Furthermore, the ability of undersown crops for weed suppression during the vegetation of the main crop was measured.

Management of undersown crops influences their competitiveness with cereals and weeds

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Summary

Undersown crops provide many benefits to the agroecosystem. However, adapted management is necessary to avoid yield reduction of cereals. Four field trials and one pot experiment were conducted in Germany from 2009 until 2012 in spring wheat, spelt and spring barley to determine the influence of fertilization and the sowing date of different undersown crop species in monoculture and mixture on the growth of cereal crops and weeds. Early sowing of undersown crops, immediately after cereals, resulted in higher dry matter production of the undersown crop than later sowing dates during leaf formation or at tillering. Grain yield was not affected by undersown crops except for one treatment with early sown perennial ryegrass in fertilized plots in 2011, which significantly reduced wheat density, grain- and straw yield. Early sown white clover significantly reduced weeds in the field experiments 2011 and 2012. The results suggest that undersown crops are able to suppress weeds without decreasing the yield of cereals, if suitable management practices are successfully implemented.

Keywords: Weed suppression, Weed-crop interaction, Weed density, Inter-cropping, Root growth, Pot experiment, Field experiment.

2.5.1 Introduction

Undersown crops provide several benefits to modern agricultural systems. Due to coverage of the soil surface, they prevent wind and water erosion and reduce the leaching of nitrogen (Känkänen and Eriksson, 2007). Undersown crops are also able to enhance soil organic matter, which results in increased cation exchange capacity, higher water storage capacity and improved soil structure (Breland, 1995). Subsequent crops achieved higher yields when undersown crops were grown in the previous crop (Bergkvist et al., 2011).

In addition to those benefits, undersown crops are able to inhibit weed germination and growth of weed seedlings by soil coverage and modification of intercepted sunlight (Ballaré and Casal, 2000; Kruk et al., 2006). Also the release of allelochemicals from root or shoot tissue of undersown crops can reduce germination and growth of weeds (Overland, 1966). After weed establishment, undersown crops could be strong competitors of weeds for resources. Undersown crops should be easy to establish and not interfere with cereals or become a weed in the subsequent crop due to seed propagation or regrowth (Bezuidenhout et al., 2012; Carof et al., 2007; den Hollander et al., 2007; Liedgens et al., 2004).

Short growing, late flowering and shade tolerant cultivars of perennial ryegrass (*Lolium perenne L.*), Italian ryegrass (*Lolium multiflorum Lam.*), red fescue (*Festuca rubra L.*), white clover (*Trifolium repens L.*), red clover (*Trifolium pratense L.*), persian clover (*Trifolium resupinatum L.*) and subterranean clover (*Trifolium subterraneum L.*) are commonly used as undersown crops in cereals in Central Europe (Bezuidenhout et al., 2012; Carof et al., 2007; den Hollander et al., 2007; Echtenkamp and Moomaw, 1989; Enache and Ilnicki, 1990; Kunelius et al., 1992; Liedgens et al., 2004). The main advantage of legume species is their ability to fix atmospheric nitrogen and the rapid soil coverage due to their shallow angled leaves which is an important factor for weed suppression (Mallarino et al., 1990). Grasses also offer good weed suppression, and provide excellent forage quality as well as improve soil structure with their fibrous root system (Breland, 1995). Using mixtures of grass and legume species may combine the beneficial effects of both partners (Akemo et al., 2000; Linares et al., 2008; Wortman et al., 2012).

Suitable management practices are needed to prevent a reduction of the cereal yield while achieving adequate growth of undersown crops. Management practices include determination of undersown crop density, fertilization and time of sowing. Especially, the sowing date and emergence of plants influences their competitive ability, which allows cultivation of potentially competitive undersown crops in sensitive cereals (Knezevic and Horak, 1998; Uscanga-Mortera et al., 2007).

The objectives of this study were to determine growth and impact of different undersown crops on cereal crops and weeds in relation to their sowing date and the fertilization.

2.5.2 Materials and Methods

Experimental sites

Field experiments were conducted from 2009 to 2012 in southwestern Germany at the Meiereihof experimental station (48°71′ N, 9°21′ E, 435 m altitude), located near the University of Hohenheim in 2009 and 2010, and at the Ihinger Hof experimental station (48°74′ N, 8°92′ E, 478 m altitude) in 2011 and 2012. A pot experiment was conducted at the Institute of Phytomedicine in Hohenheim (48°70′ N, 9°20′ E, 407 m altitude) in 2012. In all field experiments, the soil type was a Haplic Luvisol with "clay loam" soil texture of topsoil. Soil used in the pot-experiment was from the experimental station Ihinger Hof with a "clay loam" soil texture. Soil mineral nitrogen (N_{min}) content of topsoil (90 cm) was 15.0 kg ha^{-1}, 10.7 kg ha^{-1}, 65.8 kg ha^{-1} and 40.0 kg ha^{-1} in the field experiment 2009, 2011, 2012 and in the pot experiment, respectively. No N_{min} value was available from the field experiment 2010. Annual temperature averaged 8.8 °C at Hohenheim and 9.2 °C at Ihinger Hof. Annual average precipitation reached 700 mm at Hohenheim and 794 mm at Ihinger Hof, which are typical values for agricultural areas in southwestern Germany.

Description of experiments

A randomized complete block design with four replications was established in the field trials 2009, 2010, 2012 and the pot experiment 2012. In the 2011 field experiment, a two factorial split-plot design with four replications was used. The main plot factor was "fertilization" and the sub-plot factor was "undersown crop treatment", which was a combination of plant species and sowing dates. Cereal crops in the experiments were spring wheat (*Triticum aestivum L.*) in 2009 and 2011, spelt (*Triticum aestivum subsp. spelta*) in 2010 and spring barley (*Hordeum vulgare L.*) in 2012. All experiments included different undersown crop species and sowing dates as experimental treatments (Table 4). The field experiments 2009 and 2011 contained treatments with and without N-fertilization to determinate the influence of nitrogen to the competitive ability of undersown crops and the cereal crops. A control treatment without a undersown crop was included in all experiments to measure the impact of undersown crop on cereals and weeds. Additional, an herbicide control treatment (information about applied herbicides are listed in Table 4) was included in the field experiments 2009, 2011 and 2012 to determine performance of cereals without any competition by weeds and undersown crops.

Plots in all field experiments had a size of 2 m by 10 m. Pots used in the pot experiments had a size of 20 cm by 20 cm and a height of 25 cm. Basic agronomic data and field operations for cereal and undersown crops are listed in Table 4. Cereal crops were seeded using a seed drill with double disc openers with common seeding rates for southwestern Germany. Cereal growth stages at each date of observation were determined in accordance to the BBCH scale at five randomly selected positions in the plots (Meier, 2001). Depending on the experiment, undersown crops were sown at two or three times, immediately after sowing of cereals (BBCH 00), at the three leaves stage of cereals (BBCH 13) and when the first cereal tiller was visible (BBCH 21). Undersown crops were sown at recommended rates using a plot seeder with single disc openers. Undersown crop seeds were placed on the soil surface according to usual establishment by farmers. Fertilizer and herbicides were used in accordance to common agricultural practice in southwestern Germany. Fertilizers used in the field experiment 2009 were urea-ammonium-nitrate solution at the first and second application timing and calcium-ammonium-nitrate for the third application. In the field experiment 2011 and both experiments in 2012, applied fertilizer was urea. Densities and root-/shoot-biomass of cereal crops, undersown crops and weeds were measured at the flag leaf stage (BBCH 37), at full flowering (BBCH 65) and at fully ripening of cereals (BBCH 89). Plant samples were taken from randomly selected positions in plots. To measure root-/shoot-biomass in the 2012 experiment, plants were removed from the soil to a depth of 30 cm, respectively 25 cm from the pots. Afterwards, roots were washed, separated from the shoots, dried at 80 °C for 48 hours and weighted.

Statistical analysis

Data were analysed using the statistical language R version 2.15 (R Core Team, 2012). Analysis of variance was conducted to test the statistical significance of shoot and root dry matter, yield parameters and weed density in all experiments. The requirements for statistical analysis were proved with the Shapiro-Wilk test for normality and the Levene-test for homogeneity of variance. When needed, data were $\log_{10}$ transformed to achieve the requirements for the analysis of variance. When statistical differences between treatments were identified by the analysis of variance, multiple comparison tests of means were conducted using Tukey test at a significance level of $\alpha \leq 0.05$.

Table 4: Agronomic details, cultural practices and dates of observations in field- and pot experiments. Cereal crop growth stages are given in accordance to the BBCH scale.

Location	**Meiereihof**		**Ihinger Hof**		**Hohenheim**
Year	**2009**	**2010**	**2011**	**2012**	**2012**
Cereal crop					
Species (Seeding rate)	Spring wheat (200 kg ha^{-1})	Spelt (200 kg ha^{-1})	Spring wheat (148 kg ha^{-1})	Spring barley (189 kg ha^{-1})	Spring barley (189 kg ha^{-1})
Sowing date	24. Mar. 2009	29.Oct. 2009	9. Mar. 2011	15. Mar. 2012	21. Mar. 2012
Row space	11 cm	20 cm	11 cm	11 cm	-
Undersown crop					
Species (Seeding rate)	Perennial ryegrass (20 kg ha^{-1})	Perennial ryegrass (40 kg ha^{-1})	Red fescue (40 kg ha^{-1})	Red fescue (10 kg ha^{-1})	Red fescue (10 kg ha^{-1})
	White clover (8 kg ha^{-1})	White clover (20 kg ha^{-1})	Perennial ryegrass (40 kg ha^{-1})	Perennial ryegrass (24 kg ha^{-1})	Perennial ryegrass (24 kg ha^{-1})
		Persian clover (10 kg ha^{-1})	White clover (30 kg ha^{-1})	Italian ryegrass (16 kg ha^{-1})	Italian ryegrass (16 kg ha^{-1})
			Subterranean clover (30 kg ha^{-1})	White clover (9 kg ha^{-1})	White clover (9 kg ha^{-1})
				Red clover (21 kg ha^{-1})	Red clover (21 kg ha^{-1})
				R. fescue (5.0 kg ha^{-1}) &	R. fescue (5.0 kg ha^{-1}) &
				w. clover (4.5 kg ha^{-1})	w. clover (4.5 kg ha^{-1})
				It. ryegrass (8.0 kg ha^{-1}) &	It. ryegrass (8.0 kg ha^{-1}) &
				r. clover (10.5 kg ha^{-1})	r. clover (10.5 kg ha^{-1})
Sowing date (cereal growth stage)	24.Mar. (BBCH 00)	15. Apr. (BBCH 13)	31. Mar. (BBCH 13)	15. Mar. (BBCH 00)	21. Mar. (BBCH 00)
	23. Apr. (BBCH 13)	28. Apr. (BBCH 21)	28. Apr. (BBCH 21)	10. Apr. (BBCH 13)	18. Apr. (BBCH 13)
				4. May (BBCH 21)	11. May (BBCH 21)
Cultural practice					
Nitrogen fertilization (Date)	35 kg ha^{-1} (16. Apr)	-	60 kg ha^{-1} (10. Mar.)	60 kg ha^{-1} (30. Mar.)	50 kg ha^{-1} (30.Apr.)
	35 kg ha^{-1} (5. May)		80 kg ha^{-1} (10. May)		
	67.5 kg ha^{-1} (15. Jun.)				
Herbicide application (Date)	3.9 g a.i. ha^{-1} Metsulfuron (4. May)	-	200 g a.i. ha^{-1} Ioxynil (28.Apr.)	60 g a.i. ha^{-1} Pinoxaden (2. May)	-
	14.9 g a.i. ha^{-1} Carfentrazone (4. May)		800 g a.i. ha^{-1} Isoproturon (28.Apr.)	150 g a.i. ha^{-1} Fluroxypyr (2. May)	
	600 g a.i. ha^{-1} Mecoprop-P (4. May)		40 g a.i. ha^{-1} Diflufenican (28.Apr.)	3.8 g a.i. ha^{-1} Florasulam (2. May)	
Sampling date (Cereal growth stage)					
Cereal dry matter	26. Jun. (BBCH 65)	16. Jun. (BBCH 65)	9. Jun. (BBCH 37)	18. Jun. (BBCH 65)	16. Jun. (BBCH 65)
Cereal yield	7. Aug. (BBCH 89)	9. Aug. (BBCH 89)	9. Aug. (BBCH 89)	2. Aug. (BBCH 89)	-
Undersown crop dry matter	26. Jun. (BBCH 65)	16. Jun. (BBCH 65)	-	18. Jun. (BBCH 65)	16. Jun. (BBCH 65)
Weed density / dry matter	26. Jun. (BBCH 65)	16. Jun. (BBCH 65)	7. Jun. (BBCH 37)	18. Jun. (BBCH 65)	-
			9. Aug. (BBCH 89)		
Sampling area					
	0.25 m^2	0.25 m^2	0.50 m^2	0.50 m^2	0.04 m^2

2.5.3 Results

Weather conditions

The growing season 2009 was characterized by warm and sunny weather conditions and an adequate amount of rainfall (Table 5). The following year started with dry weather in March and April, while in May and July enough precipitation occurred for good plant growth. In 2011 and 2012, it was warm and dry from March until May at both locations. While spring was dry, rainfall was high enough for good plant growth in June and July at Hohenheim and Ihinger Hof.

Table 5: Temperatures and rainfall during the growing seasons and the long-time average (lt.-av.) at Hohenheim (HOH) (which included "Meiereihof" and the Institute of Phytomedicine) and Ihinger Hof (IHO).

Location	Air temperature (°C)					Precipitation (mm)				
	Mar.	Apr.	May	Jun.	Jul.	Mar.	Apr.	May	Jun.	Jul.
HOH 2009	4.7	12.2	15.2	16.5	18.8	65.5	35.3	128.4	93.3	126.0
HOH 2010	4.8	10.0	11.6	17.5	20.8	29.4	8.6	87.1	55.0	96.9
HOH 2012	8.1	9.2	15.4	17.5	18.5	10.9	53.8	36.5	104.5	67.8
HOH lt.-av.	5.5	9.6	14.0	17.2	18.9	48.5	39.3	78.6	90.8	93.5
IHO 2011	6.0	11.5	14.3	16.5	15.8	25.2	20.9	25.0	111.4	61.6
IHO 2012	7.2	8.2	14.4	16.5	17.5	7.7	41.4	42.9	116.2	94.4
IHO lt.-av.	4.1	7.7	12.3	15.2	17.4	44.6	49.3	78.3	81.7	74.2

Undersown crop growth

In 2009, dry matter production of undersown crops was highest for the early sowing date immediately after wheat compared to the later seeding at leaf formation of wheat (Fig. 5). While similar growth of white clover and perennial ryegrass was measured in unfertilized plots among the first sowing date, in fertilized plots perennial ryegrass reached a much greater dry matter than white clover.
In 2010, dry matter production of undersown crops was almost similar to the previous year. While in 2009 white clover from the second sowing

date produced 2.4 g m^{-2} dry matter in the unfertilized plots, 2.3 g m^{-2} in the same treatment were measured in 2010. Sowing dates in 2010 had no effect on dry matter production of undersown crops.

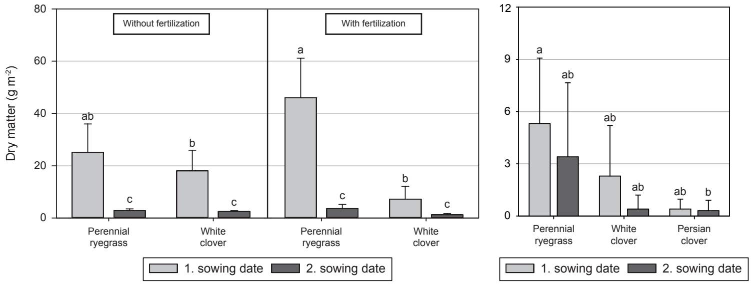

Figure 5: Dry matter of undersown crops in the field experiment 2009 (left), and 2010 (right). Bars represent mean values ± standard deviation. Within each experiment, significant differences ($\alpha \leq 0.05$)are indicated by bars topped with different letters.

In the field experiment 2012, growth of undersown crops from the first sowing date, which were seeded immediately after barley, was much higher than those from the following sowing dates (Table 6). Due to the low amount of undersown crop biomass from the second and third sowing dates at leaf formation and tillering of barley, it was not possible to collect plant material from all treatments. The highest shoot dry matter for the first sowing date was determined for Italian ryegrass, whereas perennial ryegrass produced the highest root dry matter. However, differences were not significant in both cases. The ryegrass species produced a much higher root dry matter than white and red clover, however, due to a high variance no significant difference could be detected. Lowest dry matter of all undersown crop species from the first sowing date was observed for white clover. The mixtures of Italian ryegrass with red clover achieved similar shoot and root dry matter as Italian ryegrass. Shoot and root dry matter of undersown crops from the second sowing date was much lower than those from the first. The highest shoot and root dry matter was measured in plots of Italian ryegrass, red clover and the mixture of both, whereas in other treatments only very low or no dry matter could be measured.

In the pot experiment, undersown crops that were seeded at the first sowing date immediately after barley had, similar to the field experiment, a much higher shoot and root dry matter than those from the subsequent sowing dates. In contrast to the field experiment, both clover species showed equal or higher shoot dry matter than the grass species, however, root dry matter of clover species was lower than of Italian ryegrass. The mixture of Italian ryegrass with red clover provided equal shoot dry matter as red clover and equal root dry matter as Italian ryegrass. Similar results were observed for the mixtures of red fescue with white clover. From the second sowing date at leaf formation of barley, white clover showed the highest shoot dry matter, while the highest root dry matter was recorded for perennial ryegrass. From the third sowing date at tillering of barley, dry matter contents were low for all undersown crops.

Table 6: Means (MV) and standard deviations (STD) of undersown crop dry matter in the field and pot experiment 2012. Data were recorded at time of flowering of spring barley.

Undersown species	Shoot dry matter ($g\,m^{-2}$)						Root dry matter ($g\,m^{-2}$)					
	1. sowing date		2. sowing date		3. sowing date		1. sowing date		2. sowing date		3. sowing date	
	MV	SD	MV	SD	MV	SD	MV	SD	MV	SD	MV	SD
							Field experiment					
Red fescue	9.4[y] ab	6.9	NA	-	NA	-	7.2 a	4.8	NA	-	NA	-
Perennial ryegrass	31.9 a	17.1	0.7 abc	0.9	NA	-	18.7 a	13.6	0.7 a	0.9	NA	-
Italian ryegrass	37.8 ab	29.7	3.4 a	1.7	NA	-	16.6 a	14.1	1.6 a	1.1	NA	-
White clover	2.4 b	1.3	0.3 bc	0.2	NA	-	1.3 a	0.7	0.4 a	0.4	NA	-
Red clover	10.6 ab	5.6	2.6 ab	2.0	NA	-	3.3 a	2.2	1.9 a	2.6	NA	-
R. fescue & w. clover	NA[z]	-	NA	-	NA	-	NA	-	NA	-	NA	-
It. ryegrass & r. clover	31.4 a	10.0	2.4 ab	1.5	NA	-	11.1 a	2.9	1.4 a	1.0	NA	-
							Pot experiment					
Red fescue	48.5 d	15.7	6.1 c	2.8	1.4 c	0.8	144.7 d	57.1	4.5 ab	2.2	0.1 a	0.8
Perennial ryegrass	115.7 cd	27.2	10.7 bc	6.1	2.1 c	1.0	415.4 abc	198.5	21.2 a	20.5	3.1 a	3.0
Italian ryegrass	173.5 bc	22.7	18.2 ab	10.3	2.7 c	1.3	662.4 a	175.0	20.1 ab	12.6	6.8 a	8.2
White clover	216.9 ab	22.0	35.3 a	9.3	5.9 ab	0.6	158.8 cd	57.9	11.1 ab	4.3	2.4 a	0.9
Red clover	262.1 a	26.8	17.2 ab	2.2	4.3 ab	3.2	203.7 cd	74.1	3.6 b	0.8	1.4 a	1.2
R. fescue & w. clover	206.6 ab	42.0	10.6 bc	2.0	6.8 a	1.3	229.6 bcd	87.9	5.4 ab	1.1	0.3 a	5.0
It. ryegrass & r. clover	246.6 ab	40.6	23.0 ab	11.3	3.4 c	0.9	537.7 ab	329.3	17.0 ab	15.1	2.5 a	2.0

[y] Means within the same column followed by an identical letter do not differ statistically based on the Tukey test ($\alpha \leq 0.05$).
[z] Treatments where no dry matter sampling was possible are labeled with "NA".

Cereal growth

In the field experiments 2009, 2010 and 2012, undersown crop species, sowing date and fertilization had no significant effect on the shoot dry matter of spring wheat, spelt and spring barley (Fig. 6). In 2011, fertilization significantly increased wheat dry matter, while herbicide application in fertilized plots significantly reduces wheat dry matter. In the pot experiment 2012, barley produced 2.9 $t\,ha^{-1}$ shoot dry matter compared to 9.7 $t\,ha^{-1}$ in the field experiment. Shoot growth of barley in pots was not significantly influenced by undersown crops and sowing date. However, root dry matter of barley was significantly reduced in pots of Italian ryegrass, white clover and the mixture of Italian ryegrass and red clover seeded immediately after barley.

Cereal grain and straw yield

In all four years of study, cereal yields were not affected by undersown crops except for one treatment with perennial ryegrass seeded at leaf formation of wheat in fertilized plots in 2011, which significantly reduced wheat density, grain yield and straw yield (Fig. 7). In 2011, fertilization significantly increased grain yield from 4.2 $t\,ha^{-1}$ without fertilization to 6.2 $t\,ha^{-1}$ in the fertilized treatments. In the pot experiment 2012, barley was harvested at time of anthesis, therefore, grain yield was not measured. However, undersown crops and sowing dates of undersown crops did not significantly affect the number of barley kernels per ear.

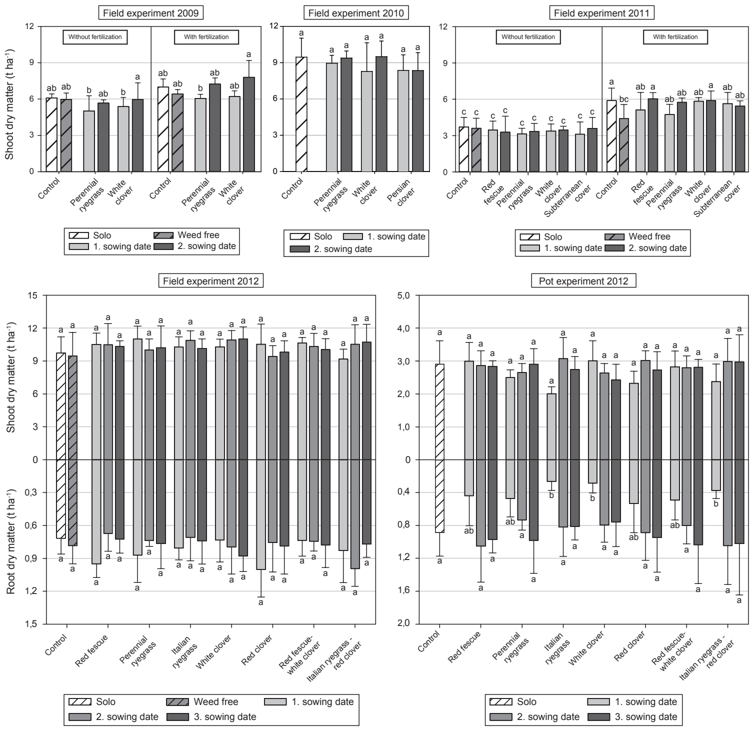

Figure 6: Dry matter of cereal crops in the experiments 2009-2012. Bars represent mean values ± standard deviation. Within each experiment, the shoot and root dry matters, significant differences ($\alpha \leq 0.05$) are indicated by bars topped with different letters.

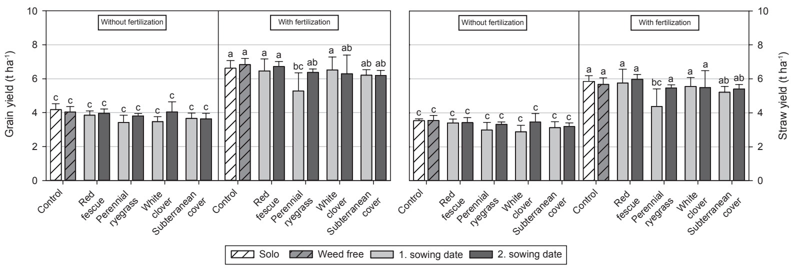

Figure 7: Grain (left) and straw yield (right) of wheat in the field experiment 2011. Bars represent mean values ± standard deviation. Within the grain and straw yield, significant differences ($\alpha \leq 0.05$) are indicated by bars topped with different letters.

Weed suppression

Weed flora in the field experiment 2009 mainly consisted of *Alopecurus myosuroides Huds.*, *Viola arvensis Murray*, *Lamium purpureum L.* and *Veronica persica Poiret*. In 2010, mainly *Stellaria media L.* and *Anthemis arvensis L.* occurred. Weed flora in 2011 and 2012 was dominated by *Chenopodium album L.* and *V. persica.*

Undersown crops did not reduce the weed dry matter in 2009 and 2010. In 2011 density of *C. album* was not significantly influenced by fertilization or the undersown crops at both sampling dates (Fig. 8). Density of *V. persica* was not influenced by undersown crops at the flag leaf stage of wheat. At time of wheat harvest, perennial ryegrass and white clover that were seeded at leaf formation of wheat reduced the density of *V. persica* in unfertilized plots. In fertilized plots, *V. persica* was almost completely suppressed by perennial ryegrass and white clover from both sowing dates and by subterranean clover of the second sowing date at wheat tillering.

In the field experiment 2012, weed density was significantly reduced in plots of white clover that was seeded immediately after barley and the mixture of Italian ryegrass with red clover that was seeded at leaf formation of barley (Fig. 9). However, undersown crops were not able to influence the shoot and root dry matter of weeds (data not presented).

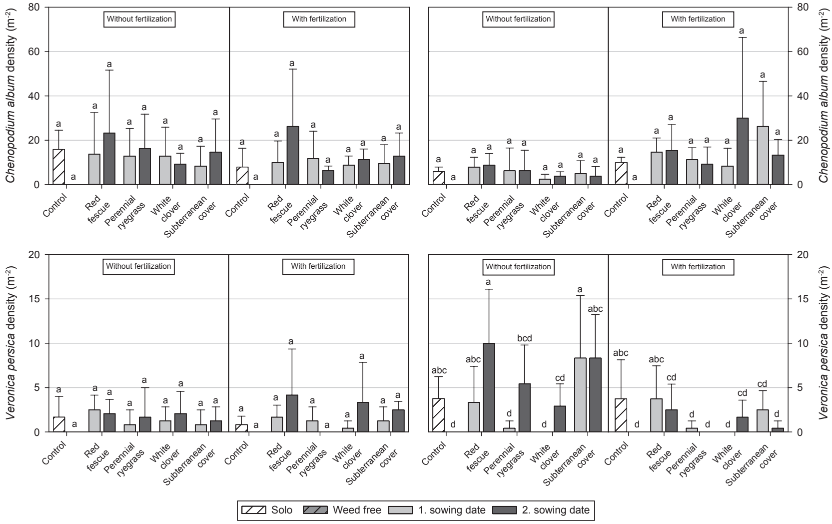

Figure 8: Weed density of *Chenopodium album* (top) and *Veronica persica* (below) at flag leaf stage (left column) and harvest (right column), in the field experiment 2011. Bars represent mean values ± standard deviation. Within each weed species and measurement date, significant differences ($\alpha \leq 0.05$) are indicated by bars topped with different letters.

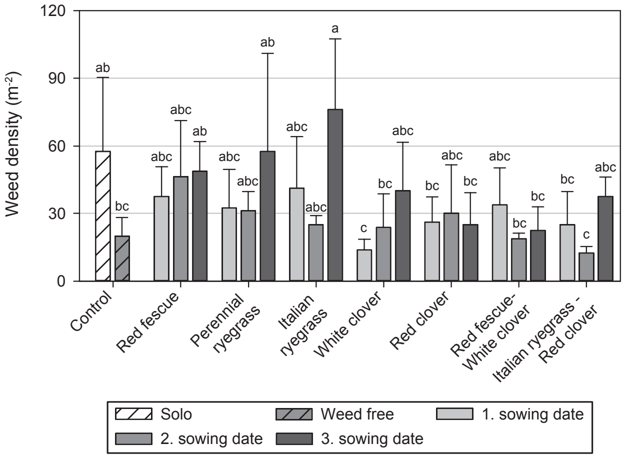

Figure 9: Weed density in the field experiment 2012. Bars represent mean values ± standard deviation. Significant differences ($\alpha \leq 0.05$) are indicated by bars topped with different letters .

2.5.4 Discussion

Undersown crop growth

Undersown crops that were seeded together with cereals showed better vegetative growth than those from the subsequent sowing dates in the field experiments 2009, 2012 and in the pot experiment. Due to a longer growing period, less competition from the cereal crop after emergence and more available sunlight, undersown crops performed much better at early sowing dates (Knezevic and Horak, 1998; Uscanga-Mortera et al., 2007).

Dry matter of the undersown crops varied widely between the experiments, which was mainly a result of different weather conditions and competitiveness of cereals. While grass species reached a higher shoot dry matter than clover species in fertilized and dense cereal crops, clovers grew equal or better in unfertilized or sparse cereal stands. This is probably due to the higher competitiveness of grass species in light-limited environments and the reduced exploitation of available nutrients by clover species as a result of their smaller root system (Martin and Field, 1984). Due to lower barley density in the pot experiment 2012 and higher light interception, competition for light between clovers and barley was probably reduced, resulting in superior growth of clovers (Carof et al., 2007). This observation suggests that results from pot experiments are not easily transferable to field conditions and should only be considered as a complement to field studies. In the field experiments 2009 and 2012, dry matter of white clover was lower than for perennial ryegrass. Both experiments in 2012 suggest better root growth of the two ryegrass species compared to white and red clover. These observations agree with results from Kunelius et al. (1992), Høgh-Jensen and Schjoerring (2001), Ross et al. (2001) and Känkänen and Eriksson (2007).

The mixture of Italian ryegrass and red clover in both experiments in 2012 had equal shoot and root dry matter as the superior of both partners grown in single stand. Little information is available to date about mixtures of undersown crops, while in stands of cover crops and grassland species the improved growth of mixtures compared to monocultures has been documented (Akemo et al., 2000; Høgh-Jensen and Schjoerring, 2001; Linares et al., 2008; Sleugh et al., 2000; Wortman et al., 2012). Therefore, we assume that synergistic effect will also occur in mixtures of undersown crops.

Cereal growth

Undersown crops did not influence cereal growth in any of the field experiments, which supports the results of Carof et al. (2007), who found that cereals were very competitive against undersown crops. In 2011, fertilization and herbicide application had a much higher influence on wheat dry matter than the undersown crop treatments. In the pot experiment, no significant influence of any undersown crop on shoot growth of barley was measured. However, root dry matter of barley was significantly reduced in pots with Italian ryegrass, white clover and the Italian ryegrass-red clover mixture which were seeded immediately after barley. Due to its competitive root system, Italian ryegrass has the ability to interfere with root growth of cereals. However, this may only occur if ryegrass was seeded early in cereals (Kunelius et al., 1992; Liedgens et al., 2004).

Results from the pot experiment also show that the root system of cereal crops could be damaged by undersown crops even if no depression on shoot growth is visible. Therefore it is important to study not only the shoot but also the root system of cereals, to prevent growth and yield decrease caused by undersown crops due to a reduced uptake of water and nutrients.

Cereal grain and straw yield

Grain yield of cereal crops was not influenced by undersown crops in this study except for one fertilized treatment with early sown perennial ryegrass, which was caused by a reduction of wheat density. This underlines the high response of ryegrass to nitrogen fertilization, especially if no light competition occurs in early growth stages (Cowling and Lockyer, 1965; Iqbal and Wright, 1997; Scursoni et al., 2012).

The results suggest that, under similar conditions, the tested undersown crops may suitable for extensive and also for high yielding cropping systems. To avoid yield loss of fertilized cereals, it is important to match up undersown crops and cereals regarding their competitiveness, by selection of an adequate sowing date. Especially undersown crops with a high potential competitiveness e.g. ryegrass species, or red clover, should not be sown before the three leaves stage of cereals.

Weed suppression

In 2009 and 2010, weed density was not reduced by undersown crops. Also in 2011, no influence of undersown crops on density of *C. album* was observed. However, density of *V. persica* was significantly reduced by the undersown crops. Also in the field experiment 2012, weed density was reduced by white clover and the Italian ryegrass-red clover mixture. Undersown crops are able to reduce germination and emergence of weed seeds by shifting the red/far-red ratio of the sunlight, which is perceived by the plants (Ballaré and Casal, 2000; Kruk et al., 2006). After emergence of weeds, vigorous undersown crops are able to suppress short growing weeds like *V. persica* by competition for water, nutrients and especially light (Aerts et al., 1991). However, undersown crops have problems to reduce growth of strong competitive weeds such as *C. album*. Therefore, a dense cereal canopy with a high ability to shade weeds is important for sustainable and effective weed suppression (Liebman, 1989).

Shading should be the main factor of weed suppression by undersown crops, because competition for water and nutrients or the release of allelochemicals would also affect cereal yield (Appleby et al., 1976; Carof et al., 2007; den Hollander et al., 2007). Therefore, clover species with their shallow leaf angle are well suited as undersown crops maybe in combination with intensively rooting grass species to suppress weed species in cereals.

Conclusions

The results suggest that undersown crops can be included in integrated weed management strategies even in high yielding cereal production systems. To avoid yield losses it is important to match up undersown crops, sowing dates and the fertilization regime. Undersown crops with high competitiveness, e.g. ryegrass species and red clover should be seeded between the three leaves stage and tillering of cereal crops. Undersown crops with lower competiveness, like red fescue and white clover should be seeded before the three leaves stage of cereal crops, especially in fertilized cereal crops, to ensure adequate vegetative growth. If undersown crops were sown at adequate times, reduction of weed density and dry matter was possible without affecting cereal grain yields.

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3 General Discussion

3.1 Growth of new cover crop species in Central Europe

Seven new cover crop species were tested during the study in pot and field experiments to evaluate their ability for cultivation in Central Europe. The cover crop species offered different characteristics regarding their emergence, soil coverage and dry matter production which make them suitable for for a wide range of cropping situations.

Under southwest German conditions in 2011, tartary buckwheat covered almost completely the soil within a period of six weeks and produced the highest amount of shoot dry matter eight weeks after planting. The rapid soil coverage of buckwheat species was already mentioned in previous studies which emphasize their fast initial growth and soil coverage (Campbell, 1997; Marshall and Pomeranz, 1982). Due to its fast growth tartary buckwheat could be an interesting plant species for cultivation as cover crop in a winter wheat after winter wheat cropping situation, which mostly offers a fallow period of only eight weeks under climatic conditions in south Germany. However, tartary buckwheat is a frost sensitive cover crop and therefore not suitable for regions with early frosts in fall.

Forage radish offers a similar growth within the first few weeks after sowing as yellow mustard, oilseed radish and phacelia but shows reduced dry matter accumulation than tartary buckwheat eight weeks after planting. However, in comparison to tartary buckwheat it still produces a high amount of dry matter if growing conditions in fall are less favorable and early frost nights occur. While producing similar shoot dry matter to yellow mustard and oilseed radish, forage radish builds the highest root dry matter of all tested plant species. The suitability of forage radish as summer annual cover crop was also confirmed in previous field experiments at the eastern coast of the USA in which forage radish offered growth characteristics similar to those reported in this study (Lawley et al., 2011). Because of its good adaption to fall weather conditions and the high dry matter accumulation, forage radish seems to be well suited for cultivation as summer annual cover crop after grain cereals in Central Europe.

Lopsided oat produced an comparable amount of dry matter to common cover crop species and previous field experiments in southern USA (Price et al., 2006; Reeves et al., 2005). Beside a good shoot growth, lopsided oat also offers a fast initial root growth which results in a high amount of root dry matter and an intensive rooting of the upper soil layer. The fast initial root growth of lopsided oat is not uncommon for plant species of the *Poaceae* family and a beneficial characteristic especially for the usage as cover crop (White and Weil, 2010). The studies suggest that seeding of lopsided oat before the end of July results in fast development into generative growth stages caused by photoperiodic sensitivity to long daylenght (Loskutov, 2001; Sampson and Burrows, 1972). However, also under such condition, a successful suppression of weeds can be possible. Therefore, seeded after beginning of August, lopsided oat seems to be a suitable summer annual cover crop for cultivation in Central Europe.

Like the previous three plant species, niger and sorghum are also suitable for cultivation as cover crops after grain cereals. However, in comparison to tartary buckwheat, forage radish and lopsided oat, both plant species require higher temperatures during their vegetation for good growth. Therefore, early seeding dates or sufficient number of warm and sunny days in fall are required for their beneficial cultivation. Niger and sorghum could be well suited as cover crops after harvest of winter barley in south west Germany with seeding dates before mid of July.
Seeded at the beginning of July, niger is able to build $790\,\mathrm{g\,m^{-2}}$ of shoot dry matter within a period of twelve weeks, which is a very high value for cover crops in Central Europe. However, also at seeding date in mid of August niger offers a good dry matter production and produces comparable shoot dry matter to yellow mustard. Because of its broad and shallow angled leaves niger covers the soil fast and can help to

prevent erosion from heavy rainfalls which often occur during summer months in Central Europe. Although sorghum is a monocotyledonous plant species, soil coverage is similar to niger and yellow mustard due to its broad leaves. While sorghum produced a dry matter amount comparable to niger, its root system is much more developed, which enables an intensive exploration of the upper soil layer (Rosolem et al., 2002). In the conducted field experiments sorghum was able to produce a root dry matter of $190\,\mathrm{g\,m^{-2}}$ while niger and lopsided oat only offered under similar conditions a root dry matter of $70\,\mathrm{g\,m^{-2}}$ and $60\,\mathrm{g\,m^{-2}}$. The superior root growth of sorghum found in this study was also reported in previous field experiments and indicates very well its belowground growth potential, which is an important requirement for cover crops (Rosolem et al., 2002).

In the conducted field experiments, grain amaranth offered comparable growth to oilseed radish and phacelia. The dry matter amount of grain amaranth observed in this study was similar to previously reported values from western Brazil (Boer et al., 2008). Considering only the dry matter production, cultivation of grain amaranth could be an enrichment for the spectrum of cover crop species in Central Europe. However, for uniform emergence, desired plant density and good growth grain amaranth requires a fine seedbed and a precise seed deposition, which are unfavorable characteristics for cover crop establishment.
Red oat covered the soil in the lowest amount of all tested plant species six weeks after planting. Compared with yellow mustard, oilseed radish and phacelia, red oat produced similar dry matter at Ihinger Hof, while only a reduced amount of dry matter was measured at Meiereihof. Therefore, the tested variety of red oat and grain amaranth should not be cultivated in pure stand until further research clarifys their suitability for cover crop cultivation. However, both species can be integrated into cover crop mixtures to improve their biodiversity and resilience (Akemo et al., 2000; Linares et al., 2008; Wortman et al., 2012).

The results suggested that the tested plant species, except grain amaranth and red oat may be well suitable for cultivation as summer annual cover crops in Central Europe. However, to maximize benefits from their cultivation it is important to consider the particular requirements of each plant species. By enlarging the number of possible cover crops species, farmers have a greater choice to select a suitable cover crop for their cropping system and location. This might help to increase cover crop cultivation particularly in high yielding crop rotations or at unfavorable locations. In such intensive cropping systems, the tested cover crop species could help to preserve soil fertility and protect the soil against harmful environmental and agricultural impacts.

3.2 Weed suppression by cover crops

3.2.1 Requirements for weed suppression by cover crops

In the conducted study, the weed reduction potential of the tested cover crop species mainly depends on the amount of soil coverage and dry matter accumulation, which are both main components of a high aboveground competitiveness. Especially the fast and complete soil coverage through the cover crop canopy was an important factor for weed suppression. Cover crop species that were able to cover the soil almost completely within a period of six weeks like yellow mustard and tartary buckwheat showed the best ability for weed suppression during the conducted experiments, whereas cover crop species with a low soil coverage like red oat had problems to stop growth of weeds. The importance of a fast and complete soil coverage for successful weed control by cover crops was also reported from other field experiments in different climatic environments and should be the main requirement to a cover crop which is cultivated for weed control (Brennan and Smith, 2005; Uchino et al., 2011).

However, the field experiments showed that fast soil coverage is not only important for reduction of weed growth, it additionally reduce further emergence of weed seedlings. In the studies, a significantly reduced number of weed seedlings was counted in plots of cover crop species with fast soil coverage, already four weeks after planting at Meiereihof in the field experiment 2011. During the subsequent measurement dates, almost no additional increase of weed seedlings was observed in plots of yellow mustard and tartary buckwheat, while in weedy control plots the number of weeds increased until the second measurement eight weeks after planting. The reduced germination of weed seedlings in the cover crop plots results from a change in the red-far-red ratio of sunlight caused by specific absorption of several wavelength on photosynthetically active plant tissue of cover crops (Ballaré and Casal, 2000; Batlla et al., 2000; Kruk et al., 2006).

However, not only the above but also the below ground competitiveness is important for a successful reduction of weed growth and density. Only with a well developed root system, cover crops have the ability to suppress weeds by competition for water and nutrients (Belcher et al., 1995). Especially cover crops like lopsided oat, which has only a reduced competitiveness for light due to its small and stepper angled leaves, require a well developed root system for successful weed suppression.

Beside the competition about growth factors, cover crops can also release allelopathic active chemicals from their plant tissue, which reduces or even avoid germination and growth of weeds (Bezuidenhout et al., 2012; Creamer et al., 1996). In the conducted measurements it was not possible to separate the below ground competitiveness of cover crops into physical and allelophatic effects. However, the still detectable weed suppression in plots of red oat which produced only a reduced shoot and root dry mater indicates the release of allelophatic active chemicals into the rhizosphere.

3.2.2 Weed suppression during vegetation of cover crops

If a competitive crop stand was established, no further increase of weed dry matter could be observed during cover crop vegetation subsequent to the first measurement four weeks after planting. Especially tartary buckwheat and yellow mustard showed a high ability to reduce shoot and root dry matter of weeds and volunteer grain. Both cover crop species were able to reduce weed growth by up to 96 % already eight weeks after planting. Also forage radish, lopsided oat and niger showed a high weed suppression ability and reduced weed growth by more than 95 % until the end of the vegetation period.

While fast soil coverage is advantageous to reduce weed pressure by preventing weed germination during the cover crop cultivation, it could be unfavorable in long-term view or already in the next cash crop. To avoid increased germination of weeds and volunteer grain in the following cash crop, it could be better if sunlight reaches the soil surface as long as possible and just when almost all germinable weed seeds have emergence a fast canopy closure occurs. A delayed soil coverage of still competitive cover crops is mainly provided by lopsided oat, sorghum and forage radish. Therefore these cover crops could have the ability to reduce the weed seedbank. However, the influence of the different cover crop species on the weed seed bank was not analyzed in this study. Although weed seeds do not germinate due to fast soil coverage by cover crops, they could be destroyed by other mechanisms for example by invertebrate seed predation which increases under a cover crop canopy (Gallandt et al., 2009; Westerman et al., 2003).

In this study only the suppression of annual weed species and volunteer cereals was investigated. However, caused by reduced tillage and crop diversity, perennial weeds are becoming more important in Central Europe (Buhler et al., 1994). Concerning this topic, previous field experiments show that specific cover crop species like buckwheat and sorghum are able to suppress perennial weeds (Bicksler and Masiunas, 2009). Therefore, cultivation of such highly competitive cover crops especially in intensive cropping systems is important to reduce or prevent the propagation of annual and also perennial weeds.

3.2.3 Weed suppression after vegetation of cover crops in early spring

For the management of a cropping system, the weed situation in spring is important for further decisions prior seeding of the subsequent cash crop. Especially the application of a burn down herbicide or the intensity of tillage mainly depends on the occurend weed density in spring.

The weed density in spring was mainly influenced by the competitiveness and frost tolerance of the cover crop species. During their vegetation in fall, competitive cover crop species were able to completely suppress the growth of weeds and volunteer cereals. However, frost sensitive cover crop species like niger, grain amaranth, sorghum and tartary buckwheat freeze off in first frosty nights in fall. Due to early death, no further competition about light, water and nutrients occurs, which resulted in regrow of already suppressed weeds or the emergence of new weed seedlings. Therefore, density of living weeds and volunteer cereals in plots of frost sensitive cover crops was higher than in plots of more frost tolerant cover crop species like oilseed radish, forage radish and phacelia.

In plots of more frost tolerant cover crops, only a reduced density of less than three plants per square meter or even no living weed and volunteer grain was detected at the measurement in spring. Due to the almost complete weed suppression in spring, it could be possible for farmers to save the application of foliar active burndown herbicides like glyphosate prior seeding of the next cash crop.

3.3 Management of undersown crops in cereals

In high yielding cropping systems, undersown crops are only used in a reduced range today. However, even for high yielding cereal cropping systems, usage of undersown crops is beneficial and not necessarily connected with yield reduction.

During five experiments from 2009 until 2012, reduction of growth and yield caused by undersown crops was only detected in two cases. The first case occurred in the pot experiment 2012, when a reduced root dry matter of barley was measured in pots of Italian ryegrass, white clover and the mixture of Italian ryegrass and red clover, which were seeded together with barley. A reduction of main crop yield was measured in the field experiment 2011 when the competitive plant species perennial ryegrass was seeded at the three leaves stage of spring wheat under a sufficient nitrogen regime. In all other cases, no influence of undersown crops on growth and yield of cereal main crops could be measured.

Results from the field experiments suggested that neither in cropping systems with reduced availability of nitrogen nor in cropping systems with sufficient nitrogen fertilization undersown crops decrease yield if the sowing date is harmonized with the competitiveness of the undersown crop species and the main crop. These results are confirmed by earlier findings from field experiments in Finland which also suggested that undersown crops do not decrease yield of the main crop if adapted cultural practice occurs (Känkänen and Eriksson, 2007). To avoid main crop injury it is important to harmonize the competitiveness of the used undersown crop species with the time of establishment, especially if additional nitrogen was supplied. Highly competitive undersown crop species like Italian ryegrass, perennial ryegrass and red clover should not be seeded before cereals reach the three leave stage to avoid interference on main crop growth and yield. Best seeding time for low competitive undersown crops like red fescue or white clover is together with the main crop or before cereals reach the three leaves stage, to avoid suppression of undersown crops by the main crop. However, regardless which undersown species was used, seeding dates after beginning of tillering result in most cases in almost complete suppression of undersown crops and therefore farmers should avoid such late seeding dates.

A further way to harmonize the competition ability of undersown crops to the main crop is the adaption of plant density (Känkänen and Eriksson, 2007). In the conducted experiments, however, only the sowing date of undersown crops or the fertilization regime were modified because for weed suppression a high plant density of undersown crops is necessary for a high competitive ability against weeds (Weiner et al., 2001).

3.4 Weed suppression by undersown crops

Weed density in the field experiments 2011 and 2012 was successfully reduced by early sown white clover. Furthermore, it seems that the used undersown crops were also able to reduce dry matter of weeds while not reducing main crop growth. However, no significantly different weed dry matter could be detected due to high variation. Although reduction of weed dry matter was not significant in this study, results from previously conducted field experiments offer the suitability of undersown crops for weed suppression (den Hollander et al., 2007).

Results from this study additionally suggest that undersown crops could not reduce every weed species in the same amount. Small growing weed species like common chickweed or persian speedwell are much better to control than tall growing weeds like lamb's quarters. The main reason therefore is the small plant height of undersown crops, which is required to avoid main crop injury and interferences during the harvest process (Hively and Cox, 2001). Due to the small habitus, undersown crops could not suppress taller growing weeds by shading, which is a main factor influencing the competitiveness of undersown crops against weeds (Carof et al., 2007).

The studies offered that successful weed suppression by undersown crops without decreasing main crop growth or yield is also possible in high yielding cropping systems, if adapted cultivation practice is implemented. Therefore, herbicide reduction by undersown crops, is possible if an adapted cropping management occurs and mainly small weeds grows in the field.

3.5 Improvement for further research

In cover crop experiments, soil coverage was measured to quantify the growth and weed suppression ability of the different plant species. While soil coverage could be well used as indicator for plant growth, its information value regarding the weed suppression ability of a cover crop stand is reduced (Van Henten and Bontsema, 1995). Even if cover crops completely cover the soil surface, enough sunlight for growth could reach weeds due to unfavorable leaf and shoot morphology (O'Connell et al., 2004; Sekimura et al., 2000). Furthermore, not only the quantity of sunlight is important, but also the light quality that influences weed growth and development (Li et al., 2001). Therefore, measurement of the photosynthetically active radiation under a cover crop canopy would be more suitable to evaluate the light competitiveness of different cover crop species.

To quantify the growth and weed suppression ability of cover crops, undersown crops and weeds, the root dry matter was measured in this study. However, to quantify the competitive ability of plant species for water and nutrients, root dry matter is less suitable than the root length, the root surface or the root hair density (Caldwell and Richards, 1986; Itoh and Barber, 1983; Ma et al., 2001). Consequently, measurement of those root characteristics, could be more accurate to determine the belowground competition ability of a cover crop species. However, measurement of root growth, root surface or even root hair density is very expensive and under field conditions extremely difficult to realize due to heterogeneous soil conditions and complex analysis procedures (Fitter and Stickland, 1992; Newman, 1966; Sanders and Brown, 1978).

3.6 Possible topics of further research

3.6.1 Cover Crops

Further research projects should analyze if the already tested new cover crop species suppress weeds only by physical competition for light, water and nutrients, or if they also reduce weed growth by the release of allelophatic substances as described for many other plant species (Bezuidenhout et al., 2012; Creamer et al., 1996). If cover crops dispense allelophatic substances, it is interesting to know, if those chemical compounds have a general effect on all plants or only on certain plant families or species, which would be more desirable.

Furthermore, not only direct suppression of weeds by cover crop cultivation should be investigated, also the mid and long term effects on the weed abundance in the crop rotation are an important issue. Therefore, it is necessary to measure the abundance of weeds in the following cash crop and explore the underlying mechanisms. Already former field experiments indicate that cover crop cultivation reduced the weed density in the following cash crop (Teasdale et al., 1991). However, many factors influence the weed abundance in cash crops fallowing cover crop cultivation. The residue management, and in particular the amount of tillage have a huge influence on the weed abundance and the underlying mechanisms. The amount of tillage mainly determines if midterm effects on weed emergence result from physical effects of soil coverage by residues or from chemical components generated during decomposition after cover crop incorporation.

For long-term effects it is important to analyze the influence of cover crop cultivation on the weed seedbank. Therefore, it is important to observe to which amount cover crop cultivation influences the emergence of weed seeds and furthermore if certain weeds species are able to produce fertile seeds even if high competition by cover crops occurs. Previous research has already suggested that a combination of tillage and cover crops cultivation could influence or reduce the weed seedbank (Clements et al., 1996; Mirsky et al., 2010; Teasdale et al., 1991). However, the particular influence of certain cover crops and differences within cover crop species have not been evaluated yet.

Only if cover crop cultivation in combination with reduced tillage does not result in an increased weed seedbank it is a suitable tool for longterm reduction of herbicides.

3.6.2 Undersown crops

In this study, the ability of undersown crops to suppress weeds varied considerably within the years. Therefore it is important to find solutions which make the system more reliable. Especially the usage of different plant species in a mixture instead of a single undersown crop species would be a way to improve the reliability of undersown crop cultivation under variable environmental conditions. Therefore, it is important to find suitable mixture ratios and varieties which complement each other and combine the advantages of single species without decreasing main crop growth or yield formation.

4 Summary

The agronomic situation in Germany is characterized by a reduction of crop diversity within crop rotations, which is mainly a consequence of present economic conditions. This results in rare change between fall and spring seeded crops, combined with increasing weed populations. Furthermore, economic pressure and the interests of soil protection result in decreased tillage intensity, especially a reduced usage of the moldboard plow. While this is a positive trend from the perspective of soil and water conservation, from the view of weed science this cultivation practice has serious consequences because the combination of non-inversion tillage and permanent cultivation of only fall or spring seeded crops leads to a noticeable rise of weed populations. Especially in minimum or no-tillage cropping systems, control of increased weed pressure usually succeeds only by a frequently application of herbicides. The integration of cover crops and undersown crops into such cropping systems could be a step to reduce the amount of herbicides during crop cultivation but also within a fallow period.

Cultivation of cover crops during fallow periods could influence the agricultural ecosystem in many positive ways. Beside others benefits, cover crops are able to improve the soil structure, increase water infiltration and protect the soil from wind and water erosion. Cover crops are a habitat for beneficial insects and could positively affect the microbiology of the soil due to shading the soil surface and the release of root exudates into the rhizosphere. Furthermore, cover crops are able to suppress the growth of weeds and volunteer crops. The suppression of weeds and volunteer cereals could result either from direct competition for light, water and nutrients or from the release of allelopathic substances produced by living or decomposing cover crop tissue.

In Germany mainly yellow mustard, oilseed radish and phacelia are grown as cover crops. All three cover crop species are well adapted to cool temperatures and short daylenght in fall and offer under those unfavorable growth conditions still an adequate dry matter accumulation and weed suppression. However, the positive effects of cover crop cultivation are much higher if they are seeded immediately after harvest of the previous crop in summer and not in fall when unfavorable weather conditions inhibit their growth. Unfortunately, yellow mustard, oilseed radish and phacelia are not suitable for early seeding dates in summer. Because of their long-day characteristics, early seeding dates result in short vegetative development with reduced soil shading, dry matter production and weed suppression. Therefore, new cover crop species are required which offer suitable adaption to early seeding date but also to less favorable growing conditions in fall which ensure good growth and adequate weed control under different environmental conditions.

Not only cover crops, also undersown crops have the ability to improve soil quality and reduce the growth of weeds. For a successful suppression of weeds an adequate growth of undersown crops is required. However, excessive growth of undersown crops can also decrease growth and yield formation of the main crop, especially if sufficient nitrogen is available. Therefore, the coordination of sowing time and fertilization is important to harmonize the competitive strength of both partners. In this way it is possible to cultivate high competitive undersown crops such as Italian ryegrass together with sensitive main crops like spring barley.

The aim of this study was to determine the influence of cover crop and undersown crop cultivation on arable farming systems from the perspective of weed science. Furthermore it should be clarified in which way it is possible to integrate cover crops and undersown crops in intensive cropping systems.

Within the cover crop topic this was done by the search for new cover crop species which are suitable for cultivation in Central Europe to expand the range of available cover crop species for lots of cropping situations and site conditions. Additionally the weed suppression ability of different cover crop species in fall and spring was analyzed to determine if it is possible to avoid a mechanical or chemical weed control prior seeding the next cash crop. For this purpose, six field and two pot experiments were conducted at four sites in southwest and east Germany between 2010 and 2012. During these experiments, emergence, soil coverage the shoot and root dry matter of cover crops were measured and furthermore their weed suppression ability was determined. Within the undersown crop topic the influence of different management practices on growth of undersown crop as well as growth and yield formation of the main crop was investigated. Furthermore, it was researched if it is possible to achieve a suppression of weeds by undersown crops. For this purpose, four field and one pot experiment were conducted at three locations in southwest Germany between 2009 and 2012. During these experiments, influence of seeding date and fertilization on the shoot and root growth of undersown crops were measured. Furthermore, the influence of undersown crops on growth and yield formation of main crops and on growth of weeds were determined.

The conducted experiments relating the cover crop topic showed that from the new cover crop species especially tartary buckwheat, forage radish and lopsided oat are well suited for cultivation. Under southwest German conditions, tartary buckwheat offered a rapid soil cover and was able to cover the soil surface almost completely within a period of six weeks after sowing. Furthermore, tartary buckwheat produced the highest amount of shoot dry matter eight weeks after sowing. Forage radish was also able to cover the soil surface quickly and produced the highest root dry matter of all tested plant species. In contrast to tartary buckwheat, forage radish tolerates light frosts and has therefore the ability to protect the soil until the end of the growing season. Lopsided oat produced a well-developed shoot and root system during the experiments and was able to deal with cool and unfavorable weather condition in fall. However, lopsided oat is better suitable for later sowing dates after end of July due to its photoperiodic characteristics, which causes a reduced vegetaive growth. The two subtropical cover crop species niger and sorghum offered a good suitability for cultivation as cover crops. However, both reached their full potential especially at early sowing dates at the beginning of July. Niger was able to build a high amount of shoot dry matter at early sowing dates and also at later sowing dates in mid of August a comparable shoot growth to yellow mustard was observed. Furthermore, niger was able to cover the soil surface quickly due to its favorable leaf morphology. Although sorghum is a member of the *Poaceae* family, due to its broad leaves it could cover the soil surface in a comparable time to dicotyledonous cover crops. Additionally, sorghum offered an intense rooting of the topsoil caused by its vigorous root system. Grain amaranth showed similar growth to yellow mustard, oilseed radish and phacelia, but due to its high requirements for seedbed preparation it is less suitable for cultivation in pure stands. Red oat offered only a small soil cover and dry matter production in the experiments. However, for finalized statements further research is required.

The shoot and root growth of weeds could be effectively reduced by the successful establishment of a cover crop stand in fall. In plots of competitive cover crops like yellow mustard, oilseed radish, tartary buckwheat and lopsided oat, no further growth of weeds and volunteer cereals occurs after the first measurement in fall four weeks after cover crop planting. However, cover crops can not only reduce weed growth, they also reduce the density of weeds and volunteer cereals. The study shows that a successful suppression of weeds mainly requires an early and complete soil shading and a high above ground dry matter. Results from the experiments offer that not only cover crops with a high above ground competitiveness like tartary buckwheat are able to suppress weeds, but also cover crop species like lopsided oat with a reduce competitiveness for light have the ability to highly reduce weed growth. However, these cover crop species need, to a greater extent than broadleaf cover crops, a well-developed root system to obtain a high competitive ability for water and nutrients. The weed-suppressing effect of cover crop cultivation was measurable not only in fall during growth, but also in spring after freezing of cover crops. Especially in plots of late freezing cover crop species like oilseed radish and phacelia only a very reduced plant density or even no living weeds and volunteer grains were observed.

The conducted experiments relating the undersown crop topic demonstrate that it is possible to integrate undersown crops in high yielding cereal cropping systems without decreasing growth and yield formation of the main crop. During the four conducted field experiments, a reduction in grain yield was only observed when perennial ryegrass was seeded at the three leaves stage of spring wheat and grew under sufficient nitrogen conditions. To achieve adequate growth of undersown crops while avoiding yield reduction, it is necessary to use specific sowing dates for different undersown crop species. Undersown crops with a low competitiveness such as red fescue or white clover should be established simultaneously with the main crop or before it reaches the three leaf stage. Undersown crops with a higher competitiveness such as red clover, perennial ryegrass and especially Italian ryegrass should not be established together with the main crop. They are better suited for later sowing dates e.g. at the three-leaves stage of the main crop. Seeding dates of undersown crops after the beginning of tillering resulted only in a reduced growth and small dry matter accumulation.

The study shows that undersown crops are able to reduce weed density during main crop growth. However, the habitus of weeds was an important factor influencing the weed suppression ability of undersown crops. Undersown crops were able to reduce the density of small growing weed species such as *Veronica persica* while density of high-growing weeds like *Chenopodium album* were not affected. The experiments in this study offer that is possible to successfully integrate cover crops and undersown crops into modern agricultural systems without reducing their productivity. Furthermore it was demonstrated that due to the cultivation of cover crops and undersown crops it is possible to control the growth of weeds not only during but also between cash crop vegetation. By these methods, under certain conditions a reduction of the required amount of herbicides is possible, which can be a contribution to a more sustainable food production.

5 Zusammenfassung

Die ackerbauliche Situation in Deutschland ist geprägt durch eine Verringerung der Anzahl angebauter Kulturpflanzen, was vor allem auf wirtschaftliche Rahmenbedingungen zurückzuführen ist. Diese Entwicklung resultiert oftmals in einem nur noch seltenen Wechsel zwischen Sommerungen und Winterungen, was in vielen Fällen mit einem Anstieg der Unkrautpopulation verbunden ist. Zusätzlich führen wirtschaftlicher Druck sowie die Belange des Bodenschutzes zu einer reduzierten Intensität der Bodenbearbeitung, insbesondere zu einer starken Einschränkung des Pflugeinsatzes. Was aus dem Blickwinkel des Boden- und Gewässerschutzes als positiv zu bewerten ist, hat aus herbologischer Sicht erhebliche Konsequenzen für das Ackerbausystem, da vor allem die Kombination aus nichtwendender Bodenbearbeitung sowie unterlassenem Wechsel zwischen Sommerungen und Winterungen zu einem spürbaren Anstieg der Unkrautpopulation führt. Besonders bei minimaler oder unterlassener Bodenbearbeitung gelingt die Kontrolle des erhöhten Unkrautdruckes zumeist nur durch einen gesteigerten Einsatz von Herbiziden. Die Integration von Zwischenfrüchten und Untersaaten kann in solchen Ackerbausystemen ein Baustein zur Reduzierung des Herbizideinsatzes innerhalb der Vegetationsperiode sowie während einer Brachezeit sein.

Durch den Anbau von Zwischenfrüchten während einer Brache kann das Agrarökosystem auf vielfältige Weise positiv beeinflusst werden. So können Zwischenfrüchte unter anderem zu einer Verbesserung der Bodenstruktur, einer Erhöhung der Wasserinfiltration sowie zu einer Verringerung der Wind- und Wassererosion beitragen. Weiterhin sind Zwischenfrüchte ein Habitat für nützliche Insekten, können die Mikrobiologie des Bodens positiv beeinflussen sowie das Wachstum von Unkräutern und Ausfallgetreide unterdrücken. Die Unterdrückung von Unkräutern sowie Ausfallgetreide durch Zwischenfrüchte kann hierbei entweder durch direkte Konkurrenz um Licht, Wasser sowie Nährstoffe oder durch Ausscheidung allelopathisch wirksamer Substanzen aus lebendem oder totem Pflanzengewebe erfolgen.

In Deutschland werden vor allem Gelbsenf, Ölrettich sowie Phacelia als Zwischenfrüchte angebaut. Sie sind gut an die kühlen Temperaturen und kürzere Tageslänge im Herbst angepasst und könne auch unter ungünstigen Wachstumsbedingungen ausreichend Trockenmasse bilden und Unkräuter unterdrücken. Jedoch sind die positiven Effekte des Zwischenfruchtanbaues weit höher, wenn dieser nicht erst im Herbst unter kühleren Witterungsbedingungen, sondern schon im Sommer während oder kurz nach Ernte einer entsprechenden Vorfrucht beginnt. Jedoch sind Gelbsenf, Ölrettich und Phacelia aufgrund ihrer photoperiodischen Eigenschaften für solch frühe Aussaattermine ungeeignet. Ihr ausgeprägter Langtagcharakter resultiert bei zu früher Aussaat in einer beschleunigten vegetativen Entwicklung, was eine reduzierte Bodenbeschattung, Trockenmassebildung sowie Unkrautunterdrückung zur Folge hat. Für frühe Aussaattermine werden deshalb neue Zwischenfruchtarten benötigt welche jedoch auch bei ungünstigeren Wachstumsbedingungen im Herbst eine ausreichende Trockenmassebildung sowie Unkrautkontrolle gewährleisten können.

Nicht nur Zwischenfrüchte, auch Untersaaten können das Agrarökosystem in vielfältiger Weise positiv beeinflussen und bei richtiger Anwendung zu einer Reduzierung von Herbiziden sowie einer Verbesserung der Standorteigenschaften beitragen. Da Untersaaten räumlich und zeitlich parallel zu einer Deckfrucht angebaut werden, besteht jedoch die Gefahr, dass diese vorallem in gut mit Stickstoff versorgten Anbausystemen durch die Untersaat in ihrem Wachstum sowie ihrer Ertragsbildung negativ beeinflusst wird. Um ein ausreichendes Wachstum der Untersaat zu gewährleisten, ohne hierbei jedoch die Deckfrucht, in ihrer Ertragsbildung zu beeinträchtigen ist der Saatzeitpunkt der Untersaat von entscheidender Bedeutung. Durch Anpassung des Saatzeitpunktes ist es möglich auch konkurrenzkräftige Untersaaten wie Welsches Weidelgras in empfindlichen Deckfrüchten wie Sommergerste anzubauen.

Ziel dieser Studie war es, aus herbologischer Sicht den Einfluss von Zwischenfrüchten und Untersaaten auf moderne Ackerbausystemen zu ermitteln sowie festzustellen, auf welchem Wege diese auch in intensiven Anbausystemen Verwendung finden können.

Innerhalb des Themenkomplexes “Zwischenfrucht” wurde dies umgesetzt durch die Suche nach neuen Zwischenfruchtarten, welche für den Anbau in Mitteleuropa geeignet sind, um so das Spektrum an verfügbaren Zwischenfruchtarten für vielfältige Anbausituationen und Standortgegebenheiten zu erweitern. Zusätzlich wurde die Unkrautunterdrückende Wirkung unterschiedlicher Zwischenfrüchte im Herbst sowie zu Vegetationsbeginn im Frühjahr analysiert um festzustellen, ob potentiell auf den Einsatz einer mechanischen oder chemischen Unkrautregulierung vor Aussaat der nachfolgenden Kulturpflanze verzichtet werden kann. Hierzu wurden in den Jahren 2010 bis 2012 sechs Feld- sowie zwei Topfversuche an vier Standorten in Süd- sowie Ostdeutschland durchgeführt. Im Verlauf dieser Versuche wurde das Auflaufen, die Bodenbedeckung sowie die ober- und unterirdische Trockenmasse der Zwischenfruchtarten bestimmt und ihre Fähigkeit zur Reduzierung des Unkrautwachstums sowie der Unkrautdichte untersucht. Innerhalb des Themenkomplexes “Untersaat” wurde untersucht, ob es möglich ist durch Anpassung unterschiedlicher Anbauverfahren mittels Untersaaten eine Unterdrückung von Unkräutern zu erzielen, ohne hierbei jedoch Wachstum sowie Ertragsbildung einer Getreidedeckfrucht zu beeinträchtigen. Dieser Themenkomplex wurde während der Jahre 2009 bis 2012 in vier Feldversuchen sowie einem Topfversuch an drei Standorten in Süddeutschland untersucht. Während der Durchführung der Versuche wurde die ober- sowie unterirdische Trockenmasse der Untersaaten in Abhängigkeit des Saattermines sowie der Stickstoffdüngung bestimmt. Weiterhin wurde der Einfluss der Untersaaten auf Wachstum sowie Ertragsbildung der Deckfrucht sowie die Fähigkeit zur Reduzierung des Unkrautwachstums und der Unkrautdichte ermittelt.

Die durchgeführten Untersuchungen des Themenkomplexes “Zwischenfrucht” zeigten, dass von den erstmals in Mitteleuropa angebauten Zwischenfruchtarten besonders Tatarischer Buchweizen, Futterrettich sowie Rauhafer eine sehr gute Anbaueignung aufweisen. Tatarischer Buchweizen zeichnete sich unter südwestdeutschen Bedingungen durch eine schnelle Bodenbedeckung aus und konnte bereits sechs Wochen nach Aussaat annähernd die komplette Bodenoberfläche beschatten. Weiterhin bildete er die höchste Sprosstrockenmasse aller untersuchten Zwischenfrüchte acht Wochen nach Aussaat. Futterrettich konnte ebenfalls den Boden zügig bedecken und bildete die größte Wurzelmasse aller getesteten Pflanzenarten. Im Gegensatz zu Tatarischem Buchweizen verträgt er auch leichte Fröste und kann so bis zum Ende der Vegetationsperiode den Boden schützen.

Rauhafer bildete in den Untersuchungen ein gut ausgebildetes Spross- sowie Wurzelsystem und kam ebenfalls mit kühleren Witterungsbedingungen im Herbst gut zurecht. Für Aussaattermine vor Ende Juli ist Rauhafer jedoch weniger geeignet, da er bei diesen aufgrund photoperiodischer Eigenschaften nur eine reduzierte vegetative Entwicklungsdauer aufweist. Auch die beiden subtropischen Zwischenfruchtarten Ramtillkraut sowie Sorghum weisen eine gute Anbaueignung auf, können ihr volles Potential jedoch besonders bei frühen Saatterminen gegen Anfang Juli ausspielen. Ramtillkraut konnte nicht nur bei frühen Saatterminen Anfang Juli eine hohe Sprosstrockenmasse bilden, sondern zeigt auch noch bei späteren Saatzeitpunkten Mitte August vergleichbare Werte wie Gelbsenf. Ramtillkraut war in der Lage, aufgrund seiner günstigen Blattmorphologie die Bodenoberfläche zügig zu beschatten. Sorghum konnte trotz seiner Zugehörigkeit zur Pflanzenfamilie der Süßgräser aufgrund seiner relativ breiten Blätter den Boden in vergleichbarem Maße wie dikotyle Zwischenfrüchte beschatten, zeichnete sich jedoch zusätzlich durch eine intensive Durchwurzelung des Oberbodens aus. Amarant zeigte vergleichbares Wachstum wie Gelbsenf, Ölrettich sowie Phacelia, ist aber aufgrund seiner Unsicherheiten bei der Etablierung als Reinsaat eher ungeeignet. Mittelmeer-Hafer konnte in den Versuchen nur eine geringe Bodenbedeckung sowie Trockenmassebildung aufweisen. Für abschließende Aussagen bedarf es jedoch noch weiterer Untersuchungen.

Das Spross- sowie Wurzelwachstum von Unkräutern konnte durch die erfolgreiche Etablierung eines Zwischenfruchtbestandes im Herbst effektiv reduziert werden. So wurde in Parzellen konkurenzkräftiger Zwischenfrüchte wie Gelbsenf, Ölrettich, Tatarischer Buchweizen und Rauhafer kein weiteres Wachstum der Unkräuter sowie des Ausfallgetreides im Anschluss an den ersten Probenahmetermin vier Wochen nach Aussaat mehr festgestellt. Durch Zwischenfruchtanbau konnte nicht nur das Wachstum sondern ebenfalls die Anzahl vorhandener Unkräuter und Ausfallgetreides reduziert werden. Voraussetzung für eine erfolgreiche Unterdrückung der Unkräuter ist hierbei vor allem eine frühe und vollständige Bodenbeschattung sowie eine hohe oberirdische Trockenmasseproduktion. Wie sich während den Versuchen zeigte, konnten jedoch ebenfalls Zwischenfrüchte wie Rauhafer, die aufgrund ihrer Blattmorphologie nur eine reduzierte Bodenbeschattung aufweisen, sehr gut das Unkrautwachstum hemmen. Hierfür benötigten sie jedoch, in stärkerem Maße als breitblättrige Zwischenfrüchte ein gut ausgebildetes Wurzelsystem für eine hohe Konkurrenzfähigkeit um Wasser und Nährstoffe. Die Unkrautunterdrückende Wirkung durch den Zwischenfruchtbestand konnte nicht nur im Herbst sondern ebenfalls im Frühjahr nach Absterben der Zwischenfrucht festgestellt werden. Besonders in Parzellen von spät abfrierenden Zwischenfrüchten wie Ölrettich und Phacelia konnte zu Vegetationsbeginn oftmals nur eine sehr geringe Unkrautdichte oder ausschließlich abgestorbene Unkräuter sowie Ausfallgetreide beobachtet werden.

Die durchgeführten Untersuchungen des Themenkomplexes "Untersaat" belegen, dass es möglich ist Untersaaten auch in intensiv geführte Anbauysteme zu integrieren, ohne die Ertragsbildung der Deckfrucht zu beeinträchtigen. Während der vier durchgeführten Feldversuche konnte nur in einem Fall, durch Deutsches Weidelgras welches zum Drei-Blatt-Stadium eines Sommerweizens etabliert wurde, bei bedarfsgerechter Stickstoffdüngung eine Reduzierung des Kornertrages festgestellt werden. Um ein ausreichendes Wachstum der Untersaat bei gleichzeitiger Vermeidung einer Ertragsreduzierung zu erreichen, ist es notwendig spezifische Saatzeitpunkte für die jeweiligen Untersaaten einzuhalten. Konkurrenzschwache Untersaaten wie Rotschwingel oder Weißklee sollten zeitgleich mit der Deckfrucht oder vor Erreichen des Dreiblattstadiums etabliert werden. Konkurrenzkräftigere Arten wie Rotklee, Deutsches Weidelgrass, aber vor allem Welsches Weidelgras sollten nicht gemeinsam mit der Deckfrucht etabliert werden, sondern sind vorteilhafter für spätere Saatzeitpunkte zum Dreiblattstadium der Deckfrucht. Etablierungszeitpunkte nach Beginn der Bestockung führten in den durchgeführten Versuchen nur zu einem spärlichen Wachstum der Untersaat. Es konnte gezeigt, werden das Untersaaten in der Lage sind, die Unkrautdichte während der Vegetation einer Hauptfrucht zu reduzieren. Jedoch war hierbei die Morphologie der Unkräuter entscheidend. So konnte die Anzahl niedrig wachsende Unkräuter wie *Veronica persica* durch Untersaaten verringert werden, wohingegen hochwachsende Unkräuter wie *Chenopodium album* nicht beeinträchtigt wurden. Die im Rahmen dieser Studie durchgeführten Untersuchungen zeigten, dass Zwischenfrüchte und Untersaaten erfolgreich in moderne Anbausysteme integriert werden können, ohne deren Produktivität zu beeinträchtigen. Es konnte gezeigt werden dass durch den Anbau von Zwischenfrüchten und Untersaaten das Wachstum von Unkräutern unterdrückt wird. Hierdurch ist es möglich unter gewissen Umständen eine Verringerung der benötigten Herbizdmenge zu erreichen, was zu einer umweltgerechteren und nachhaltigeren Produktion beiträgt.

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Erklärung/Declaration

Hiermit erkläre ich, dass ich die vorliegende Dissertation selbständig angefertigt habe, nur die angegebenen Quellen und Hilfsmittel benutzt und wörtlich oder inhaltlich übernommene Stellen als solche gekennzeichnet habe.
Diese Dissertation wurde entsprechend der Promotionsordnung der UniversitätHohenheim zum Dr. sc. agr., Stand 14. Februar 2013 sowie den Durchführungsbestimmungen der Fakultät Agrarwissenschaften zur Promotionsordnung der Universität Hohenheim zum Dr. sc. agr., Stand 17.07.2013, angefertigt.

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