AGRONOMIC ASPECTS OF INTERCROPPING SPRING OR WINTER PEAS AND CEREALS AS INFLUENCED BY PLOUGHING SYSTEM

DISSERTATION

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L'agriculture est le premier métier de l’homme; c’est le plus honnête, le plus utile et par conséquent le plus noble qu’il puisse exercer.
Der Ackerbau ist und bleibt die erste Beschäftigung des Menschen; sie ist die ehrenvollste, die nützlichste und folglich auch die edelste von allen, die er betreiben kann.

Jean-Jacques Rousseau[*]

Alles Wissen und alle Vermehrung unseres Wissens endet nicht mit einem Schlusspunkt, sondern mit Fragezeichen. Ein Plus an Wissen bedeutet ein Plus an Fragestellungen, und jede von ihnen wird immer wieder von neuen Fragestellungen abgelöst.

Hermann Hesse[†]

Toute image forte devient.
Jedes starke Bild wird Wirklichkeit.

Antoine de Saint-Exupéry[‡]

”

[*] Rousseau, J.-J., 1762. Émile ou de l’éducation, Livre III, L’âge de force: de 12 à 15 ans. J. Náulme, Den Haag / Rousseau, J.-J., 1995. Emil oder über die Erziehung: Drittes Buch. Schöningh, Paderborn.

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Abbreviations and acronyms

ANOVA	Analysis of variance
a.s.l.	Above sea level
BBCH	Biologische Bundesanstalt für Land- und Forstwissenschaft, Bundessortenamt und Chemische Industrie
C	Crop stand
Ca	Calcium
CAL	Calcium acetate lactate
C_t	Total soil carbon
cm	Centimetre
CO_2	Carbon dioxide
CP	Crude protein
cv.	Cultivar
D	Sampling date
DAS	Days after sowing
DLG	Deutsche Landwirtschafts-Gesellschaft
DP	Deep ploughing
Dptr.	Departure
d.m.	Dry matter
e.g.	exempli gratia (for example)
EFB	E.F.B. 33
EPPO	European and Mediterranean Plant Protection Organization
et al.	Et alii (and others)
Fig.	Figure
g	Gram
GfE	Gesellschaft für Ernährungsphysiologie
GLIMM	Generalized Linear Mixed Model
GLM	Generalized Linear Model
h	Hour
ha	Hectare

HSI	Hue Saturation Intensity colour model
Ht.	Height
IC	Intercrop
ISO	International Organization for Standardization
K	Kelvin
K	Potassium
kg	Kilogram
kN	Kilonewton
kPa	Kilopascal
kW	Kilowatt
L	Mechanical soil loading
L0	Mechanical soil loading: control level
L1	Mechanical soil loading: 25.5 kN
L2	Mechanical soil loading: 45.1 kN
m	Metre
m^2	Square metre
ME	Metabolisable Energy
mg	Milligram
Mg	Magnesium
Mg	Megagram
Min.	Minimum
mm	Millimetre
MJ	Megajoule
MPa	Megapascal
N	Nitrogen
NIR	Near-Infrared
NIRS	Near-Infrared Spectroscopy
No.	Number
NP	Number of panicles per plant
NK	Number of kernels per panicle
n.s.	non-significant

N_t	Total soil nitrogen
P	Phosphorus
P	Ploughing system
PAR	Photosynthetically active radiation
pH	Potential of hydrogen
RGB	Red Green Blue colour model
r.h.	Relative humidity
s	Second
S	Site
SAS	Statistical Analysis System
SEM	Standard error of the mean
SC	Sole crop
SP	Shallow ploughing
t	Ton
Tot.	Total
TR	Triticale
vs.	Versus
WRB	World Reference Base for Soil Resources
µmol	Micromole
%	Percent
% v/v	Percent volume per volume
°C	Degree centigrade
°E	Degree east/longitude
°N	Degree north/latitude

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1 General introduction

Peas (*Pisum sativum* L.) and other grain legumes are a valuable source of N due to their symbiotic nitrogen fixing ability and a protein-rich, high-energy domestic feed for livestock. Provided that grain legumes effectively fix N_2, they improve the performance of succeeding non-legumes. Consequently, grain legumes contribute to the maintenance of soil fertility in organic crop rotations, which is defined as the capability of a soil to provide growth factors in appropriate amounts and compositions for a productive plant growth (Stockdale et al., 2002). Adequate nutrient supply is a major problem in stockless organic farming systems; hence, the use of fertility-building crops like grain legumes deserves special attention in these systems (Watson et al., 2002).

Despite the importance of peas in organic farming systems, the proportion of area under pea cultivation of total land under organic cultivation decreased continuously in the last decade in Germany (Böhm, 2009). Yield instability is a major problem in spring pea production, which may partially be responsible for the decrease in pea cultivation. Variability of pea grain yields relate to a number of abiotic and biotic factors, including delayed sowing due to high soil moisture in spring, compacted soil structures, water stress particularly during flowering, unfavourable temperatures, diseases and pests (Biarnès-Dumoulin et al., 1996; Cousin, 1997; Heath and Hebblethwaite, 1985; Ranalli and Cubero, 1997; Vocanson and Jeuffroy, 2008). Moreover, the low weed competitive ability of semi-leafless peas and severe lodging in normal-leafed pea crop stands may result in serious problems involving yield losses (Corre-Hellou et al., 2011; Harker et al., 2001; Harker et al., 2008; Schouls and Langelaan, 1994; Spies et al., 2011). These abiotic and biotic factors not only negatively affect pea grain yield but also grain protein content (Bourion et al., 2007).

Peas and other grain legumes are more susceptible to poor soil structure than other crops like cereals (Jayasundara et al., 1998). Tillage and mechanical soil loading strongly influence soil structure as well as chemical and biological soil properties. As a consequence, the performance of grain legumes is closely related to soil management and tillage practices. This is of central importance in organic farming, since organic systems aim at long-term preventive crop management strategies with the use of low external inputs and avoid a rapid intervention in crop production (Watson et al., 2002).

Mouldboard ploughing is the prevalent tillage system on organically managed farms in Germany and effective weed control is the most important criteria for the choice of the plough by organic farmers (Wilhelm, 2010). The need to decrease the environmental impact of agriculture and to enhance soil quality has increased the interest in a reduction of tillage depth and intensity. A reduction in ploughing depth decreases fuel consumption and increases labour productivity compared to deep ploughing (Kouwenhoven et al., 2002; Plouffe et al., 1995). In addition, non-inversive tillage systems or systems with reduced tillage depth promote microbial activity, enhance organic carbon content and improve soil structure in the upper tilled soil layer (Berner et al., 2008; Emmerling, 2007; Mäder and Berner, 2011; Peigné et al., 2007; Ulrich et al., 2010).

There is currently only limited information available on the performance of peas in reduced tillage systems under organic farming conditions. A reduction in tillage depth and intensity, however, may have beneficial effects for the cultivation of peas. Mechanical soil loads were better supported in reduced tilled soils than in deep ploughed soils due to a higher soil strength (Wiermann et al., 2000; Yavuzcan et al., 2005), which may reduce the risk of compacted soils and thus pea yield losses. Owing to a lower nitrogen mineralisation rate in spring, pea was also found to fix more nitrogen in reduced tilled than in deep ploughed soils (Matus et al., 1997; Reiter et al., 2002). This may help to improve nitrogen inputs in the nutrient cycle of organic farms.

Peas have been shown to produce similar or significantly higher grain yields after reduced tillage compared to mouldboard ploughing with the use of chemical weed control (Young et al., 1994). A reduction in tillage intensity in organic farming, particularly a renunciation of soil inversion, however, is coupled with an increase in weed pressure (Brandsæter et al., 2011; Gruber and Claupein, 2009; Mäder and Berner, 2011; Peigné et al., 2007). Abandoning mouldboard ploughing under organic farming conditions, therefore, is a challenge. This is of particular concern for the cultivation of semi-leafless peas, due to their weak weed competitive ability (Spies et al., 2011). Thus, shallow ploughing could be an optimal match between good soil quality, environmental benefits, sufficient weed control and good yield performance. Nevertheless, weed control may require increased attention to avoid weed-related yield losses and agronomic practices are needed to assure an optimal cultivation of peas in shallow ploughed soils.

Intercropping, the cultivation of at least two crops on the same field at the same time (Willey, 1979), provides advantages for the cultivation of peas in organic farming systems, and intercropping peas and cereals is a way to counteract pea yield instability and losses. Intercropping often refers to a system where component crops are grown simultaneously in alternate rows, whereas mixed cropping is defined as a system where component crops are grown without any distinct row arrangement (Andrews and Kassam, 1976; Federer, 1993; Ruthenberg, 1971). According to Willey (1979) or Mead and Riley (1981), intercropping and mixed cropping are often used interchangeably. Therefore, in this thesis, intercropping is used as a general term irrespective of the spatial arrangement of the component crops.

Pea-cereal intercrops produce higher total grain yields than pea sole crops (Begna et al., 2011; Hauggaard-Nielsen et al., 2001; Neumann et al., 2007). The complementary use of growth resources in intercrops with a combination of plants that differ in their temporal or spatial use of different growth factors like peas and cereals may, in part, be responsible for this better performance (Corre-Hellou et al., 2007). Yield advantages in pea-cereal intercrops are also based on positive effects on weeds and diseases. Pea-cereal intercrops suppress weeds to a greater extent than pea sole crops (Begna et al., 2011; Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001; Hauggaard-Nielsen et al., 2008; Kimpel-Freund et al., 1998; Poggio, 2005) and intercropped peas were less infected by important yield-reducing pea diseases like ascochyta blight than sole cropped peas (Fernández-Aparicio et al., 2010; Hauggaard-Nielsen et al., 2008; Schoeny et al., 2010). In addition, the cereal partner has a supporting effect and prevents pea lodging in intercrops (Kontturi et al., 2011). Consequently, pea-cereal intercrop grain yields are in many cases more stable compared to pea sole crops (Jensen, 1996; Kontturi et al., 2011). Intercrops compensate to a certain extent for the total failure of one or the partial failure of all companion crops, which is a possible explanation for the stability of intercropping systems (Morse et al., 1997; Willey, 1979). In addition, intercropping peas and cereals positively affects the grain quality of peas (Hauggaard-Nielsen et al., 2001; Neumann et al., 2007) and of the cereal partner (Bedoussac and Justes, 2010; Jensen, 1996; Kontturi et al., 2011; Trydeman Knudsen et al., 2004).

Thus, intercropping peas and cereals may be one option to successfully cultivate peas in shallow ploughed soils. A study by Neumann et al. (2007) showed no significant differences in the yield performance of pea and oat sole or intercrops between mouldboard ploughing and reduced tillage with the use of chemical plant protection. The large number of studies devoted to the subject of pea cropping strategies, such as intercropping, has not however included tillage practices and soil management under organic farming conditions and to date there have been no publications on the interaction of pea sole or intercropping and ploughing system with regard to weed infestation, yield performance and grain quality. Also, the effect of mechanical soil loading on the performance of peas in different ploughing systems is unknown. Furthermore, studies on phytosanitary aspects of intercropping dealt mainly with weeds and diseases and often excluded pea pests as a yield-reducing factor. Therefore, there is limited information on the pest reducing effect of pea-cereal intercrops. The few studies that have been devoted to the pea aphid infestation in pea sole crops and pea-cereal intercrops, however, indicate a beneficial effect of intercropping (Bedoussac, 2009; Seidenglanz et al., 2011).

Winter peas are a promising alternative to spring peas due to their better N_2-fixing capacity (Urbatzka et al., 2011b), yield performance (Chen et al., 2006) and yield stability (Urbatzka et al., 2011a). Autumn-sown peas may be useful on heavy soils that do not guarantee an early sowing of spring peas due to unfavourable soil conditions in spring. Owing to the earlier flowering and maturity in winter peas, summer drought is better supported by winter than by spring peas (Poetsch, 2007). A temporally advanced plant development also provides benefits for winter peas with regard to an infestation with pea pests, e.g. aphids, compared to spring peas (Poetsch, 2007). The cultivation of winter peas results in a longer time gap for soil preparation after harvest or the cultivation of an intermediate crop. Although winter hardiness is an aim in long-term breeding programs in Western Europe, insufficient winter hardiness is still a problem in winter pea cultivation (Bourion et al., 2003). Consequently, agronomic practices potentially improving winter survival have to be considered in the cultivation of winter peas. Intercropping winter peas and cereals has been shown to be able to partly decrease winter losses (Murray et al., 1985; Urbatzka et al., 2012). There is currently, however, no knowledge on the performance of sole and intercropped winter peas under Northern German conditions.

Given the importance of maintaining soil fertility, of providing sufficient animal feed and of reducing the environmental impact of agricultural practices, special attention has to be paid to an expansion of domestic grain legume cultivation and to an integration of reduced tillage in organic farming systems. Owing to the good weed suppressive ability, the positive yield response and the potential to increase yield stability, an intercropping of peas and cereals may be particular suited for the cultivation of peas in reduced tilled soils in organic farming. The main objective of this thesis is thus to investigate and determine the effects of pea crop stand (sole vs. intercropping), ploughing system (deep vs. shallow ploughing) and the interaction between both factors on annual weed infestation, yield performance and grain quality in spring and winter peas. In addition, the thesis will provide insight into the effect of mechanical soil loading in shallow and deep ploughed soils on the performance of sole and intercropped peas. The focus is on a stockless organic farming system in the first phase after conversion from deep to shallow ploughing. A better understanding of the benefits and limitations of sole or intercropping peas and cereals in different ploughing systems may contribute to progress with regard to an exploitation of pea yield potential and a reduction in yield variability and, hence, help to maintain soil fertility and to meet the requirements for protein and feed supply.

To finally evaluate the intercropping of spring and winter peas and the suitability of reduced ploughing depth in organic pea cultivation, the following elementary research questions have to be answered:

1| What are the effects of sole vs. intercropping and of shallow vs. deep ploughing on the annual weed infestation in semi-leafless or normal-leafed spring or winter pea cultivation?

2| Which factors account for the differing weed infestation in pea sole crops, pea-cereal intercrops and cereal sole crops?

3| Does pea sole cropping after shallow ploughing result in higher weed infestation than pea sole cropping after deep ploughing, and is intercropping able to compensate for this higher weed infestation after shallow ploughing?

4| Does and how does intercropping winter peas and triticale reduce pea pest problems?

5| Does intercropping winter peas of differing leaf type and triticale lower crop winter losses and improve winter pea lodging resistance in different ploughing systems?

6| What are the effects of sole vs. intercropping peas and cereals and of deep vs. shallow ploughing on biomass accumulation and yield performance of component crops and succeeding winter wheat?

7| What are the effects of mechanical soil loading during seedbed preparation or sowing and its interaction with different ploughing systems on yield performance of spring pea and oat sole or intercrops?

8| What are the effects of crop stand, winter pea flower colour, ploughing system, mechanical soil loading and their interactions on grain quality and energetic feed value of peas and cereals?

The structure of this thesis takes the form of six chapters, including this introductory chapter. Chapter Two to Five present the findings of the research. The final chapter draws upon the entire thesis, tying up the different aspects of sole and intercropping spring and winter peas after differing ploughing systems. The following research topics are addressed in Chapter Two to Five:

Chapter Two deals with the effects of ploughing system and mechanical soil loading during seedbed preparation or sowing operations on soil structure, weed infestation, yield performance and grain quality in spring pea sole crops, pea-oat intercrops and oat sole crops at sites in Eastern and Northern Germany.

The focus of Chapter Three is the differing weed suppressive ability in spring pea sole crops, pea-oat intercrops and oat sole crops. In this context, the interaction between ploughing system and the sole or intercropping of semi-leafless peas and oats was assessed. Besides, factors underlying the differing weed suppressive ability in sole and intercropped peas and oats were identified.

Different aspects of winter pea-cereal intercropping in differing ploughing systems in Northern Germany were explored in Chapters Four and Five. Chapter Four describes the cultivation of a semi-leafless, white-flowered and a normal-leafed, coloured-flowered winter pea cultivar, sole and intercropped with triticale, after shallow and deep ploughing with regard to agronomic aspects like winter losses, lodging resistance, yield performance, grain quality and preceding crop effect. Chapter Five covers the aspect of intercropping as a tool for weed management after shallow and deep ploughing and for pest control in organic farming systems.

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2 Effect of ploughing system and mechanical soil loading on soil physical properties, weed infestation, yield performance and grain quality in sole and intercrops of pea and oat in organic farming

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Abstract

The effect of ploughing system and mechanical soil loading on the performance of sole and intercrops of pea and oat was investigated in field experiments under organic farming conditions at two sites (Eastern Germany: sandy loam, Northern Germany: loam) in 2009 and 2010. The two ploughing systems were short-term shallow ploughing to a soil depth of 7-10 cm and deep ploughing to 25-30 cm. Wheel loads of 26 and 45 kN, which correspond to typical rear wheel loads of field machinery used during sowing operations, were compared to an uncompacted control. Shallow ploughing resulted in a greater penetration resistance in the 14-28 cm soil layer compared to deep ploughing. An increase in mechanical soil loading intensity increased the bulk density and decreased the air capacity in the 10-15 cm soil layer, whereas the penetration resistance was not affected. The annual weed infestation in pea sole crops was higher after shallow than after deep ploughing at both sites. Pea-oat intercrops compensated for the higher weed infestation after shallow ploughing at one site due to their excellent weed suppressive ability. Dependent on oat productivity, pea-oat intercrops produced comparable or higher grain and protein yields than pea sole crops. Intercropped pea yield components and grain protein yields were significantly lower than those of sole cropped peas. The ploughing system did not affect pea grain yields in either year and oat yields in 2009. Due to a better emergence, the grain and protein yield of sole and intercropped oats was significantly higher after shallow ploughing in 2010. Mechanical soil loading did not have any effect on the yield performance of sole and intercropped peas and oats in 2009. In 2010, mechanical soil loading of 26 kN and 45 kN decreased the pea grain yield by 12 % and 21 %, respectively. In addition, the pea crude protein significantly decreased with increasing mechanical soil loading from 234.3 g kg^{-1} (uncompacted control) to 213.8 g kg^{-1} (45 kN) at one site. Neither the grain yield nor the grain quality of sole and intercropped oats was affected by the mechanical soil loading in 2010. Total grain and crude protein yields decreased with increasing mechanical soil loading after deep ploughing, whereas no significant differences were revealed after shallow ploughing. The present study confirms the positive qualities of pea-oat intercrops with regard to weed suppression and plant performance. Shallow ploughing mitigates the risk of a decrease in plant performance caused by heavy field traffic and provides an alternative to deep ploughing even in low weed competitive, organically farmed grain legumes.

Keywords: soil compaction, weed suppression, yield components, crude protein, Metabolisable Energy

2.1 Introduction

The management of organic cropping systems is based on long-term strategies and avoids cultivation practices that allow rapid intervention in crop production (Watson et al., 2002). The organic crop production therefore largely depends on soil characteristics, inherited or modified through cultivation, as well as on the performance of fodder and grain legumes. Grain legumes like pea (*Pisum sativum* L.) are of particular concern for the maintenance or promotion of soil fertility in stockless organic farming systems or in mixed systems with low stocking density, in which adequate nutrient supply is a major problem (Watson et al., 2002).

An alternative to the intensive deep soil cultivation with a mouldboard plough to a soil depth of 25-30 cm is the technique of shallow ploughing. A reduction in plough working depth of 10-20 cm compared to normal deep ploughing has several advantages with regard to climate and soil protection. As a smaller volume of soil is tilled using shallow ploughing, it reduces the CO_2 release from the soil into the atmosphere (Chen and Huang, 2009; Reicosky and Archer, 2007), the fuel consumption and therefore the fuel costs as well as the CO_2 emissions derived from fuel combustion processes (Kouwenhoven et al., 2002; Plouffe et al., 1995). As pointed out by Børresen and Njøs (1994) and Pagliai et al. (1998), soil aggregates after shallow ploughing tend to be more stable than after deep ploughing, which reduces the risk of surface crust formation and erosion. Furthermore, shallow ploughing has been shown to have a higher microbial activity in the upper tilled soil layer than in the same horizon under deep ploughing (Curci et al., 1997; Vian et al., 2009).

The impact of the ploughing system on the yield performance is inconsistent and largely depends on site-related and agronomic factors. Håkansson et al. (1998) have demonstrated that topsoil texture and ploughing depth effects on grain yields are related. The authors showed that deep ploughing resulted in highest yield performance in sandy, clay and clay loam soils, whereas shallow ploughing led to a better soil structure and therefore gave the best results in soils with a high fine silt fraction. Furthermore, the cultivated crops seem to react differently on shallow or deep ploughed soils. Organically and conventionally farmed cereals had comparable, lower or higher yields after shallow than after deep ploughing (Baigys et al., 2006; Bakken et al., 2009; Riley and Ekeberg, 1998). In contrast, the limited number of studies comparing the impact of ploughing depth on pea grain yields supports the assumption that peas respond negatively to shallow ploughing (Baigys et al., 2006; Pranaitis and Marcinkonis, 2005). Others, however, found no effect of reduced tillage on pea grain yields (Neumann et al. 2007). An effect of the ploughing depth on the grain quality was mostly not detected (Bakken et al., 2009; Riley and Ekeberg, 1998).

Lower pea and cereal grain yields after shallow ploughing under organic and conventional conditions were often attributed to higher annual and perennial weed infestation compared to deep ploughing (Børresen and Njøs, 1994; Brandsæter et al., 2011; Håkansson et al., 1998). In spite of advantages for climate and soil, the crop production after shallow ploughing in organic farming may be limited by a strong weed-crop competition. This is of special interest when crops with a weak weed competitive ability were cultivated, like semi-leafless peas grown as sole crops (Spies et al., 2011).

A possible approach to successfully cultivate peas after shallow ploughing may be the intercropping of peas and cereals such as oat (*Avena sativa* L.). Pea-oat and other cereal intercrops produce better weed suppression than pea sole crops (Begna et al., 2011; Corre-Hellou et al., 2011; Kimpel-Freund et al., 1998). Peas and cereals complement one another in the N use with cereals being competitive to a greater degree in the use of soil mineral N and therefore forcing intercropped peas to depend more on N derived from N_2-fixation than in pea sole crops. As a result, the N use in pea-cereal intercrops is more efficient than in pea sole crops (Hauggaard-Nielsen et al., 2009). These issues of pea-cereal intercrops contribute to the higher total grain yields in intercrops than in pea sole crops and mostly result in better pea, cereal or total intercrop grain quality properties (Begna et al., 2011; Hauggaard-Nielsen et al., 2001, 2008; Neumann et al., 2007).

In regions with slow warming and drying soils, the optimal spring pea sowing date often does not coincide with adequate soil conditions for seedbed preparation and sowing. A delay in sowing beyond the middle of March, however, is associated with a continuous decrease in pea yield performance (Aufhammer, 1998). Thus, farmers tend to prepare the seedbed and sow when the soil can be sensitive to soil compaction. Pea development and growth is considerably influenced by compacted soil structures. As a consequence of mechanical resistance, the root growth rate and length of peas were reduced (Boone et al., 1994; Castillo et al., 1982). Owing to an insufficient aeration in compacted soils, the *Rhizobium* nodulation on pea roots was significantly lower than under non-compacted soil conditions (Grath and Håkansson, 1992; Grath and Arvidsson, 1997). The reduced root growth, which limits the explorable soil volume, and the lower N_2-fixation were accompanied by a decline in uptake of nitrogen and other macro or micro nutrients (Castillo et al., 1982; Grath and Håkansson, 1992). These negative effects are coupled with an earlier senescence and considerable yield losses (Boone et al., 1994; Grath and Arvidsson, 1997; Vocanson and Jeuffroy, 2008). Grain legumes are considered particularly susceptible to compacted soils and more sensitive to abiotic soil conditions than cereals (Batey, 2009; Jayasundara et al., 1998). However, previous studies noted no significant difference in the sensitivity between peas and cereals (Grath and Arvidsson, 1997; Henderson, 1991). To date, no study of which we were aware has evaluated the influence of soil compaction during pre-sowing and sowing operations on the growth and the performance of grain legume-cereal intercrops.

Depending on operation width and wheel characteristics, 32 to 57 % of the area in ploughed fields is over run at seedbed preparation and 19 to 39 % at sowing (Kroulík et al., 2009). If the soil is sensitive to soil compaction, these operations can therefore have considerable impact on growth, yield and grain quality of pea, oat and presumably pea-oat intercrops. Due to the absence of short-term strategies compensating for the effects of poor soil structure on plant growth and yield performance, this applies particularly to organic crop production. Also, Droogers et al. (1996) found that the probability of a loamy soil to be trafficable without risking soil compaction was lower under long-term organic management than under conventional management due to lower bulk density values at the soil surface and higher soil water contents. Thus, the authors concluded that the risk of soil compaction is higher under organic than under conventional farming, most notably under deep ploughing. The intensity of primary tillage influences the impact of seedbed and sowing operations on soil properties and plant growth. Owing to higher soil strength, a soil under reduced tillage supported a soil compaction in spring to a higher degree than a soil under deep ploughing to 25 cm soil depth (Wiermann et al., 2000). Bakken et al. (2009) suggested that the risk of soil compaction in the upper subsoil is higher under deep ploughing than under shallow ploughing, which is explained by the higher amount of loose soil under deep ploughing. However, there is currently only very limited published data on the effect of soil compaction during seedbed preparation or sowing on the soil structure and the crop production in deep and shallow ploughed soils.

In this study, the impact of ploughing system and mechanical soil loading during seedbed preparation or sowing on the performance of organically farmed pea and oat sole or intercrops is concerned. In doing so, we focused on soil physical conditions, annual weed infestation, yield structure and performance as well as on grain quality aspects. Our main objectives were to: (a) quantify the effect of shallow ploughing as well as of mechanical soil loading during seedbed preparation and sowing on the performance of the grain legume pea and the non-legume oat, (b) examine to which extent pea-oat intercrops react differently to shallow ploughing and to mechanical soil loading than the respective sole crops, (c) study the relation between ploughing system and mechanical soil loading and (d) finally, assess the suitability of organic grain legume production after short-term shallow ploughing.

2.2 Material and methods

2.2.1 Site characteristics

The field experiments were conducted at the Agricultural Teaching and Research Station of the Free State of Saxony at Köllitsch, Eastern Germany (51°50'N, 13°12'E, 88 m a.s.l.), and at the Experimental Station of the Thünen-Institute of Organic Farming at Trenthorst, Northern Germany (53°46'N, 10°30'E, 43 m a.s.l.), in 2009 and 2010. The soil type at Köllitsch was a Dystric Cambisol with a clay, silt and total sand content in the topsoil of 9.6 %, 20.9 % and 62.2 % (sandy loam according to World Reference Base (WRB) for Soil Resources). The soil type at site Trenthorst was classified as a Stagnic Luvisol and the soil texture as a loam (20.8 % clay, 37.7 % silt, 39.2 % sand in 0-30 cm) according to WRB. Post-sowing soil characteristics and nutrient analysis data of the experimental fields in Köllitsch and Trenthorst are presented in Table 1.

Table 1: Characteristics of the topsoil (0-20 cm) at Köllitsch and Trenthorst in 2009 and 2010

		pH ($CaCl_2$)	P (CAL)	K (CAL)	Mg ($CaCl_2$)	N_t	C_t
Year	Site		mg kg^{-1}			%	
2009	Köllitsch	5.5	35	49	136	0.13	1.10
	Trenthorst	6.8	123	174	188	0.14	1.25
2010	Köllitsch	5.6	36	61	126	0.13	1.21
	Trenthorst	6.1	83	177	121	0.12	1.27

The 30-year mean annual precipitation in Köllitsch is 542 mm with a mean temperature of 9.0°C, whereas 706 mm and 8.8°C were calculated for Trenthorst. The mean temperature and the precipitation at the experimental sites differed considerably from the long-term average in most months during the growing period in 2009 and 2010 (Table 2). The period from sowing to harvest was notably warmer than the 30 year-average with the exception that the 2010 mean temperature at Köllitsch was nearly consistent with the long-term average. The precipitation during the sowing-harvest period varied at the sites with Köllitsch being marginally drier in both years and Trenthorst considerably drier in 2009 and wetter in 2010 compared with the 30-year average.

Table 2: Air temperature and precipitation during the 2009 and 2010 growing period and departure from 30-year average at Köllitsch and Trenthorst

		Köllitsch				Trenthorst			
		Air temperature °C		Precipitation mm		Air temperature °C		Precipitation mm	
Year	Month/Period	Average	Dptr.	Total	Dptr.	Average	Dptr.	Total	Dptr.
2009	April	12.2	+3.8	9	− 27	11.5	+3.8	10	− 33
	May	14.4	+0.7	54	+ 1	12.8	+0.4	35	− 6
	June	15.6	−0.9	45	− 9	14.1	−0.9	54	− 18
	July	19.0	+0.6	91	+ 25	18.2	+0.9	72	− 13
	August	19.7	+1.6	75	+ 9	18.9	+2.0	19	− 58
	Sowing-harvest	15.8	+1.5	199	− 12	15.2	+1.1	168	−151
2010	April	8.9	+0.5	31	− 5	10.6	+2.9	19	− 25
	May	11.3	−2.4	100	+ 46	11.3	−1.1	97	+ 56
	June	16.6	+0.1	11	− 43	15.5	+0.5	73	0
	July	21.4	+3.0	63	− 4	19.8	+2.5	11	− 74
	August	17.9	−0.2	180	+114	17.1	+0.2	189	+112
	Sowing-harvest	14.4	+0.1	197	− 14	15.7	+1.6	375	+ 56

Dptr.: Departure from 30-year average (1978-2007). Weather station in Köllitsch was established in 1994. Therefore, precipitation and temperature data for the 1978-1994 period were taken from the nearest National Meteorological Service weather station in Doberlug-Kirchhain (51.64°N, 13.56°E).

2.2.2 Trial description, experimental factors and management

The split-plot experiments with four replicated blocks comprised three factors at both sites: ploughing system, mechanical soil loading and crop stand. The factor ploughing system was assigned to the main plot and the subplot was the combination of the factors mechanical soil loading and crop stand. The plot size was 1.44 × 15 m at Köllitsch and 2.75 × 15 m at Trenthorst. The previous crops were winter wheat (*Triticum aestivum* L.) at Köllitsch and oilseed rape (*Brassica napus* L.) at Trenthorst. At the Köllitsch site, white mustard (*Sinapis alba* L.) was grown as a catch crop between wheat harvest and the start of the experiments.

The experimental factor ploughing system comprised deep (DP) and shallow ploughing (SP). Deep ploughing included stubble tillage by a precision cultivator followed by mouldboard ploughing to a depth of 25-30 cm. In the shallow ploughing system, a skim plough (Stoppelhobel, Zobel-Stahlbau, Germany) was used for stubble and primary tillage and the soil was inverted to a soil depth of 4-6 cm and 7-10 cm, respectively. At Köllitsch, primary tillage was performed in spring, whereas the experimental fields at Trenthorst were ploughed in autumn (Table 3). In the years before the experiments started, mouldboard ploughing to a depth of 25-30 cm was applied at the experimental sites. Secondary tillage consisted of one pass with a rotary harrow or a precision cultivator to a soil depth of 8-10 cm.

Table 3: Dates of soil preparation, mechanical soil loading, sowing and harvest at Köllitsch and Trenthorst in 2009 and 2010

	2009		2010	
	Köllitsch	Trenthorst	Köllitsch	Trenthorst
Stubble tillage (DP/SP)	27 August[1]	8 September[1]	16 August[2]	16 September[2]
Primary tillage (DP/SP)	4 April	13 October[1]	23 March	22 October[2]
Secondary tillage (DP/SP)	14 April	16 April	24 March	19 April
Mechanical soil loading	15 April	17 April	1 April	28 April
Seedbed preparation	15 April	17 April	1 April	29 April
Sowing	17 April	18 April	2 April	29 April
Harvest	1 August	19 August	24 July	4 September

[1]2008, [2]2009

The mechanical soil loading was carried out after secondary tillage. The factor mechanical soil loading included one control level without mechanical soil loading (L0) and two different mechanical soil loading intensities (L1, L2). Specifications for the mechanical soil loading in L1 and L2 are shown in (Table 4). The tyre inflation pressures in L0 and L1 were chosen according to the manufacturer's recommendations. A tractor pulled, purpose-built trailer with an axial mounted Michelin MultiBib 650/65 R 38 radial tyre was used for the mechanical soil loading in L1. Additional ballast weights were mounted on the trailer for the mechanical soil loading in L2. L1 and L2 plots were subjected to one pass (track by track) with the wheel. A driving speed of 1.7-1.9 m s^{-1} was chosen in order to simulate sowing. The tyre was raised when plots without mechanical soil loading (L0) were passed. The L1 and L2 treatments correspond to a rear-wheel load of a tractor (120 kW) with a tractor-mounted sowing combination and a working width of 3 m in working and transport position, respectively. The volumetric soil water content values after sowing in spring 2009 and 2010 are presented in Table 5. After mechanical soil loading, the plots were harrowed to a soil depth of 5 cm and the crops were sown. The area exposed to mechanical soil loading was not overrun by tractor wheels during harrowing and sowing.

Table 4: Characteristics of the wheel used for the mechanical soil loading treatment L1 and L2

Parameter	Mechanical soil loading treatment	
	L1	L2
Wheel load (kN)	25.5	45.1
Tyre inflation pressure (kPa)	60	160
Tyre contact area (m^2)	0.48	0.49
Contact area pressure (kPa)	54.0	93.3

Table 5: Volumetric water content at two soil depths after sowing in deep and shallow ploughed fields at Köllitsch and Trenthorst in 2009 and 2010

		Volumetric water content (%)			
		2009		2010	
Soil depth (cm)	Ploughing system	Köllitsch	Trenthorst	Köllitsch	Trenthorst
0-30	DP	22.7	22.8	27.5	23.3
	SP	25.1	22.2	26.8	22.3
30-60	DP	22.3	22.0	26.9	21.9
	SP	21.8	23.6	28.3	22.5

The factor crop stand included semi-leafless spring pea cv. Santana pea sole cropping (Pea SC, 80 germinable kernels m^{-2}), oat cv. Dominik sole cropping (Oat SC, 300 germinable kernels m^{-2}) and pea-oat intercropping (IC, 80 germinable kernels pea and 60 germinable kernels oat m^{-2}). Row-spacing of sole crops and the intercrop was 13.0 cm and 12.5 cm at Köllitsch and Trenthorst, respectively. Identical seed lots were used at both sites.

The field experiments were managed in accordance with the European organic standards (Commission Regulation (EC) No. 889/2008). No mechanical weed control was performed to determine the weed suppressive ability of the pea-oat intercrops compared to the respective sole crops. The most important weed species in the field experiments at Köllitsch were *Chenopodium album* L., *Polygonum aviculare* L., *Stellaria media* (L.) Vill. and *Lamium purpureum* L.. *S. media* was the most frequent species in Trenthorst followed by *L. purpureum* and *Capsella bursa-pastoris* (L.) Medik..

2.2.3 Sampling procedures and measurements

The penetration resistance was measured using an electronic penetrometer with a built-in data-logger (Penetrologger, Eijkelkamp Agrisearch Equipment, The Netherlands). The attached cones had a 60° top angle and a base area of 1 cm². The values were recorded at each cm to a soil depth of 70 cm. Ten measurements were performed in each plot before plant emergence. At the time of the penetrometer measurement, the soil water content was determined gravimetrically in the 15-20 cm soil layer. For the evaluation of the bulk density and the air capacity undisturbed soil cores with a volume of 250 cm^3 were taken from the 10-15 cm soil layer, using soil sampling cylinders. The sampling of two replicate cores per plot was performed on firm soil and the analysis was carried out according to ISO 11272 (1998). Additionally, the true density was determined with a helium pycnometer and the water retention at 6 kPa was measured in accordance with ISO 11274 (1998) in order to calculate the air capacity.

The annual weed biomass was determined from an area of 0.5 m^2 at pea flowering and of 1 m^2 at maturity. Weeds were cut 1 cm above the soil surface and dried at 60°C to constant weight. A yield structure analysis was performed from a representative area of 1 m^2, which was also used for the weed biomass determination at maturity. Therefore, the number of plants, number of pods and panicles per plant, as well as the grain yield was recorded. In addition, the grain yield was assessed from a combine harvest of an area of 21.6 m^2 at Köllitsch and of 17.5 m^2 at Trenthorst. Grain samples were dried, cleaned and in the case of pea-oat intercrops separated in component crops. Finally, the thousand seed mass was determined. Weed biomass values and grain yields were expressed on a dry matter basis.

To assess the grain nutrient concentration and the feed energy value, the oven-dried (50°C) pea and oat grain samples were ground with a sieve of 1 mm (Tecator Cyclotec 1093, Foss, Denmark) and 0.5 mm (ZM 100, Retsch, Germany), respectively. Near-Infrared (NIR) Spectroscopy (NIRLab, Büchi, Switzerland) was used to analyse the crude protein, crude fat, crude ash, crude fibre, starch and sugar content of the pea and oat grain samples. The Metabolisable Energy content was predicted using the regression equations for pigs recommended by the German Society of Nutrition Physiology (GfE, 2008) and tabular crude nutrient digestibility percentages for pigs (DLG, 2002).

2.2.4 Statistical Analysis

As a consequence of the differing weather conditions in 2009 and 2010, the statistical analysis was performed separately for the experimental years. The Köllitsch and Trenthorst sites represent two soil-climate regions in Germany and the experiments were performed on existing experimental stations. According to Piepho et al. (2003) it is in this case appropriate to classify the site as a fixed factor. Therefore, site as well as ploughing system, mechanical soil loading and crop stand were regarded as fixed effects. Normal distributed data were analysed with Proc MIXED in SAS 9.2 using ANOVA and subsequent comparisons of means (Tukey test). Weed biomass data were log-transformed to achieve normality. Residuals of the yield component count data showed a non-normal distribution, which was not improved by a current transformation. For this reason, data analysis was undertaken in Proc GLIMMIX. This procedure allows an analysis of non-Gaussian distributed data with random effects (Bolker et al., 2011; Schabenberger, 2005). Means and standard error were then reported on the inverse linked scale. Repeated measure analysis was performed on the penetration resistance (repeated factor: soil depth) and weed biomass (repeated factor: sampling date) data. The soil parameters were measured within the first six weeks after sowing; hence, the factor crop stand was not considered in the statistical analysis of these data.

2.3 Results

2.3.1 Physical soil conditions

The analysis of the penetration resistance showed a significant three-fold interaction between ploughing system, site and soil depth. The penetration resistance was not significantly affected by the ploughing system at Köllitsch in the first experimental year (Fig. 1). However, there was a tendency to higher values after shallow ploughing in the soil depth range between shallow and deep ploughing working depth (8-30 cm). At Trenthorst, shallow ploughing resulted in a significantly higher penetration resistance in the 16-24 cm soil layer compared to deep ploughing in the same experimental year. Comparable results were obtained for Trenthorst in the second experimental year, with significantly higher soil penetration resistance values after shallow ploughing in the 14-28 cm soil layer. The results of the penetration resistance in the subsoil at Köllitsch in 2010 varied, especially after deep ploughing, from those obtained in 2009. In the subsoil from 44 cm soil depth on, penetration resistance values were significantly greater after deep than after shallow ploughing. The penetration resistance tended to increase slightly from mechanical soil loading level L0 to L2 (data not shown). Yet, there was neither a significant main effect nor a significant interaction containing the experimental factor mechanical soil loading in 2009 and 2010. The soil moisture content during penetration measurement was comparable between treatments within each experiment, but higher at Köllitsch than at Trenthorst (data not shown).

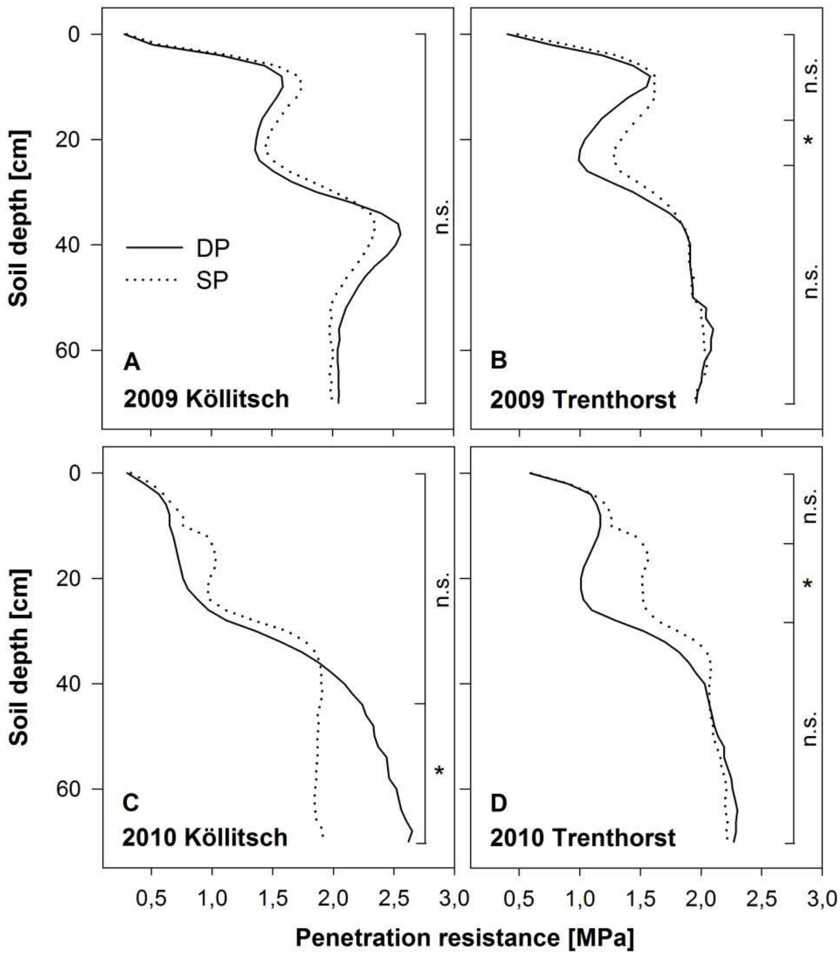

Fig. 1: Change of mean penetration resistance with soil depth after deep (DP) and shallow (SP) ploughing at Köllitsch (A, C) and Trenthorst (B, D) in spring 2009 and 2010. Asterisks indicate significant differences between ploughing systems within the same soil depth. n.s.: non-significant ($P < 0.05$).

The Köllitsch site showed a significantly higher bulk density and a lower air capacity in the 10-15 cm soil layer than the soil on the experimental fields at Trenthorst in both years (Table 6). Shallow ploughing resulted in a significantly higher bulk density in 2009 and a higher air capacity in 2010 compared with deep ploughing. The air capacity in 2009 and the bulk density in 2010, however, were not statistically different between deep and shallow ploughing. The mechanical soil loading significantly affected the bulk density, with the control (L0) resulting in the lowest and the L2-level in the highest bulk density in both years. In contrast, the air capacity decreased from L0 to L2 in both years. In doing so, a significant difference between the levels with and the level without mechanical soil loading were solely present in 2010.

Table 6: Site, tillage and mechanical soil loading effects on bulk density and air capacity in the 10-15 cm soil layer in 2009 and 2010

	2009		2010	
	Bulk density ($Mg\ m^{-3}$)	Air capacity % (v/v)	Bulk density ($Mg\ m^{-3}$)	Air capacity % (v/v)
Site				
Köllitsch	1.58 ± 0.02 a	13.0 ± 0.69 b	1.59 ± 0.01 a	7.6 ± 0.83 b
Trenthorst	1.44 ± 0.02 b	15.7 ± 0.80 a	1.42 ± 0.01 b	17.1 ± 0.43 a
Ploughing system				
DP	1.46 ± 0.02 b	15.8 ± 0.73 a	1.48 ± 0.02 a	13.0 ± 0.99 b
SP	1.51 ± 0.02 a	13.8 ± 0.92 a	1.47 ± 0.02 a	14.8 ± 0.86 a
Mechanical soil loading				
L0	1.45 ± 0.03 b	16.2 ± 1.16 a	1.45 ± 0.02 b	16.0 ± 1.16 a
L1	1.48 ± 0.02 ab	15.4 ± 0.99 a	1.48 ± 0.02 ab	13.5 ± 1.04 b
L2	1.54 ± 0.02 a	12.8 ± 0.82 a	1.49 ± 0.02 a	12.3 ± 1.13 b

Values are means ± SEM. Means within each effect and column with different letters are significantly different ($P < 0.05$).

2.3.2 Weed biomass

The annual weed biomass was affected by a significant crop stand × ploughing system × site interaction in both experimental years. The weed biomass was significantly higher in pea sole crops than in oat sole crops (Fig. 2). Also, the pea-oat intercrop took up an intermediate position between the sole crops at both sites and in both years. Pea sole cropping after shallow ploughing resulted in a tendentially (2009 at Köllitsch) or a significantly higher annual weed infestation compared to deep ploughing, which was most pronounced at Köllitsch in 2010 with a harvested annual weed dry biomass of 207 $g\ m^{-2}$ after shallow and of 129 $g\ m^{-2}$ after deep ploughing. At Köllitsch, weed biomass values in pea-oat intercrops after deep ploughing were comparable to those after shallow ploughing, whereas shallow ploughing caused a significantly higher weed infestation in pea-oat intercrops compared to deep ploughing at Trenthorst in both years. Dependent on year and site, the annual weed biomass in oat sole crops reacted variably to the different ploughing systems (Fig. 2). There was a significant crop stand × mechanical soil loading × site interaction in 2009 and an interaction between ploughing system, mechanical soil loading and site affecting the weed biomass accumulation in 2010. Unlike in pea sole crops, the mechanical soil loading did not affect the weed biomass in pea-oat intercrops and oat sole crops at both sites in 2009. Pea sole cropping without mechanical soil loading, however, resulted in least weed biomass accumulation at Köllitsch and highest accumulation at Trenthorst. In 2010, there were significant differences between mechanical soil loading treatments except for shallow ploughed soils at Trenthorst. In the case of significant differences, the weed biomass in the control without mechanical soil loading ranked between the L1 and the L2 level (data not shown).

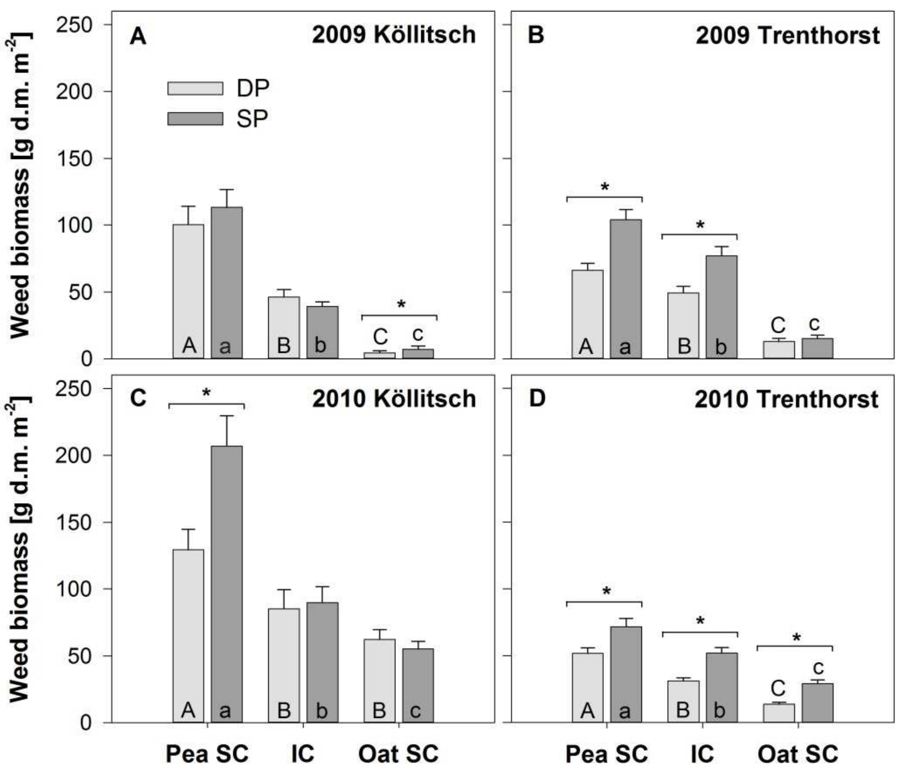

Fig. 2: Weed shoot biomass as affected by the interaction of crop stand and ploughing system at Köllitsch (A, C) and Trenthorst (B, D) in 2009 and 2010. Values are means of two sampling dates (pea flowering, harvest) and SEM (error bars). Different capital letters indicate significant differences ($P < 0.05$) between crop stands after deep ploughing (DP), whereas different lowercase letters show significant differences between crop stands after shallow ploughing (SP). Asterisks indicate significant differences between ploughing systems within the same crop stand. Pea SC: pea sole crop, IC: pea-oat intercrop, oat SC: oat sole crop.

2.3.3 Yield components and performance

2.3.3.1 Pea yield structure

The pea yield structure analysis (Table 7) showed a significant effect of the site on the number of plants m^{-2} (Köllitsch: 76, Trenthorst: 60 plants m^{-2}) and the individual seed mass (Köllitsch: 181, Trenthorst: 245 mg) for the harvest in 2009. In addition, sole cropped peas showed significantly greater number of seeds per pod (SC: 2.9, IC: 2.6) and higher individual seed mass (SC: 213 g, IC: 209 mg) compared to intercropped peas at both sites. The number of pods did not significantly differ between ploughing systems except that intercropped peas possessed a lower number of pods per plant after shallow ploughing at Trenthorst, leading to a significant crop stand × ploughing system × site interaction. The pea grain yield was affected by the same three-fold interaction showing the same result as for the number of pods per plant. At Köllitsch, sole cropped pea grain yields were significantly greater than those of intercropped peas independent of the ploughing system, whereas this significant crop stand difference was only present after shallow ploughing at the Trenthorst site (Fig. 3). Contrary to the number of pods per plant, the pea grain yield of sole and intercropped peas after deep ploughing corresponded with the values of the same crop stand after shallow ploughing. The pea yield components and the yield performance in the mechanical soil loading treatments did not differ significantly from one another (Table 7).

Table 7: Probabilities of the pea yield component analysis for crop stand (C), ploughing system (P), mechanical soil loading (L), site (S) and their interactions in 2009 and 2010

	2009					2010				
Effect	Plants m^{-2}	Pods $plant^{-1}$	Seeds pod^{-1}	Seed mass	Grain yield	Plants m^{-2}	Pods $plant^{-1}$	Seeds pod^{-1}	Seed mass	Grain yield
C	n.s.	<.0001	0.0451	0.0175	<.0001	0.0141	0.0252	<.0001	0.0009	<.0001
P	n.s.	n.s.	n.s.	n.s.	n.s.	0.0155	n.s.	n.s.	<.0001	n.s.
L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.0089	n.s.	n.s.	<.0001
S	<.0001	n.s.	n.s.	<.0001	0.0065	<.0001	0.0017	<.0001	0.0038	n.s.
C×P	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.0204	n.s.	n.s.
C×L	n.s.	n.s.	n.s.	n.s.	n.s.	0.0291	n.s.	n.s.	n.s.	n.s.
C×S	n.s.	0.0058	n.s.	n.s.	<.0001	n.s.	0.0012	<.0001	n.s.	0.0045
P×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
P×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.0365	n.s.	n.s.	n.s.
C×P×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.0006	0.0476	0.0059	n.s.
C×P×S	n.s.	0.0366	n.s.	n.s.	0.0351	n.s.	n.s.	n.s.	n.s.	n.s.
C×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
P×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	0.0335	n.s.	n.s.	n.s.	n.s.
C×P×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.0024	n.s.	n.s.	n.s.

n.s.: non-significant at the 0.05 probability level

Unlike in 2009, there were interactions containing the factor mechanical soil loading for all pea yield components in 2010, finally resulting in a significant influence of this experimental factor on the pea grain yield (Table 7). The pea grain yield decreased with increasing mechanical soil loading from 1.49 t ha^{-1} in L0, over 1.31 t ha^{-1} in L1, to 1.18 t ha^{-1} in L2. The experimental factor ploughing system and other experimental factors interacted significantly in influencing all pea grain yield components. Nonetheless, the ploughing system did not have any impact on the pea grain yield in 2010. The pea grain yield, however, was significantly affected by an interaction of crop stand and site, which can be explained by a significantly lower intercropped pea grain yield at Köllitsch (1.03 t ha^{-1}) than at Trenthorst (1.26 t ha^{-1}) and similar sole cropped pea grain yields at both sites (Köllitsch: 1.53 t ha^{-1}, Trenthorst: 1.46 t ha^{-1}). Independent of the site, intercropped peas yielded significantly less than sole cropped peas (Fig. 3).

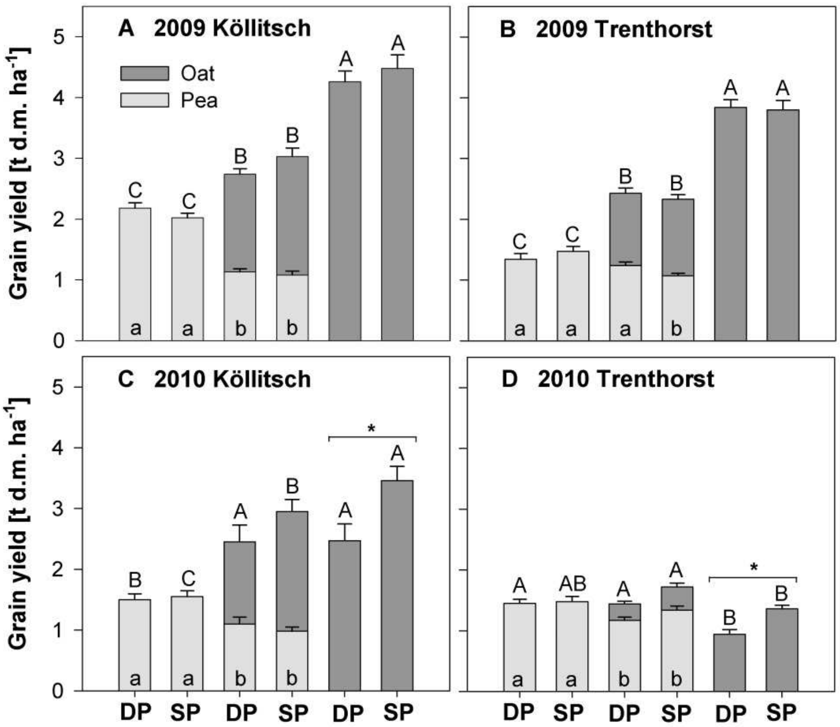

Fig. 3: Grain yield performance as affected by the interaction of crop stand and ploughing system at Köllitsch (A, C) and Trenthorst (B, D) in 2009 and 2010. Values are means and SEM (error bars). Different capital letters indicate significant differences (P < 0.05) between crop stands within each ploughing system concerning total grain yield. Different lowercase letters denote significant differences between sole cropped and intercropped pea grain yields within each ploughing system. Asterisks indicate significant differences between deep (DP) and shallow (SP) ploughing within each crop stand with regard to total grain yield.

2.3.3.2 Oat yield structure

As expected due to differing sowing densities, oat yield components were affected by the factor crop stand in both years (Table 8). However, the reactions were not always identical at both sites resulting in significant interactions between crop stand and site. Intercropped oats showed a significantly higher number of panicles per plant than sole cropped oats at both sites in 2009 and 2010. Besides, the individual oat seed mass was significantly lower in sole crops than in intercrops at Trenthorst, but comparable at Köllitsch in both experimental years. In addition, the number of kernels per panicle reacted variably to the crop stand at both sites and in both years. Shallow ploughing caused a significantly greater number of kernels per panicle in 2009 (DP: 43, SP: 47) and 2010 (DP: 21, SP: 24) as well as a significantly higher emergence leading to a higher number of plants m^{-2} in 2010 (DP: 155, SP: 170). Sole and intercropped oat grain yields were significantly higher after shallow ploughing compared to deep ploughing at both sites in 2010, whereas no significant differences occurred in 2009 (Table 8). Moreover, oat yielded significantly less at Trenthorst than at Köllitsch independent of the crop stand (Table 8, Fig. 3).The mechanical soil loading did not have any significant effect on oat yield components or the oat grain yield in 2009 (Table 8). Furthermore, the mechanical soil loading did not influence yield components and the oat grain yield in 2010, with the exception that the individual intercropped oat seed mass reacted positively to an increasing mechanical soil loading.

Table 8: Probabilities of the oat yield component analysis for crop stand (C), ploughing system (P), mechanical soil loading (L), site (S) and their interactions in 2009 and 2010

	2009					2010				
Effect	Plants m^{-2}	NP[1]	NK[2]	Seed mass	Grain yield	Plants m^{-2}	NP[1]	NK[2]	Seed mass	Grain yield
C	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0225	<.0001	0.0155	<.0001
P	n.s.	n.s.	0.0388	n.s.	n.s.	0.0094	n.s.	0.0158	n.s.	0.0007
L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
S	<.0001	n.s.	n.s.	<.0001	0.0015	<.0001	n.s.	0.0388	0.0002	<.0001
C×P	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.0295	n.s.
C×S	<.0001	0.0065	0.0499	0.0075	n.s.	<.0001	n.s.	<.0001	0.0058	<.0001
P×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
P×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×P×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×P×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
P×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×P×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

n.s.: non-significant at the 0.05 probability level, [1]NP: number of panicles per plant, [2]NK: number of kernels per panicle

2.3.4 Total grain yield

Total grain yields were, except for pea sole crops in 2010, significantly greater at Köllitsch than at Trenthorst (Fig. 3). The total grain yield was highest in oat sole crops followed by pea-oat intercrops and least in pea sole crops at both sites in 2009. Pea sole crops produced the lowest grain yield at Köllitsch in the second experimental year, too. The grain yield of the oat sole crop was significantly higher than the total intercrop yield after shallow ploughing at Köllitsch in 2010 as opposed to deep ploughing, which resulted in comparable oat sole crop and total intercrop yields. Pea sole crops and pea-oat intercrops showed a better yield performance than oat sole crops at Trenthorst in 2010. In addition, oat sole crops yielded significantly more after shallow than after deep ploughing at both sites in 2010. In contrast, pea sole crop and total intercrop yields did not differ significantly between ploughing systems.

Total grain yields in the three mechanical soil loading treatments were comparable after shallow and deep ploughing in 2009. However, there was a significant interaction between ploughing system and mechanical soil loading concerning total grain yields in 2010. An increase in mechanical soil loading intensity reduced the total grain yield after deep ploughing, whereas no significant differences between mechanical soil loading treatments were present after shallow ploughing. Contrary to the treatment without mechanical soil loading, shallow ploughing caused significantly higher total grain yields in L1 and L2 compared to deep ploughing (Fig. 4A).

2.3.5 Grain quality

2.3.5.1 Crude protein and Metabolisable Energy content

Intercropped peas showed a significantly higher crude protein content than sole cropped peas at Köllitsch (SC: 253.1, IC: 259.5 g kg^{-1}), whereas no significant differences between sole and intercropped peas were observed at Trenthorst (SC: 247.1, IC: 244.6 g kg^{-1}), resulting in a significant crop stand × site interaction in 2009 (Table 9). Unlike in 2009, the crop stand did not affect the pea crude protein content in the second experimental year. Also, a significant interaction between mechanical soil loading and site was detected with pea crude protein content being influenced by mechanical soil loading at Köllitsch but not at Trenthorst in both experimental years. The L1 mechanical soil loading at Köllitsch resulted in a significantly higher crude protein content than the L0 and the L2 level (L0: 255.3, L1: 259.6, L2: 253.9 g kg^{-1}) in 2009, while the pea crude protein content decreased significantly with increasing mechanical soil loading in 2010 (L0: 234.3, L1: 223.5, L2: 213.8 g kg^{-1}). The analysis of variance in 2010 also produced a significant two-fold interaction containing the factors ploughing system and mechanical soil loading, showing that an increase in mechanical soil loading significantly reduced the pea crude protein content after deep ploughing (L0: 242.8, L1: 234.7, L2: 224.5 g kg^{-1}) but not after shallow ploughing (L0: 238.0, L1: 234.4, L2: 236.1 g kg^{-1}). Shallow ploughing resulted in significantly higher pea crude protein contents in L2 compared to deep ploughing, whereas no significant differences between deep and shallow ploughing were observed in L0 and L1. The ploughing system, however, had no influence on the pea crude protein content in 2009.

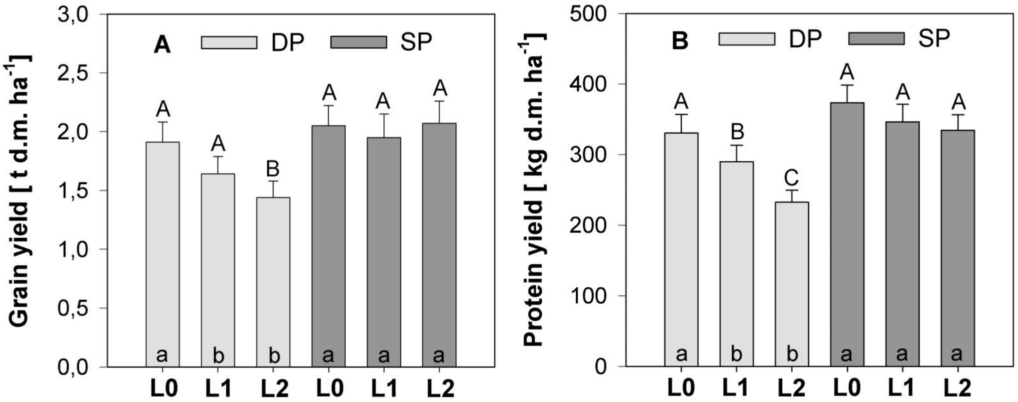

Fig. 4: Total grain (A) and crude protein yield (B) as affected by the interaction of ploughing system and mechanical soil loading in 2010. Values are means and SEM (error bars). Different capital letters denote significant differences ($P < 0.05$) between mechanical soil loading treatments (L0-L2) within the same ploughing system. Different lowercase letters indicate significant differences between ploughing systems within the same mechanical soil loading. DP: deep ploughing, SP: shallow ploughing.

The statistical analysis of the pea Metabolisable Energy (ME) content (Table 9) revealed no significant differences between sole and intercropped peas except that intercropped peas had a significantly lower ME content than sole cropped peas after shallow ploughing in 2009 (SC: 15.69, IC: 15.65 MJ kg^{-1}) and at site Trenthorst in 2010 (SC: 15.80, IC: 15.78 MJ kg^{-1}). Shallow ploughing resulted in a significantly higher pea ME content at Trenthorst in 2009 (DP: 15.68, SP: 15.71 MJ kg^{-1}) and at Köllitsch in 2010 (DP: 15.62, SP: 15.64 MJ kg^{-1}), but in a significantly lower sole cropped pea ME content in the unloaded treatment compared to deep ploughing in 2010. Apart from that, the ME content did not differ significantly between ploughing systems and mechanical soil loading treatments in both experimental years.

The ploughing system and the mechanical soil loading significantly affected the oat crude protein content in 2009 but not in 2010 (Table 9). Shallow ploughing resulted in significantly lower oat crude protein content than deep ploughing (DP: 119.5, SP: 115.5 g kg^{-1}). Moreover, the mechanical soil loading in L1 significantly decreased the oat crude protein content compared to the control, whereas the crude protein content in L2 corresponded to that of the control (L0: 118.5, L1: 115.5, L2: 117.5 g kg^{-1}). The crude protein of intercropped oats was higher than that of sole cropped oats, although this was not statistically significant for Köllitsch in 2010. A significant crop stand × site interaction affected the oat grain ME content in 2009 and 2010 (Table 9). The ME content was significantly higher in intercropped oats than in sole cropped oats at Trenthorst in 2009 (SC: 12.44, IC: 12.81 MJ kg^{-1}) and 2010 (SC: 12.19, IC: 12.62 MJ kg^{-1}). In contrast, the ME content at site Köllitsch was identical for intercropped and sole cropped oats in both experimental years (2009: 12.15, 2010: 11.85 MJ kg^{-1}). Neither the ploughing system nor the mechanical soil loading affected the oat ME content.

Table 9: Probabilities of the pea and oat crude protein and Metabolisable Energy (ME) content for crop stand (C), ploughing system (P), mechanical soil loading (L), site (S) and their interactions in 2009 and 2010

	Crude protein content				ME content			
	2009		2010		2009		2010	
Effect	Pea	Oat	Pea	Oat	Pea	Oat	Pea	Oat
C	n.s.	<.0001	n.s.	<.0001	<.0001	<.0001	n.s.	<.0001
P	n.s.	0.0236	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
L	0.0476	0.0143	<.0001	n.s.	n.s.	n.s.	n.s.	n.s.
S	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	0.0003
C×P	n.s.	n.s.	n.s.	n.s.	0.0028	n.s.	n.s.	n.s.
C×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×S	<.0001	<.0001	n.s.	0.0427	n.s.	<.0001	0.0364	<.0001
P×L	n.s.	n.s.	<.0001	n.s.	n.s.	n.s.	n.s.	n.s.
P×S	n.s.	n.s.	n.s.	n.s.	0.0326	n.s.	0.0060	n.s.
L×S	0.0308	n.s.	<.0001	n.s.	n.s.	n.s.	n.s.	n.s.
C×P×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.0210	n.s.
C×P×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
P×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×P×L×S	n.s.	n.s.	n.s	n.s.	n.s.	n.s.	n.s.	n.s.

n.s.: non-significant at the 0.05 probability level

2.3.5.2 Crude protein yield

Pea and total crude protein yields were significantly affected by a three-fold interaction between crop stand, ploughing system and site in the first experimental year (Table 10). In addition, the crude protein yield of sole cropped oats reacted positively to an increasing mechanical soil loading at Köllitsch and negatively at Trenthorst, leading to a significant interaction containing all experimental factors (Table 10). Pea sole crops after deep ploughing revealed the highest total crude protein yield followed by pea-oat intercrops and oat sole crops, whereas no significant differences between pea and oat sole or intercrops were identified after shallow ploughing at Köllitsch in 2009 (Fig. 5A). In contrast to Köllitsch, highest total crude protein yields were obtained in pea-oat intercrops at Trenthorst in 2009 (Fig. 5B). The total crude protein yield of pea sole crops, pea-oat intercrops and oat sole crops did not differ significantly between shallow and deep ploughing in 2009.

Table 10: Probabilities of pea, oat and total crude protein yield for crop stand (C), ploughing system (P), mechanical soil loading (L), site (S) and their interactions in 2009 and 2010

	Crude protein yield					
	2009			2010		
Effect	Pea	Oat	Total	Pea	Oat	Total
C	<.0001	<.0001	0.0004	<.0001	<.0001	<.0001
P	n.s.	n.s.	n.s.	n.s.	<.0001	<.0001
L	n.s.	n.s.	n.s.	<.0001	n.s.	<.0001
S	<.0001	<.0001	<.0001	0.0068	<.0001	0.0002
C×P	n.s.	n.s.	n.s.	n.s.	n.s.	0.0273
C×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×S	<.0001	n.s.	0.0010	0.0203	0.0003	<.0001
P×L	n.s.	n.s.	n.s.	0.0459	n.s.	0.0145
P×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×P×L	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×P×S	0.0457	n.s.	0.0270	n.s.	n.s.	n.s.
C×L×S	n.s.	0.0359	n.s.	n.s.	n.s.	n.s.
P×L×S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
C×P×L×S	n.s.	0.0181	n.s.	n.s.	n.s.	n.s.

n.s.: non-significant at the 0.05 probability level

The pea sole crop and the intercrop showed a significantly higher total crude protein yield than the oat sole crop after deep ploughing at Köllitsch in 2010 (Fig. 5C). In contrast, intercropping after shallow ploughing resulted in significantly higher values than pea and oat sole cropping. Independent of the ploughing system, pea sole and pea-oat intercrops gave the best results at Trenthorst in 2010 (Fig. 5D). Besides, the total crude protein yield in 2010 was affected by a significant crop stand x ploughing system interaction (Table 10), with shallow ploughing causing significantly higher total crude protein yields in the intercrop and the oat sole crop at both sites compared to deep ploughing (Fig. 5). Shallow ploughing produced higher oat crude protein yields than deep ploughing involving a significant ploughing system main effect (Table 10, DP: 140 kg ha^{-1}, SP: 197 kg ha^{-1}).

Furthermore, intercropped peas showed lower crude protein yields than sole cropped peas, which was not significant after deep ploughing at Trenthorst in 2009 (Fig. 5B).

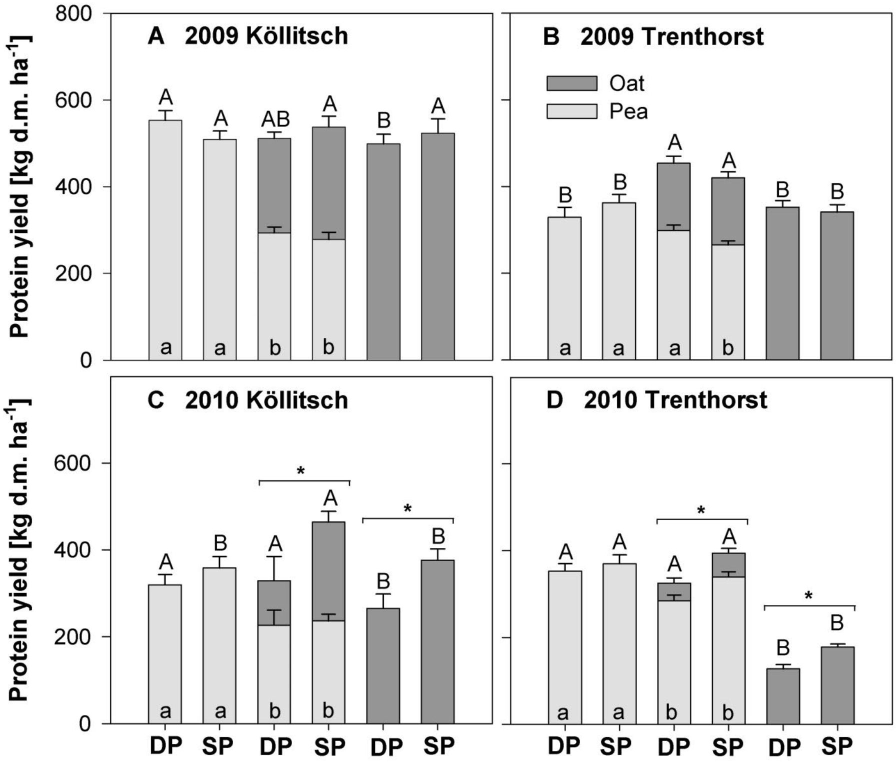

Fig. 5: Crude protein yield as affected by the interaction of crop stand and ploughing system at Köllitsch (A, C) and Trenthorst (B, D) in 2009 and 2010. Different capital letters indicate significant differences (P < 0.05) between crop stands within the same ploughing system. Different lowercase letters denote significant differences between sole cropped and intercropped pea crude protein yields within the same ploughing system. Asterisks indicate significant differences between deep (DP) and shallow (SP) ploughing within each crop stand concerning total crude protein yield. DP: deep ploughing, SP: shallow ploughing.

Mechanical soil loading had no impact on the pea and the total crude protein yield in 2009 and the oat crude protein yield in 2010 (Table 10). However, there was a significant interaction between ploughing system and mechanical soil loading affecting the pea and the total crude protein yield in the second experimental year (Table 10). Total crude protein yields decreased with increasing mechanical soil loading after deep ploughing, whereas values did not differ significantly between mechanical soil loading treatments after shallow ploughing. Moreover, the L1 and L2 mechanical soil loading treatments produced significantly higher total crude protein yields after shallow ploughing compared to deep ploughing (Fig. 4B).

2.4 Discussion

2.4.1 Physical soil conditions

The bulk density and the air capacity in the 10-15 cm soil layer varied in both experimental years with regard to ploughing system effects (Table 6). In the first year, shallow ploughing resulted in a significantly higher bulk density and a tendentially lower air capacity, whereas in 2010 the bulk density was comparable in both ploughing systems and the air capacity showed significantly higher values after shallow ploughing. These inconsistent results have also been described by Børresen and Njøs (1994) for the soil layer between shallow and deep ploughing working depth. The authors found significantly higher, lower and similar bulk densities in the 13-17 cm layer of a loam soil for a long-term ploughing system of 12 cm compared to 24 cm in different years. After six years of shallow ploughing to 10 cm and deep ploughing to 30 cm, there were no significant differences in bulk density and air capacity in the 13-17 cm soil layer (Riley and Ekeberg, 1998). The increase in mechanical soil loading intensity increased the bulk density and decreased the air capacity below the seedbed at both sites and in both years. Root and plant growth limiting values for the bulk density were reported to be 1.75-1.80 g cm^{-3} for sandy loam soils and 1.60-1.70 g cm^{-3} for loam soils (Hazelton and Murphy, 2007; USDA-NRCS, 1996). None of the ploughing system and mechanical soil loading combinations at Köllitsch or Trenthorst reached these critical limits in either experimental year. Several studies and reports have indicated that an air capacity of at least 10 % at a water suction of 5 kPa is necessary for normal root growth (Hazelton and Murphy, 2007; Huber et al., 2008). In 2009, the measured air capacity values were non-critical at both sites, which was also the case at Trenthorst in 2010. The air capacity at Köllitsch was below this limit in 2010 with the exception of the treatment combination shallow ploughing without mechanical soil loading.

The penetration resistance was not significantly affected by the mechanical soil loading. Shallow ploughing contributed to an increase in penetration resistance in the soil layer between shallow and deep ploughing working depth (Fig. 1). This effect, however, was less pronounced for Köllitsch than for Trenthorst, where significant differences were apparent. The ploughing system had no effect on the penetration resistance in the subsoil, with the exception of Köllitsch having significantly higher values after deep ploughing below a soil depth of 44 cm in 2010. This fact might rather be attributed to heterogeneous soil conditions in the subsoil caused by a former floodplain resulting in higher inherent soil strength in parts of the deep tilled soil strips than to an impact of the ploughing system. Our results for the effect of deep and shallow ploughing on the mechanical soil resistance are consistent with those reported by Kouwenhoven et al. (2002) and Bakken et al. (2009). Generally, penetrometer resistance values exceeding 2 to 3 MPa, which were partially present at the plough pan and in the subsoil in the present study, are reported as critical limits for root and plant growth (Allmaras et al., 1988; Dexter, 1986; Horn and Fleige, 2009; Lipiec and Håkansson, 2000). However, it has to be considered that this critical limit is dependent on the crop species. In a loamy sand with a penetration resistance of 1.8 MPa and a bulk density of 1.40 Mg m^{-3}, the pea root elongation rate was 55 % of the rate in peas grown in a soil with 0.06 MPa and 0.85 Mg m^{-3} (Bengough and Young, 1993). The root growth in oats as opposed to peas seems to be restricted at values that were above this general limit. Ehlers et al. (1983) reported that root growth in oats was limited at penetration resistance values between 3.6 and 5.1 MPa in the topsoil of a loess soil.

2.4.2 Weed biomass

Significantly higher annual weed biomass values were observed in pea sole crops than in pea-oat intercrops and particularly in oat sole crops at both sites and in both years (Fig. 2). These results demonstrate the good weed suppressive ability of pea-oat intercrops, which has been reported for pea-oat and other pea-cereal intercrops in previous studies (Begna et al., 2011; Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001; Kimpel-Freund et al., 1998). This may be due to a faster canopy development and a greater soil surface shading in pea-cereal intercrops than in pea sole crops (Kimpel-Freund et al., 1998), a release of weed suppressive allelochemicals through oat root exudation (Baghestani et al., 1999; Kato-Noguchi et al., 1994) and a stronger weed-crop competition for water or nutrients in intercrops than in pea sole crops.

The effect of the ploughing system on the weed biomass production depended on the crop stand and to some extent on the site. The weed infestation in pea sole crops was greater after shallow ploughing compared with deep ploughing at both sites (Fig. 2). Presumably due to the good weed suppressive ability, the pea-oat intercrop at the Köllitsch site compensated for the higher weed growth after shallow ploughing and therefore showed weed biomass values comparable to those after deep ploughing. Shallow ploughing at Trenthorst, however, resulted in significantly higher annual weed infestation in pea-oat intercrops, too. This is related to a better weed suppressive ability of pea-oat intercrops at Köllitsch than at Trenthorst, which was not caused by differences in crop biomass formation (data not shown). We might therefore suppose differences in weed species composition as well as species-specific sensitivity to be the dominating factors of the differing weed suppression at both sites. As shown by Mohler and Liebman (1987), the weed suppressive ability is highly dependent on the weed species.

Jurik and Zhang (1999) have reported that small-seeded weeds emerged to a greater extent from a wheel-tracked than from a non-wheel-tracked soil area, whereas large-seeded species were not affected by a soil compaction. The authors concluded that a slightly higher soil water content and a better seed-soil contact were the causes of the higher weed germination in the wheel-tracked soil. This experience stands in contrast to results of Vleeshouwers (1997), who noted a significant decrease in weed emergence of three weed species with an increase in soil penetration from 0.4 to 1.0 MPa at different soil depths. The present study, however, shows no clear evidence of mechanical soil loading on the weed infestation in pea and oat sole or intercrops.

2.4.3 Grain yield

In spite of identical sowing rates, most of the pea grain yield components were affected by the crop stand, with intercropped peas having lower yield component values than sole cropped peas. As a result, grain yields of intercropped peas were tendentially or significantly lower than those of sole cropped peas (Fig. 3). This result is in close agreement with those obtained by Neumann et al. (2007) and Kontturi et al. (2011). Lower intercrop pea grain yields can be explained by a high competitive ability of the cereal partner oat. Probably due to the better performance of sole and intercropped oats and therefore a higher oat competitive ability, this effect was more pronounced at Köllitsch than at Trenthorst. Even though some yield components were influenced by a significant ploughing system main effect or an interaction containing the factor ploughing system, the grain yield of intercropped or sole cropped peas after shallow ploughing did not differ from that after deep ploughing. This finding is in contrast to other published data comparing the short-term effect of ploughing depth on sole cropped pea grain yields. Baigys et al. (2006)

have compared deep ploughing to 23-25 cm with shallow ploughing to 14-16 cm under conventional conditions. They found that pea grain yields after deep ploughing were 34.7 % higher than those after shallow ploughing. In another study, deep ploughing to a soil depth of 22-25 cm has been shown to produce significantly higher pea grain yields than shallow ploughing to 10-12 cm, which was attributed to higher weed infestation after shallow ploughing compared to deep ploughing (Pranaitis and Marcinkonis, 2005). Our results suggest that the higher weed infestation in pea sole crops after shallow ploughing compared with deep ploughing was not yield relevant.

Mechanical soil loading reduced the pea grain yield by 12.1 % in L1 and 20.8 % in L2 compared to the control. In doing so, sole and intercropped peas reacted similarly to the mechanical soil loading in 2010 (Table 7). Other experiments with applied wheel loads of 50 to 85 kN and therefore greater wheel loads than in the present study have cited yield reductions in pea sole crops between 6 % and 43 % compared with the non-compacted control (Henderson, 1991; Vocanson and Jeuffroy, 2008). In 2009, however, the mechanical soil loading did not have any influence on pea yield components (Table 7). Differences in mechanical soil loading impact on peas between experimental years may result from drier soil conditions, in particular in the topsoil at Köllitsch, during mechanical soil loading in 2009 (Table 5). The impact of soil water content during compaction on pea yield performance was confirmed by Boone et al. (1994). The authors found that an applied wheel load of 45 or 85 kN under moderate soil wetness resulted in higher yields compared with the non-compacted control, whereas tendentially lower yields were noted under wet soil conditions.

Contrary to peas, yield components and the grain yield of sole or intercropped oats did not show differences between mechanical soil loading treatments (Table 8). Yet, in the case of seed mass in 2010, intercropped oats profited by a mechanical soil loading. These results indicate that yield performance in peas is more susceptible to a moderate soil compaction than that in oats. This finding is in contrast to other published data demonstrating no difference in the sensitivity of peas and cereals to soil compaction (Grath and Arvidsson, 1997; Henderson, 1991).

Probably due to high precipitation in May 2010, reduced tillering was observed in oat. This resulted in considerably lower oat grain yields in 2010 than in 2009, which was most notable at Trenthorst (Fig. 3). The reduction of the ploughing depth did not have any negative influence on oat grain yields. The significantly higher sole and intercropped oat grain yield in 2010 after shallow ploughing, however, was related to a better emergence and a higher number of kernels per panicle (Table 8). The inconsistent effects of shallow and deep ploughing on the yield performance in oats and other cereals were confirmed by Riley and Ekeberg (1998) and Bakken et al. (2009). The lower grain yield of peas in the intercrop was compensated for by the cereal partner. In agreement with the findings in previous studies (Begna et al., 2011; Kimpel-Freund et al., 1998; Neumann et al., 2007), pea-oat intercrops produced significantly higher total grain yields than pea sole crops provided that oat productivity was high which did not apply to Trenthorst in 2010 (Fig. 3).

2.4.4 Grain quality

Intercropping improved the oat crude protein content compared to sole cropping, which is concordant with results for cereals intercropped with peas of previous studies (Hauggaard-Nielsen et al., 2001, 2008; Lauk and Lauk, 2008; Neumann et al., 2007). Higher grain N respectively crude protein content in intercropped cereals is explained by higher soil N availability for intercropped cereals compared to sole cropped cereals (Hauggaard-Nielsen et al., 2008). Owing to a lower oat plant density in the intercrop, this difference in oat crude protein content might also be attributed, in part, to a lower intra-specific competition. Sole and intercropped peas did not differ significantly in grain crude protein content, with the exception that intercropping positively affected crude protein content at Köllitsch in 2009. Neumann et al. (2007) reported that significantly higher intercropped pea crude protein content was due a change in nitrogen allocation resulting in lower intercropped than sole cropped pea straw N contents. However, there were no significant differences in pea straw N content and in nitrogen harvest index (data not shown) explaining the significantly higher grain crude protein content in intercropped peas at Köllitsch in 2009. In summary, our results clearly show that the high competitive ability of oats in the intercrop involving reduced pea grain yields compared to sole cropped peas had no effect on the grain crude protein content in peas. Our data, therefore, confirm previous findings of Hauggaard-Nielsen et al. (2008).

The crop stand did mostly not affect the Metabolisable Energy (ME) content in peas. In exceptional cases, however, the ME content of intercropped peas was significantly lower than that of sole cropped peas depending on ploughing system or site. Intercropping significantly increased the ME content of oats at Trenthorst, whereas the ME content of oat sole crops at Köllitsch tallied with values for intercropped oats in both experimental years. These results indicate that the impact of the crop stand on the ME content of peas and cereals is more variable compared to the crude protein content and depends highly on site or tillage related factors.

Reduced tillage without soil inversion significantly increased the grain N content of sole and intercropped peas, whereas grain N content of sole and intercropped oats was significantly lower than after deep ploughing (Neumann et al., 2007). Others, however, found no difference in protein content and other grain quality properties in cereals after short-term shallow and deep ploughing under organic conditions (Bakken et al., 2009; Brandsæter et al., 2011). The experiments in the present study have not identified differences in sole and intercropped pea crude protein content between ploughing systems except for the L2 mechanical soil loading treatment in 2010 (Table 9). In addition, only few significant effects of the ploughing system were found on the ME content in peas. Moreover, the ploughing system did not affect the oat crude protein content in 2010 and the oat ME content in either experimental year. Shallow ploughing in 2009, however, significantly decreased the oat crude protein content. Higher oat grain yields after shallow ploughing, most notably at Köllitsch, resulting in a protein dilution and reduced soil N availability after shallow ploughing coupled with dry soil conditions particularly at Trenthorst may have contributed to this negative effect in 2009.

Previous studies have proven that the concentration and the total uptake of plant nutrients in pea and oat are reduced due to compacted soil structures (Castillo et al., 1982; Grath and Håkansson, 1992; Petelkau and Dannowski, 1990). Grath and Arvidsson (1997) compared the effect of different compaction levels on the macro-nutrient concentration of pea and barley in a sandy loam soil. The authors demonstrated for peas that only the highest compaction treatment, nine passes with a wheel load of 65.3 kN, caused significantly lower grain N contents compared to the non-compacted control, whereas barley was already found to have lower grain N values after one pass with the same wheel load. In our study, the grain crude protein content in the control without mechanical soil loading and the L2 treatment with a wheel load of 45.1 kN did not differ significantly in either peas or oats in 2009. In 2010, however, an increase in mechanical wheel loading significantly decreased the crude protein content of peas at Köllitsch but not at Trenthorst. This finding is in contrast to pea grain yields demonstrating a mechanical soil loading induced yield reduction at both sites (Table 7). The Köllitsch site showed a higher soil water content at the time of mechanical soil loading implementation, a significantly higher bulk density and an insufficient aeration compared to the Trenthorst site in 2010 (Table 5, Table 6). Compacted soil structures and restricted aeration significantly reduce nodulation and N_2-fixation in peas (Grath and Håkansson, 1992; Grath and Arvidsson, 1997). Thus, sufficient nitrogen supply may have been more problematic at Köllitsch than at Trenthorst. The mechanical soil loading had no impact on the crude protein of sole and intercropped oats in 2010 (Table 9). The differing reaction of the plant species to the mechanical soil loading at Köllitsch support the assumption that peas are more sensitive to soil compaction than oats, which may be due to the fact that N_2-fixation is important for N uptake in peas and cereal N uptake is highly dependent on mass flow (Grath and Arvidsson, 1997). Although mechanical soil loading negatively affected the crude protein content in sole and intercropped peas in 2010, an increase in mechanical soil loading did not decrease the feed energy value of peas as well as of oats in both experimental years (Table 9).

Pea-oat intercropping resulted in comparable or significantly higher total crude protein yields than pea sole crops and in significantly higher values compared to oat sole crops except for Köllitsch in 2009 (Fig. 5). Similar results were reported by Neumann et al. (2007) and by Lauk and Lauk (2008). In contrast to findings of Neumann et al. (2007), crude protein yields of pea sole crops were only significantly lower than those of oat sole crops on condition that oat performance was low. In addition, intercropped peas generally yielded less protein than sole cropped peas. Pea sole crops, pea-oat intercrops and oat sole crops performed similarly in both ploughing systems pertaining to protein yield in 2009 (Fig. 5A, B). Owing to oat yield formation problems after deep ploughing, sole and intercropped oat and hence total intercrop crude protein yields were significantly higher after shallow ploughing in 2010 at both sites (Table 10, Fig. 5C, D). With the exception of minor effects on oat sole crops after shallow ploughing, mechanical soil loading did not have any impact on crude protein yields in 2009. In 2010, however, pea and total crude protein yields, as opposed to oat crude protein yields, were affected by the mechanical soil loading (Table 10).

Due to a higher amount of loose soil after deep ploughing, Bakken et al. (2009) suggested that the risk of a soil compaction in the upper subsoil is higher after deep than after shallow ploughing. This study did not show a relationship between ploughing system and mechanical soil loading with regard to physical soil properties in either year. In 2010, however, when pea productivity was significantly lower in treatments with applied mechanical soil loads than in the unloaded control, the effect of the mechanical soil loading on grain yield and quality parameters was dependent on the ploughing system. Total grain yield, pea protein content, pea and total protein yields decreased significantly with an increase in mechanical soil loading after deep ploughing, whereas no differences were revealed after shallow ploughing (Fig. 4). Thus, shallow ploughed soils better support mechanical soil loads than deep ploughed soils resulting in a significantly better crop performance. The better resistance of shallow ploughed soils to mechanical soil loading can be attributed to an increased soil strength in the untilled soil layer (Fig. 1). Similar results were reported by Wiermann et al. (2000) and Yavuzcan et al. (2005) for reduced tillage systems as compared to deep ploughing.

Under the conditions of this study, at least 43 % of the area is passed over at seedbed preparation and sowing using the simulated tractor and an operation width of 3 m. Decreases in crop growth and nutrient uptake caused by a soil compaction during sowing operations may therefore have considerable effects on crop productivity. As shown in this study, the relationship between tillage operations, soil structural effects and crop reactions were not always clear. This becomes particularly apparent with regard to mechanical soil loading effects. Despite lower soil moisture conditions during mechanical soil loading in 2009, the effect of this factor on soil structure was almost comparable in both experimental years. However, significant effects of this experimental factor on the yield performance and the grain quality were only detectable in 2010. Our results confirm previous observations of Bakken et al. (2009) who found that experimentally caused changes in the soil structure were not automatically detected in plant yield and quality characteristics and vice versa. Raper et al. (2005) suggested several environmental and agronomic factors, e.g., soil variability in fields, weather conditions or susceptibility of chosen crop cultivar as being responsible for this lack of relationship between soil loading and plant production. The considerable difference in quantity and distribution of the precipitation in 2009 and 2010 may be regarded as one possible explanation for the differing findings in this study.

2.5 Conclusions

Pea-oat intercrops were less infested with weeds and showed a greater yield performance as well as a comparable or better grain quality than pea sole crops provided that the companion crop oat performed well. Thus, our results confirm the positive qualities of grain legume-cereal intercrops in organic farming. Despite higher annual weed infestation, shallow ploughing resulted in a comparable or higher yield performance and grain quality in sole and intercropped peas and oats compared to deep ploughing. Besides, there was some evidence that short-term shallow ploughed soils better support mechanical soil loads. On the basis of the data from this study, we therefore conclude that shallow ploughing is a possible alternative to deep ploughing even for grain legumes with a low weed suppressive ability in organic farming. Owing to their good weed suppression and their ability to partly or totally compensate for the higher weed growth after shallow ploughing, intercrops with cereals have the potential to improve pea production in reduced tilled soils. However, future studies will be necessary to evaluate the long-term effects of a reduction of the ploughing depth in fields with high annual and perennial weed pressure.

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3 Weed suppressive ability in sole and intercrops of pea and oat and its interaction with ploughing system and crop interference in organic farming

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Abstract

The cultivation of weak weed competitive pea sole crops after reduced ploughing depth may result in weed problems in organic farming. Intercropping peas and cereals is one option to manage weed problems. However, little evidence exists on the weed suppressive ability of pea-cereal intercrops in different ploughing systems. The effect of crop stand (pea and oat sole or intercropping) and ploughing system (10-12 vs. 25-27 cm) on weed infestation, PAR transmission and weed nitrogen as well as water supply was investigated in field experiments. In order to determine causes for the differing weed suppressive ability in pea and oat sole or intercrops, a pot experiment and a bioassay were conducted complementary to the field experiments. Crop stand and ploughing system did not interact with regard to annual weed infestation. The weed suppressive ability increased from pea sole crops to oat sole crops, whereas shallow ploughing resulted in a significantly higher weed infestation than deep ploughing. Shallow ploughing affected the weed N supply and in some cases the PAR transmission but not the weed water supply. While crop-weed competition for light was not essential for the differing weed suppressive ability, competition for water and nitrogen were detected to be key factors. As root exudates of the examined oat cultivar showed a growth inhibiting potential, allelopathy may also have contributed to the good weed suppression in oat sole and intercrops. Results from this study indicate that pea-oat intercropping is not able to compensate for the higher weed infestation after shallow ploughing.

Keywords: shallow ploughing, competition, allelopathy, *Pisum sativum*, *Avena sativa*

3.1 Introduction

The cultivation of pea (*Pisum sativum* L.) and other grain legumes is of central importance for the maintenance of soil fertility and the production of protein-rich animal feed in organic farming. A reduction in ploughing depth has advantages particularly with regard to fuel consumption and soil carbon dioxide losses (Plouffe et al., 1995; Reicosky and Archer, 2007), and is therefore of special interest in organic farming.

Shallow ploughing, however, is related to an increase in annual and perennial weed infestation (Brandsæter et al., 2011; Gruber and Claupein, 2009). Semi-leafless peas have a weak weed suppressive ability (Spies et al., 2011). A reduction in ploughing depth may therefore decrease the performance of semi-leafless peas, which negatively affects the maintenance of soil fertility. Pranaitis and Marcinkonis (2005) have demonstrated that a decrease in ploughing depth reduces the pea grain yield performance, which was due to an increase in weed infestation. Thus, weed management in pea is essential to avoid harvest difficulties and yield loss particularly with regard to a reduction in ploughing depth.

Peas are often grown in an intercrop with cereals, e.g. oat (*Avena sativa* L.). In addition to better grain yielding capability, this is due to a good weed suppressive ability (Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001; Kimpel-Freund et al., 1998). An intercropping with cereals could be one option to avoid weed problems in pea cultivation after shallow ploughing and may potentially compensate for this higher weed infestation compared to deep ploughing. Little evidence exists on the weed infestation and weed suppressive ability in sole and intercropped peas and oats after in different ploughing systems.

A possible cause for the weed suppression in pea-oat intercrops is a crop-weed competition for growth factors such as light, nutrients or water. Moreover, oat root exudates contain chemicals with a growth inhibiting allelopathic potential (Baghestani et al., 1999; Kato-Noguchi et al., 1994). Thus, oat allelopathy may also be involved in the weed suppression in pea-oat intercrops. Allelopathy, a biochemical interaction between neighbouring plants via secondary plant compounds, and competition contribute to plant interference (Fuerst and Putnam, 1983; Weston and Duke, 2003). A reduction in ploughing depth alters the chemical, physical and biological soil environment and may therefore exert influence on factors involved in the differing weed suppressive ability of pea and oat sole or intercrops.

This study was performed in order to examine the interaction between crop stand and ploughing system with regard to weed infestation and weed suppressive ability in peas and oats. In addition, a portion of this study was dedicated to determining causes for the differing weed suppressive ability in sole and intercropped pea and oat.

3.2 Materials and methods

The data derived from a field experiment, a pot experiment and a bioassay, which complemented one another. The experiments were performed at the Thünen Institute of Organic Farming experimental station, Trenthorst, Northern Germany (53°46'N, 10°30'E, 43 m a.s.l.).

3.2.1 Field experiment

The field experiments were conducted on a Stagnic Luvisol with a loam soil texture (according to World Reference Base for Soil Resources; 20.8 % clay, 37.7 % silt and 39.2 % sand in the 0-30 cm topsoil layer) and a pH of 6.5 in 2009 and 2010. The proportions of total carbon and nitrogen in the topsoil were 1.2 % and 0.13 %, respectively. The preceding crop was winter wheat (*Triticum aestivum* L.).

The experiments were carried out as a split-plot design of four replications with the ploughing system as the main plot and the crop stand as the subplot (2.75 m × 15 m). The experimental factor ploughing system consisted of deep (DP) or shallow (SP) ploughing. Deep ploughing included stubble tillage by a precision cultivator (8-10 cm soil depth) followed by mouldboard ploughing (25-27 cm soil depth), whereas a skim plough (Stoppelhobel, Zobel-Stahlbau, Germany) was used for stubble tillage (4-6 cm soil depth) and primary tillage (10-12 cm soil depth) in the shallow ploughing system. Primary tillage was performed in autumn. Secondary tillage in deep and shallow ploughing comprised one pass with a cultivator followed by one pass with a rotary harrow in spring prior to seeding. In the years before starting differentiated tillage experiments, mouldboard ploughing to 25-30 cm was applied at the experimental fields. The factor crop stand comprised semi-leafless spring pea cv. Santana sole cropping (80 germinable kernels m^{-2}), oat cv. Dominik sole cropping (300 germinable kernels m^{-2}) and pea-oat intercropping (80 germinable kernels pea and 60 germinable kernels oat m^{-2}). For the intercrop, seeds were mixed and sown at 12.5 cm row spacing.

The field experiments were managed according to European organic standards (Commission Regulation (EC) No. 889/2008). No mechanical weed control was performed in the experiments.

The 30-year (1978-2007) annual precipitation at the experimental site is 706 mm with a mean temperature of 8.8°C. During the 30-year vegetation period from March until the end of August a precipitation rate of 364 mm and a mean temperature of 12.3°C were recorded. The mean temperature during the vegetation period in both experimental years was higher than the long-term average (2009: 13.4°C, 2010: 12.7°C). Moreover, the precipitation differed considerably from the 30-year vegetation period mean (2009: 237 mm, 2010: 443 mm).

The ground cover of individual annual weed species was estimated five times per plot in an area of 0.5 m^2 at the beginning of pea flowering. The species richness (number of weed species per plot) was determined in a plot size of 27.5 m^2 at the same time. Weed harvests were carried out at the beginning and the end of flowering in pea as well as at crop maturity. Annual weeds were cut 1 cm above the soil surface from an area of 0.5 m^2 at the first and second harvest as well as from an area of 1 m^2 at the final harvest. Weed biomass samples were weighted and dried at 60°C to constant weight. The fresh and dry weight of the weed biomass was used to calculate the weed biomass water content. Samples of the second and the final harvest were milled with a sieve of 0.5 mm (Foss Tecator 1093, Denmark) and analysed for total nitrogen (N) content (CNS elemental analyser, HEKAtech, Germany). The proportion of total photosynthetically active radiation (PAR) transmitted to the weed canopy level was determined on a weekly basis starting 21 (2009) and 20 (2010) days after sowing (DAS), corresponding to the leaf development in pea (BBCH 14-15) and the tillering stage in oat (BBCH 21-22). A SS1-SunScan Canopy Analysis System and a reference BF5 Sunshine Sensor (Delta-T Devices, United Kingdom) were used to measure the PAR transmitted to the weed canopy level and the incident PAR above the crop stands. In each plot, five measurements were taken across the rows on the weed canopy level and related to the incident PAR above the crop stand.

3.2.2 Pot experiment

An experiment with the factors crop stand and crop-weed interference treatment was conducted under growth chamber conditions using the divided pot technique (McPhee and Aarssen, 2001). A pea sole crop (two plants per pot), an oat sole crop (four plants per pot) or a pea-oat intercrop (two pea and two oat plants per pot) were grown in presence of the weed species *S. media* in cubic polyvinyl chloride plastic boxes (1,000 cm^3) filled with a 3:2:1 (by volume) mixture of peat, sand and perlite. The crop and the weed species were separated by differently arranged barriers dependent on the interference treatment. The four crop-weed interference treatments were shoot interference (roots separated), root interference (shoots separated), full interference (no barrier) and no interference (roots and shoots separated). *S. media* was chosen because it was the most dominant weed species in the field experiments (Table 11). In addition, the same seed lots of pea and oat were used in the field and the pot experiment.

The crops were directly sown in the pots, which were watered with tap water to 60 % of the previously determined field capacity. Just before sowing, pea was inoculated with Rhizobia bacteria (Radicin No. 4, Jost, Germany). Weed seeds (Herbiseed, United Kingdom) were pre-germinated in vermiculite (2/4 mm) in a growth chamber until the cotyledons were unfolded. The first weed seedlings in the field experiment were apparent at the leaf developmental stage in pea (BBCH 10) and oat (BBCH 11). Therefore, five weed seedlings were transferred to the pots at the corresponding pea and oat developmental stage and planted in a row on the opposite side of the crops.

Pots were arranged in a growth chamber with artificial light (12/18°C, 8/16 h, 600 µmol m^{-2} s^{-1}, 70 % r.h.) in a randomised complete block design with four replicates. The experiment was repeated three times. In order to prevent effects related to a variation in temperature and light, pots within each block were rotated every day. Pots were weighed daily and adjusted to 60 % of field capacity with tap water. Pots were fertilized twice a week with a 20 ml nutrient solution containing 9 mg N, 5 mg P, 7.5 mg K and micronutrients.

At the beginning of pea flowering, 28 days after transplanting *S. media* in the pots, weed and crop plants were cut at the soil surface to determine the weed and crop shoot dry matter. Digital image analysis was performed to analyse weed leaf colour. Four fully expanded, relatively young but fully developed leaves were taken from the main shoot of each weed and placed under a glass plate on a white background. Leaves were photographed under halogen lighting with a Canon EOS 600D using a tripod (60 cm distance to the glass plate, colour temperature 3.000 K). Subsequently, leaves were analysed for Red, Green and Blue parameters (RGB) in ImageJ (National Institutes of Health, USA). RGB values were then converted in Hue, Saturation, and Intensity (HSI) format (Gonzalez and Woods, 2002). As there was insufficient weed biomass for nutrient analysis, leaf colour images were used as they allow photosynthetic activity and macronutrient deficiencies in plants to be assessed (Majer et al., 2010; Wiwart et al., 2009). Younger leaves were chosen in order to avoid an overlay of nutrient deficiency symptoms with leaf senescence (Vollmann et al., 2011).

3.2.3 Bioassay

Root exudates from six oat plants were extracted from beakers filled with sand from emergence until the four leaves unfolded-stage every other day (according to Schumacher et al., 1983). Oat root exudates were immediately added to beakers containing sand and six plants of *S. media*, cress (*Lepidium sativum* L.) or mustard (*Sinapis alba* L.) starting from the cotyledon stage. Cress and mustard were used as sensitive receiver species to assure the reaction of *S. media*. Oat, cress and mustard seeds were directly sown in the beakers whereas *S. media* was pre-germinated as described for the pot experiment and then transferred to the beakers. The bioassay was carried out as a randomised complete block design with eight replications and was conducted twice under the same environmental conditions as the pot experiment.

The total leaf area development in *S. media* was quantified using image analysis until leaves overlapped. Subsequently a *S. media* leaf shape factor (0.693) was identified based on a separate assessment of 2,000 leaves from additionally raised *S. media* plants in order to allow non-destructive estimation of total leaf area using the model leaf area = 0.693 × length × width. Calculated area and measured area were highly correlated ($R^2 = 0.97$). Receiver species were harvested and the dry weight of roots and shoots was determined.

3.2.4 Statistical Analysis

Proc GLM (pot experiment) and Proc MIXED (field experiment, bioassay) of SAS 9.2 were used to analyse data employing ANOVA and subsequent comparisons of means (Tukey test). Weed ground cover data were transformed using arcsine square root transformation and biomass data were log transformed to achieve normality. Residuals of the PAR and the weed water content data (field experiments) showed a skewed non-normal distribution, which could not be improved by transforming data. Therefore, data analysis was performed using a binomial distribution with a logit-link function in Proc GLIMMIX. Means and standard errors were then reported on the inverse linked scale. Proc GLIMMIX allows non-normal data that involve random effects to be analysed (Bolker et al., 2009; Schabenberger, 2005). In order to account for unequal time intervals, longitudinal data sets in the field experiments and the bioassay were statistically evaluated as unequally spaced repeated measures (Littell et al., 2006). Owing to the differing weather conditions in 2009 and 2010, statistical calculations were performed separately for the experimental years.

3.3 Results

3.3.1 Effect of crop stand and ploughing system in the field experiment

3.3.1.1 Weed species composition and biomass accumulation

The most important weed species was *Stellaria media* (L.) Vill. followed by *Lamium purpureum* L. in both years. The crop stand and the ploughing system had no impact on the weed ground cover of the most dominant annual weed species at the field experiments with the exception of *Capsella bursa-pastoris* (Table 11). The weed species richness was solely affected by the factor crop stand in 2009. Oat sole cropping and pea-oat intercropping reduced the weed ground cover of *C. bursa-pastoris* as well as the species richness. Shallow ploughing resulted in a significantly lower *C. bursa-pastoris* ground cover than deep ploughing in 2010.

The annual weed biomass accumulation was affected by a significant crop stand × sampling date interaction and a significant ploughing system main effect in both experimental years (Table 12). Shallow ploughing resulted in a significantly higher weed biomass accumulation than deep ploughing, independent of the crop stand and the sampling date (Table 13). The annual weed biomass accumulation was significantly greater in the pea sole crop and the intercrop than in the oat sole crop at all sampling dates in 2009 and 2010 (Table 13). Pea sole cropping produced weed biomasses 14-42 % higher than pea-oat intercrops. In doing so, significant differences were present at the second and the third sampling date in both experimental years.

Table 11: Weed ground cover of the five most dominant annual weed species and species richness (average number of weed species per 27.5 m²) as affected by the crop stand (C) and the ploughing system (P) at the experimental fields in 2009 and 2010

	Effect			Weed ground cover (% of total weed cover)				
				Crop stand			Ploughing system	
	C	P	C × P	Pea SC	IC	Oat SC	DP	SP
2009								
S. media	n.s.	n.s.	n.s.	23.1	26.9	33.1	28.3	27.1
L. purpureum	n.s.	n.s.	n.s.	16.9	19.4	22.5	20.0	19.2
M. chamomilla	n.s.	n.s.	n.s.	14.5	14.3	12.5	12.1	15.4
C. bursa-pastoris	0.0007	n.s.	n.s.	15.0 a	13.8 a	3.1 b	12.5	8.8
G. aparine	n.s.	n.s.	n.s.	9.4	6.3	6.9	5.8	9.2
Species richness	0.0484	n.s.	n.s.	7.1 a	6.0 ab	4.9 b	6.1	5.8
2010								
S. media	n.s.	n.s.	n.s.	26.9	30.6	28.1	27.9	29.2
L. purpureum	n.s.	n.s.	n.s.	24.6	24.4	24.2	24.2	24.6
C. bursa-pastoris	0.0124	0.0022	n.s.	18.1 a	12.0 b	11.8 b	18.0 a	10.8 b
G. aparine	n.s.	n.s.	n.s.	9.6	7.5	9.2	9.2	8.3
M. arvensis	n.s.	n.s.	n.s.	5.6	5.0	8.1	3.8	8.8
Species richness	n.s.	n.s.	n.s.	6.5	5.4	6.1	6.1	5.9

n.s.: non-significant at the 0.05 probability level

3.3.1.2 PAR transmission, weed water and N content

The analysis of the PAR transmission to the weed canopy level produced a significant interaction between crop stand and sampling date in both years (Table 12). The PAR transmission to the weed canopy level decreased until 60 to 70 DAS and subsequently remained at this level in both experimental years (Fig. 6). At the beginning of crop development and growth in 2009, the highest PAR transmittance rate was found in pea sole crops, whereas oat sole cropping resulted in the lowest transmitted PAR values at weed canopy level (Fig. 6A). From 45 DAS until grain harvest, the proportion of transmitted PAR to the weed canopy level was significantly greater in oat sole crops compared with pea sole crops and intercrops. In addition, pea-oat intercrops had a lower PAR transmission than pea sole crops. In 2010, the PAR transmission to the weed canopy level was always highest in oat sole crops and nearly always lowest in pea-oat intercrops (Fig. 6B). The ploughing system had no significant effect on the PAR transmission rate in 2009, whereas significant twofold interactions containing the factor ploughing system affected the PAR transmission to the weed canopy level in 2010 (Table 12). Shallow ploughing resulted in a significantly lower PAR transmission rate to the weed canopy level in the pea-oat intercrop and the oat sole crop compared to deep ploughing. The PAR transmission did not, however, differ significantly between ploughing systems in the pea sole crop (Table 14).

Table 12: Probabilities for sampling date (D), crop stand (C), ploughing system (P) and their interactions affecting weed parameters in 2009 and 2010

	2009				2010			
Effect	Weed biomass	Weed water content	Weed biomass N content	PAR transmission to the weed canopy level	Weed biomass	Weed water content	Weed biomass N content	PAR transmission to the weed canopy level
D	<.0001	<.0001	n.s.	<.0001	<.0001	<.0001	<.0001	<.0001
C	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
P	<.0001	n.s.	n.s.	n.s.	0.0015	n.s.	n.s.	0.0004
D×C	<.0001	<.0001	<.0001	<.0001	0.0037	<.0001	n.s.	0.0014
D×P	n.s.	n.s.	0.0301	n.s.	n.s.	n.s.	0.0419	0.0113
C×P	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	<.0001
D×C×P	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

n.s.: non-significant at the 0.05 probability level

Annual weeds from pea sole crops had a significantly higher water content compared with weeds from oat sole crops at all sampling dates in both experimental years (Table 13). The weed water content in pea-oat intercrops took up an intermediate position between pea and oat sole crops (Table 13). The ploughing system did influence the weed water content neither in 2009 nor in 2010 (Table 12, Table 13).

The nitrogen content of the annual weed biomass was significantly affected by an interaction between sampling date and ploughing system in both experimental years (Table 12). Also, the statistical analysis revealed a significant sampling date × crop stand interaction in 2009 and a significant crop stand main effect in 2010. The highest weed N content was revealed in pea sole crops exempt from the maturity sampling date in 2009 (Table 15). The significantly lowest N content was found in the weed biomass from oat sole crops. Pea-oat intercropping resulted in a significantly lower weed N content compared with pea sole cropping at the end of flowering in pea in both experimental years and at maturity in 2010. Shallow ploughing caused a significantly lower weed N content at the end of flowering than deep ploughing (Table 15). The weed N content at maturity, however, did not differ significantly between shallow and deep ploughing.

Table 13: Weed biomass and weed water content as affected by the sampling date × crop stand interaction and the ploughing system in 2009 and 2010

		2009			2010		
		Weed biomass		Weed water content (%)	Weed biomass		Weed water content (%)
		(g d.m. m^{-2})	% of Pea SC		(g d.m. m^{-2})	% of Pea SC	
Sampling date × crop stand[1]							
Beginning of flower-ing	Pea SC	65.9 ± 6.4 a	100	77.6 ± 1.4 a	47.2 ± 2.9 a	100	78.5 ± 0.4 a
	IC	57.0 ± 5.9 a	86	76.4 ± 1.6 a	40.2 ± 2.7 a	85	78.0 ± 0.6 a
	Oat SC	22.2 ± 2.5 b	34	61.6 ± 2.3 b	24.0 ± 2.4 b	51	75.6 ± 0.5 b
End of flowering	Pea SC	84.9 ± 7.5 a	100	76.9 ± 0.9 a	45.9 ± 5.3 a	100	63.1 ± 0.8 a
	IC	64.4 ± 5.1 b	76	71.4 ± 1.3 b	31.8 ± 4.6 b	69	58.3 ± 1.1 b
	Oat SC	28.2 ± 2.2 c	33	45.3 ± 3.5 c	17.4 ± 2.6 c	38	57.1 ± 0.9 b
Maturity	Pea SC	104.4 ± 6.8 a	100	72.4 ± 0.9 a	76.1 ± 6.3 a	100	72.3 ± 1.0 a
	IC	61.0 ± 4.6 b	58	70.2 ± 0.8 ab	43.0 ± 4.9 b	57	69.3 ± 1.0 b
	Oat SC	5.9 ± 0.8 c	6	66.6 ± 1.2 b	19.6 ± 3.1 c	26	60.6 ± 1.1 c
Ploughing system[2]							
DP		43.2 ± 2.6 B		68.5 ± 1.2 A	28.9 ± 1.9 B		67.7 ± 0.9 A
SP		66.5 ± 4.3 A		69.4 ± 1.2 A	47.9 ± 2.7 A		68.4 ± 0.9 A

[1]Values are means of four replications ± SEM. [2]Values are means of three sampling dates and four replications ± SEM. Different lowercase letters within each column indicate significant differences ($P < 0.05$) between crop stands within the same sampling date. Different capital letters within each column indicate significant differences ($P < 0.05$) between ploughing systems.

Table 14: PAR transmission to the weed canopy level as affected by the crop stand × ploughing system interaction in 2009 and 2010

		PAR transmitted (% of incident PAR)	
Cropping system	Ploughing system	2009	2010
Pea SC	DP	30.5 ± 2.3 a	39.9 ± 2.2 a
	SP	30.8 ± 2.9 a	38.8 ± 2.2 a
IC	DP	26.1 ± 2.3 a	37.7 ± 2.3 a
	SP	26.4 ± 2.3 a	35.6 ± 2.3 b
Oat SC	DP	35.1 ± 1.9 a	52.1 ± 2.0 a
	SP	35.1 ± 1.8 a	45.7 ± 2.2 b

Values are means of four replications ± SEM, with observations from five measurements averaged per plot. Different letters within each column indicate significant differences ($P < 0.05$) between ploughing systems within the same crop stand.

3.3.2 Effect of crop stand and interference treatement in the pot experiment

The analysis of the weed shoot biomass in the pot experiment showed a significant interference treatment × crop stand interaction. There were no significant differences between the crop stands with respect to weed shoot biomass accumulation in the shoot interference treatment and the control without interference (Table 16). In contrast, the weed shoot biomass was significantly greater when growing *S. media* in root or full interference

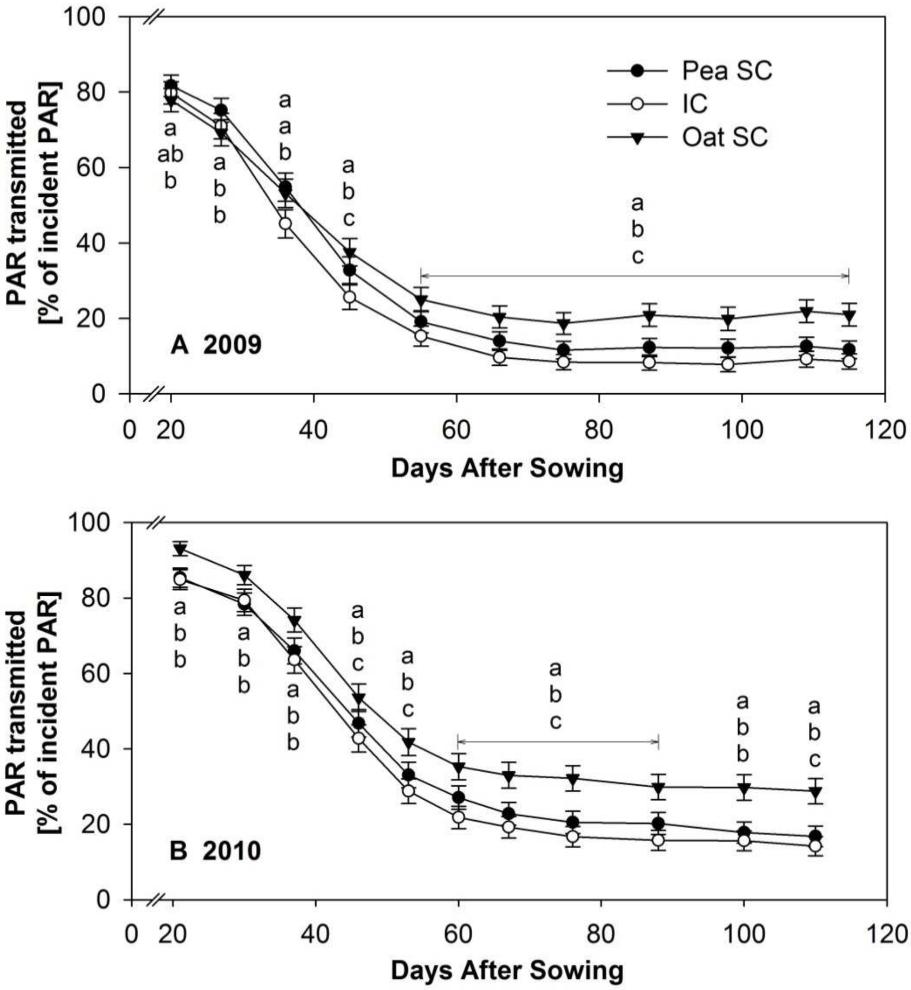

Fig. 6: Photosynthetically active radiation (PAR) transmission to the weed canopy level in pea and oat sole or intercrops in 2009 (A) and 2010 (B). Values are means of four replications ± SEM (error bars), with observations from five measurements averaged per plot. Different letters indicate significant differences (P < 0.05) between crop stands on each date.

Table 15: Weed shoot biomass N content as affected by crop stand and ploughing system in 2009 and 2010

	Weed N content (%)			
	2009		2010	
	End of flowering	Maturity	End of flowering	Maturity
Crop stand				
Pea SC	2.57 ± 0.09 a	2.01 ± 0.07 a	2.30 ± 0.11 a	2.85 ± 0.06 a
IC	2.36 ± 0.06 b	2.11 ± 0.09 a	1.99 ± 0.08 b	2.65 ± 0.07 b
Oat SC	1.22 ± 0.04 c	1.74 ± 0.04 b	1.25 ± 0.05 c	1.79 ± 0.07 c
Ploughing system				
DP	2.18 ± 0.20 a	1.92 ± 0.09 a	1.97 ± 0.16 a	2.43 ± 0.13 a
SP	1.87 ± 0.20 b	1.97 ± 0.06 a	1.73 ± 0.13 b	2.49 ± 0.17 a

Values are means of four replications ± SEM. Means within each column and effect with different letters are significantly different (P < 0.05).

with a pea sole crop than with an oat sole crop. The intercrop took up an intermediate position between the sole crops in these interference treatments. Pea-oat intercrops showed a 45-47 % lower weed shoot biomass accumulation than pea sole crops and a 16-26 % higher value than oat sole crops in the root and the full interference treatment (Table 16).

Table 16: Shoot biomass accumulation and leaf colour analysis of *S. media* as affected by the interference treatment × crop stand interaction in the pot experiment

		Weed shoot biomass		Weed leaf hue[1]
Interference treatment	Crop stand	(mg d.m. plant^{-1})	% of Pea SC	(degrees)
Shoot	Pea SC	365.8 ± 6.7 a	100	90.0 ± 0.7 a
	IC	403.3 ± 18.6 a	110	90.5 ± 0.5 a
	Oat SC	392.1 ± 34.1 a	107	89.5 ± 0.3 a
Root	Pea SC	448.1 ± 20.6 a	100	89.5 ± 0.7 a
	IC	246.0 ± 35.1 b	55	88.8 ± 1.0 a
	Oat SC	173.4 ± 32.5 b	39	86.0 ± 0.7 b
Full	Pea SC	483.7 ± 42.8 a	100	89.3 ± 1.0 a
	IC	256.3 ± 42.6 b	53	88.5 ± 0.5 a
	Oat SC	131.4 ± 31.4 c	27	84.8 ± 0.3 b
None	Pea SC	356.8 ± 16.5 a	100	89.5 ± 0.3 a
	IC	356.7 ± 7.7 a	100	90.8 ± 0.5 a
	Oat SC	348.5 ± 22.7 a	98	90.3 ± 0.9 a

[1] 0° = red, 60° = yellow, 120° = green, 180° = cyan, 240° = blue, 300° = magenta**.** Values are means of three experiments each with four replications ± SEM, with observations from five plants averaged per pot. Different letters within each column indicate significant differences (P < 0.05) between crop stands within the same interference treatment.

S. media leaf colour was a darker shade of green when growing the weed in root or full interference with a pea sole crop or a pea-oat intercrop compared with an oat sole crop (Table 16). In addition, the intercrop tended to have lower leaf hue values than the pea sole crop in both interference treatments without root separation. The weed leaf colour did not differ significantly between the crop stands in the shoot interference treatment and the treatment without interference.

3.3.3 Effect of oat cv. Dominik root exudates in the bioassay

Oat root exudates-treated *S. media* plants showed a significantly lower total leaf area than control plants from three days after the start of the root extraction until the end of the experiment (Fig. 7). The root and the shoot biomass accumulation in *S. media* as well as in cress and mustard was suppressed by the presence of oat root exudates resulting in significantly lower shoot and root biomass values compared with the control (Table 17).

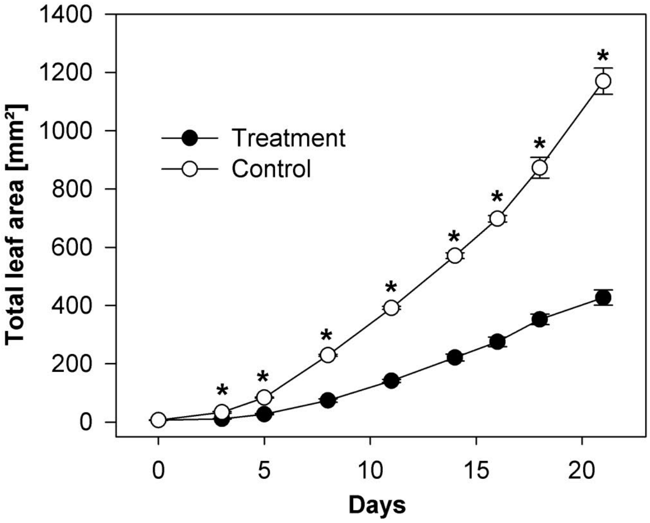

Fig. 7: Total leaf area development of *S. media* treated or untreated with oat root exudates in the bioassay. Values are means from two experiments each with eight replications ± SEM (error bars), with observations from six plants averaged per beaker. Asterisks indicate significant differences (P < 0.05) between treatment and control on each date.

Table 17: Root and shoot biomass of *S. media*, cress and mustard treated or untreated with oat root exudates in the bioassay

	Root biomass (mg plant^{-1})		Shoot biomass (mg plant^{-1})	
	Treatment	Control	Treatment	Control
S. media	50.3 ± 4.2 b	134.0 ± 16.2 a	26.2 ± 1.7 b	107.5 ± 5.3 a
cress	17.6 ± 2.5 b	43.8 ± 3.7 a	42.9 ± 2.8 b	153.6 ± 7.6 a
mustard	24.1 ± 2.3 b	48.0 ± 4.4 a	69.8 ± 5.8 b	174.4 ± 6.8 a

Values are means of two experiments each with eight replications ± SEM, with observations from six plants averaged per beaker. Means within each column with different letters are significantly different (P < 0.05).

3.4 Discussion

3.4.1 The weed suppressive ability in relation to crop stand and ploughing system

Our data corroborate the good weed suppressive ability of pea-oat intercrops and oat sole crops compared with pea sole crops. These results are in close agreement with those obtained for pea sole and pea-cereal intercrops in other field studies (Begna et al., 2011; Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001; Kimpel-Freund et al., 1998; Poggio, 2005). The species richness significantly decreased from pea sole crops to pea-oat intercrops and oat sole crops in 2009, whereas oat sole and pea-oat intercropping in 2010 solely tended to result in lower species richness (Table 11). Previous studies have come to different conclusions with regard to the effect of pea and barley sole or intercropping on species richness. A study by Mohler and Liebman (1987) showed a significantly reduced species richness in intercrops and barley sole crops at one site. Poggio (2005), however, found no significant differences in the weed species richness between pea and barley sole and intercrops. Pea-oat intercropping and oat sole cropping had only minor effects on the weed species composition. *C. bursa-pastoris* was the only species of the most dominant weed species whose weed cover declined from pea sole crops to oat sole crops (Table 11).

The proportion of the weed biomass accumulation in pea-oat intercrops in relation to the value in pea sole crops decreased from the first to the third sampling date, resulting in a significant reduction of the weed biomass accumulation in pea-oat intercrops at the end of flowering in pea and at maturity (Table 13). These results indicate that the weed suppressive ability of pea-oat intercrops enhances towards maturity. Oat sole crops, however, showed a significantly lower weed biomass accumulation compared with pea sole and pea-oat intercrops irrespective of the sampling date. The findings in the field experiment are consistent with those obtained for the full interference treatment in the pot experiment reproducing the field situation (Table 16).

Several studies have demonstrated that a reduction in ploughing depth increases the annual and perennial weed infestation (e.g. Brandsæter et al., 2011; Gruber and Claupein, 2009; Pranaitis and Marcinkonis, 2005), which is attributed, in part, to an increased accumulation of weed seeds in the upper soil level after shallow ploughing (Kouwenhoven et al., 2002). Our research has as well proven that shallow ploughing results in significantly higher weed biomass values than deep ploughing. The weed biomass accumulation was, however, not significantly affected by an interaction containing the experimental factor ploughing system (Table 12). The weed suppressive ability of pea-oat intercrops and oat sole crops after shallow ploughing did thus not differ from that after deep ploughing.

3.4.2 Effect of an aboveground crop-weed interaction on the weed suppressive ability

The weed shoot biomass accumulation did not differ significantly between interference treatments with and without shoot separation (Table 16). Results from the pot experiment therefore indicate that an aboveground crop-weed interaction is not essential for the differing weed suppressive ability in sole and intercropped peas and oats until pea flowering.

Field studies showed that pea sole crops transmitted a higher amount of PAR light to the weed canopy level than pea-oat intercrops and particularly oat sole crops until the stem elongation in oat, which explains the higher weed suppression in intercrops than in pea sole crops and the lower suppression than in oat sole crops at the beginning of plant development (Kimpel-Freund et al., 1998). This may be due to slower crop establishment in peas than in cereals (Hauggaard-Nielsen et al., 2001). These findings are in agreement with the PAR transmission course, obtained for pea and oat sole or intercrops in the 2009 field experiment (Fig. 6A). The PAR transmission to the weed canopy level in 2010, however, strongly varied from that obtained in 2009 until 40 days after sowing (Fig. 6B). Oat sole cropping resulted in the highest PAR transmission to the weed canopy level throughout the complete period of measurement in 2010. Besides, pea-oat intercrops and pea sole crops transmitted comparable amounts of PAR light at the beginning of plant development. Problems in tillering and therefore sparse oat stands contributed to the high PAR transmission rate in pea-oat intercrops and oat sole crops at the beginning of plant development in 2010. Despite the differences in PAR transmission in 2009 and 2010, the weed suppressive ability in pea-oat intercrops was comparable in both years. Moreover, oat sole crops showed the lowest weed biomass values compared with pea sole and pea-oat intercrops at pea flowering regardless of the experimental year (Table 13). The findings of this study support the assumption that differences in canopy development and therefore in PAR transmission between pea and oat sole or intercrops are not a key factor contributing to the differing weed suppressive ability until pea flowering.

Oat sole crops showed the highest PAR transmission after the beginning of pea flowering. Nonetheless, oat sole cropping resulted in least weed biomass accumulation. These data were confirmed by Kimpel-Freund et al. (1998). Thus, the effective weed suppression in intercrops and oat sole crops after the beginning of pea flowering is attributed to other factors than light competition between crops and weeds as well. Corre-Hellou et al. (2011) also found that pea-barley intercrops and barley sole crops had a higher weed suppressive ability despite a lower leaf area than pea sole crops. The authors concluded that crop-weed competition for light is not a key factor on sites with low soil N availability, whereas it may contribute to the differing weed suppressive ability in case of high soil N availability due to the promotion of biomass production and leaf area expansion under these conditions. A study by Mohler and Liebman (1987) concluded as well that the crop-weed competition for light is not crucial for the higher weed suppression in barley sole crops compared with pea sole crops.

The oat field emergence was by 11 % greater after shallow than after deep ploughing, which explains the significantly lower PAR transmission in pea-oat intercrops and oat sole crops after shallow ploughing than after deep ploughing in the second experimental year (Table 14). The reason for the higher field emergence after shallow ploughing remains unclear. Yet, the weed biomass accumulation was significantly higher after shallow ploughing, regardless of the crop stand. These findings also provide support for the hypothesis that an aboveground competition for light did not essentially contribute to the differences in weed infestation.

3.4.3 Effect of a belowground crop-weed interaction on the weed suppressive ability

Pea-oat intercropping and oat sole cropping significantly reduced the weed shoot biomass accumulation compared to pea sole crops in both interference treatments without root separation, whereas no significant differences in weed suppressive ability were observed in interference treatments with root separation (Table 16). These results clearly show that the differing weed suppressive ability is attributable to a belowground crop-weed interaction.

Weeds from pea sole crops were found to have significantly higher water content in the biomass than those from oat sole crops, irrespective of the sampling date in the field experiments. In addition, weeds from pea-oat intercrops had a middle position with regard to water content (Table 13). Thus, weed water content paralleled weed biomass accumulation. This can be assumed to indicate that a stronger crop-weed competition for water contributed to the high weed suppression in pea-oat intercrops and most notably in oat sole crops. Mohler and Liebman (1987) have demonstrated that the drought stress experienced by the most dominant weed species decreased from barley sole crops to pea-barley intercrops to pea sole crops. They concluded that the high weed suppressive ability in barley sole crops may result, in part, from a strong crop-weed competition for water. The authors offer two possible explanations for this result: a higher biomass production in barley sole crops than in pea sole crops or differences in crop physiology. The crop biomass production in 2009 increased from pea sole crops to oat sole crops, whereas pea-oat intercrops showed the highest and oat sole crops the lowest biomass production in 2010 (data not shown). Thus, differences in crop biomass production are only partially responsible for the differing weed water content in this study. The ploughing system, however, did not affect the crop-weed competition for water. Despite a uniform water supply in the pot experiment, the weed suppressive ability differed significantly between pea and oat sole or intercrops in treatments without root separation (Table 16). In conclusion, other factors, apart from the crop-weed competition for water, were responsible for the differing weed suppressive ability.

Peas have a lower competitive ability for soil N than weeds and cereals, which forces the pea to rely more on N_2-fixation in sole crops without weed control and in pea-cereal intercrops (Corre-Hellou and Crozat, 2005; Corre-Hellou et al., 2006; Hauggaard-Nielsen et al., 2001, 2009). This may explain the significantly higher weed N content in pea sole crops than in oat sole crops, regardless of the ploughing system and the experimental year (Table 15). This result correlates well with the weed biomass accumulation in pea and oat sole crops providing support for the hypothesis that the high weed suppression in oat sole crops and pea-oat intercrops is related to a crop-weed competition for soil N. Similar findings were reported by Poggio (2005) as well as by Szumigalski and Van Acker (2006) for the weed N content in sole and intercropped peas and cereals.

Majer et al. (2010) have shown that the leaf hue is linearly correlated with the leaf chlorophyll content. Nitrogen is a main constituent of chlorophyll; hence, nitrogen accumulation in plants is associated with the chlorophyll content in leaves (Evans, 1989; Shadchina and Dmitrieva, 1995). Pea sole cropping resulted in a greater leaf hue and therefore a darker shade of green in leaves of *S. media* compared with pea-oat intercrops and in particular oat sole crops in treatments without root separation, whereas no differences occurred in pots with root separation (Table 16). These results also indicate an involvement of a crop-weed competition for nitrogen in the differing weed suppressive ability in pea and oat sole or intercrops.

The weed biomass from pea sole crops was found to have a significantly lower weed N content after shallow than after deep ploughing at the end of pea flowering in both experimental years (Table 15). The N availability for weeds might therefore have been lower after shallow ploughing compared with deep ploughing, irrespective of the crop stand. The ploughing system did in general not affect the weed species composition (Table 11). The impact of the ploughing system on the weed N content at the end of pea flowering is therefore not related to a differing weed biomass composition. Weeds from deep and shallow ploughed fields, however, did not differ significantly in their N content at maturity. A reduction in tillage intensity and depth often results in a delayed N mineralisation (Berner et al., 2008; Pekrun et al., 2003). This might explain the lower weed N content after shallow ploughing at pea flowering and the equalisation of the weed N content in both ploughing systems towards maturity.

Previous studies have indicated that oat root exudates inhibit the growth of other plants and contain chemicals with allelopathic potential (Baghestani et al., 1999; Fay and Duke, 1977; Kato-Noguchi et al., 1994; Wang et al., 2009). Kimpel-Freund et al. (1998) suggested that allelochemicals could have contributed to the weed suppression in oat sole and intercrops. Root exudates of the oat cultivar used in the field and the pot experiments inhibited the growth of the tested receiver species, which already occurred in *S. media* three days after starting the experiment (Table 17, Fig. 7). Residues of pea shoots and germinating seeds have been shown to exhibit allelopathic potential (Higashinakasu et al., 2005; Kato-Noguchi, 2003; Marles et al., 2010). The weed suppressive ability in the present study, however, increased from pea sole crops over intercrops to oat sole crops. The differing weed suppressive ability is therefore related to the cereal partner. An allelopathic effect of pea seeds or root exudates on annual weeds is therefore rather unlikely.

3.5 Conclusions

The aim of this study was to evaluate the interaction between crop stand and ploughing system with regard to weed infestation and weed suppressive ability in organic farming. There were no significant interactions between crop stand and ploughing system affecting the weed infestation. We presume that this finding is closely related to the in general comparable effect of the ploughing system on the weed water as well as the N content and the light transmission in pea and oat sole or intercrops. We thus conclude that pea-oat intercrops and even oat sole crops are, despite an effective weed suppressive ability, not able to compensate for the higher annual weed infestation after short-term shallow ploughing under the conditions of this study. Nonetheless, different intercrop compositions and weed infestation levels need to be examined to clearly define the role of intercropping in different tillage systems on the weed infestation and suppression.

The results of this study indicate that a belowground interaction is responsible for the differing weed suppressive ability in pea and oat sole or intercrops. Key factors for the high weed-suppressive ability in pea-oat intercrops and oat sole crops are a strong crop-weed competition for water, nitrogen and probably a release of weed suppressive chemicals via oat root exudation. Water supply, nutrient availability and allelopathy interact under field conditions (Einhellig, 1996). The actual environmental conditions therefore have an impact on crop-weed interactions. Short-term shallow ploughing influenced the N availability for weeds and in parts the light transmission, whereas the weed water content was not affected. Long-term shallow ploughing results, for instance, in an accumulation of nutrients in the topsoil and higher soil moisture conditions (Kouwenhoven et al., 2002). It is therefore supposable that the weed suppressive ability of intercrops and oat sole crops changes in long-term shallow ploughed fields. In our study, we did not focus on weed germination and emergence. Future studies will be necessary to evaluate the effect of pea and oat sole and intercropping in different ploughing systems on weed germination and emergence.

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4 Effect of intercropping normal-leafed and semi-leafless winter peas after shallow and deep ploughing on agronomic performance, grain quality and succeeding winter wheat yield

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Abstract

Winter peas are a promising alternative to spring peas in organic farming. Intercropping winter peas and cereals may be a beneficial way to improve lodging resistance in normal-leafed and weed suppression in semi-leafless winter pea cultivars. At the same time, there is an increasing interest in a reduction in tillage intensity, e.g. operating the plough at shallow depth. A normal-leafed, coloured-flowered (cv. E.F.B. 33) and a semi-leafless, white-flowered winter pea (cv. James) were cultivated as sole crops or in intercrops with triticale on a loam soil under Northern German conditions and compared for winter survival, lodging resistance, yield performance and grain quality. The effect on the succeeding winter wheat yield was studied as well. The two ploughing systems were short-term shallow ploughing to 10-12 cm and deep ploughing to 25-27 cm. Intercropping did not improve winter survival, which was more stable with normal-leafed cv. E.F.B. 33 than with James. Owing to the low lodging resistance of normal-leafed winter peas, sole cropping is not advisable. Intercropping normal-leafed winter peas and triticale improved lodging resistance and resulted in a better yield performance (2.54-3.39 t d.m. ha^{-1}) than semi-leafless winter pea sole (0.97-1.79 t d.m. ha^{-1}) or intercrops (2.05-2.86 t d.m. ha^{-1}). E.F.B. 33 had significantly higher grain crude protein, crude fibre and macronutrient contents, whereas the crude fat, starch and sugar content as well as the energetic feed value were higher in James. Wheat yields after E.F.B. 33 sole and intercrops were higher than after the corresponding James sole or intercrops. Biomass production, yield performance and energetic feed value of winter pea sole and intercrops were comparable between ploughing systems or higher after shallow ploughing. Thus, E.F.B. 33-triticale intercrops provided better results than James sole or intercrops, except for the energetic feed value, and short-term shallow ploughing was a good alternative to deep ploughing for the cultivation of winter peas.

Keywords: organic farming, winter losses, lodging resistance, biomass accumulation, yield components, energetic feed value

4.1 Introduction

Agronomic problems in organic spring pea (*Pisum sativum* L.) cultivation, e.g., diseases, pests and yield instability have increased the interest in winter peas in Northern Germany. Winter peas are advantageous to spring peas in particular concerning the N_2-fixing capacity (Urbatzka et al., 2011b), the yield performance (Chen et al., 2006) and the yield stability (Urbatzka et al., 2011a) provided that winter survival is good.

The weak weed suppressive ability of semi-leafless winter peas as well as the low lodging resistance of normal-leafed cultivars may result in difficulties with yield formation or harvesting of sole crops. Intercropping peas and cereals reduces the infestation with weeds (Begna et al., 2011; Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001) and prevents peas from lodging (Kontturi et al., 2011; Urbatzka et al., 2011a). For these reasons, intercropping semi-leafless and normal-leafed winter peas and cereals would be one possible solution to ensure not only weak weed-crop competition, good canopy aeration as well as light interception but also to facilitate harvest operations and thus help to avoid yield losses.

Despite long-term breeding programs in Western Europe, adequate winter hardiness of winter peas is still problematic (Bourion et al., 2003). Urbatzka et al. (2012) concluded that intercropping of winter peas and cereals can be effective in protecting cultivars with inadequate winter hardiness against frost when sowing is performed late in autumn. Growing winter peas in an intercrop with cereals may, as well, reduce snow drift and therefore prevent exposure to cold temperatures and increase frost resistance, which is of particular importance for the windy weather conditions at the coastal areas in Northern Germany.

Inversion tillage is necessary to tackle weed control in organic farming. A decrease in ploughing depth, however, reduces the fuel consumption and the soil carbon dioxide loss (Plouffe et al., 1995; Reicosky and Archer, 2007). On account of the fact that organic farming is targeted at reducing the impact of human activities on the environment, a reduction in ploughing depth is more consistent with the aims of organic farming. Nonetheless, the agronomic suitability of shallow ploughing has to be examined in detail. Owing to their importance in crop rotations, principally in stockless organic farming systems, the focus should first of all be on the agronomic performance of grain legumes.

Moreover, grain legumes are considered more sensitive to non-optimal soil conditions than other crops, e.g., cereals (Jayasundara et al., 1998). Few studies have been performed to directly compare the effect of ploughing system on the performance of peas. Ploughing to a soil depth of 14-16 cm significantly reduced spring pea grain yields under conventional conditions compared to deep ploughing to a soil depth of 23-25 cm (Baigys et al., 2006). This finding was confirmed by Pranaitis and Marcinkonis (2005), who found an increase in spring pea yield performance with increasing depth of ploughing. To date, no studies have been published to confirm the use of shallow ploughing in winter pea cultivation.

The objective of this study was to evaluate the sole and intercropping of normal-leafed, coloured-flowered or semi-leafless, white-flowered winter peas and triticale after shallow and deep ploughing with regard to winter survival, lodging resistance, yield performance, grain quality and preceding crop effect.

4.2 Material and methods

4.2.1 General site and soil characteristics

The intercropping and succeeding crop experiments were carried out at the experimental station of the Thünen Institute of Organic Farming at Trenthorst in Northern Germany (53°46’N, 10°30’E, 43 m a.s.l.) in the period 2009-2012. The 30-year (1978-2007) mean annual precipitation at the experimental site is 706 mm with a mean air temperature of 8.8°C. The soil type was identified as a Stagnic Luvisol and the texture as a loam soil (18 % clay, 39 % silt and 43 % sand) according to the World Reference Base for Soil Resources. At the start of the experiments in 2009 and 2010, the organic carbon contents were 11.0 and 13.9 g kg^{-1} and the pH averaged 6.9 and 6.5, respectively, at 0-20 cm soil depth. The phosphorus, potassium and magnesium levels were non-limiting to crop production. The preceding crops at the experimental fields were triticale (2009/10, *Triticosecale* Wittmarck) and oilseed rape (2010/11, *Brassica napus* L.).

4.2.2 Experimental design and crop management

The intercropping experiments were conducted in 2009/10 and 2010/11 and comprised the factors ploughing system, winter pea cultivar and crop stand. For the factor ploughing system, deep ploughing (DP) was compared with shallow ploughing (SP). Deep ploughing consisted of stubble tillage by a precision cultivator to a soil depth of 8-10 cm and of mouldboard ploughing to 25-27 cm. Two passes with a skim plough (Stoppelhobel, Zobel-Stahlbau, Germany) were performed in the shallow ploughing system (stubble tillage: soil depth 4-6 cm, primary tillage: soil depth 10-12 cm). One pass with a precision cultivator and a rotary harrow to a soil depth of 8-10 cm and of 6-8 cm, respectively, were used for secondary tillage in both ploughing systems. Tillage, sowing and harvest dates for the intercropping experiments are presented in Table 18. In the past, experimental fields were ploughed to a soil depth of 25-30 cm.

Two winter pea EU-cultivars with different leaf types and flower colours were tested. E.F.B. 33 (shortened EFB) is a normal-leafed, coloured-flowered winter pea, whereas James is characterised as a semi-leafless type with a white flower colour. Winter peas were grown as sole crops (EFB SC, James SC, 80 germinable kernels m^{-2}) and as intercrops with triticale (EFB-TR IC, James-TR IC). Triticale was grown as well as a sole crop (TR SC, cv. Grenado) with a projected plant density of 300 plants m^{-2}. The species in the winter pea-triticale intercrops (40 germinable kernels winter pea and 150 germinable kernels triticale m^{-2}) were sown in alternate rows. The sowing depth was 4-6 cm with a row spacing of 12.5 cm.

The field experiments were conducted using a split-plot design with four replicates with the ploughing system as the main plot and the crop stand as the subplot. The plot size was 2.75 × 15 m. The field experiments were managed according to European organic farming standards (Commission Regulation (EC) No. 889/2008). No mechanical weed control was performed in the experiments.

After the harvest of the intercropping experiments, shallow and deep ploughing was performed in the same way as described above for the intercropping experiments and winter wheat cv. Achat was sown. Soil and crop management details for the succeeding crop experiments are listed in Table 18.

Long-term weather data were taken from the nearest National Meteorological Service weather station in Lübeck-Blankensee (53°81'N, 10°71'E). The air temperature and precipitation during the experimental period were recorded near the experimental sites. Snow depth was measured as well at weather station Lübeck-Blankensee and compared to snow cover observations at the experimental fields.

Table 18: Soil and crop management details in the intercropping experiments in 2009/10 and 2010/11 and the corresponding succeeding crop experiments

	2009/10		2010/11	
	Date	Crop	Date	Crop
Intercropping experiment				
Stubble tillage (DP/SP)	27 Aug. 2009		6 Sept. 2010	
Primary tillage (DP/SP)	8 Sept. 2009		4 Oct. 2010	
Secondary tillage, sowing (DP/SP)	10 Sept. 2009		11 Oct. 2010	
Harvest	21 Jul. 2010	James SC and IC, Triticale SC	19 Jul. 2011	James SC and IC
	27 Jul. 2010	EFB SC and IC	2 Aug. 2011	EFB SC and IC, Triticale SC
Succeeding crop experiment				
Stubble tillage (DP/SP)	6 Sept. 2010		20 Sept. 2011	
Primary tillage (DP/SP)	4 Oct. 2010		30 Sept. 2011	
Secondary tillage, sowing (DP/SP)	11 Oct. 2010	Winter wheat cv. Achat	2 Oct. 2011	Winter wheat cv. Achat
Harvest	20 Aug. 2011		14 Aug. 2012	

4.2.3 Specific weather conditions during the intercropping experiments

4.2.3.1 Intercropping experiment 2009/10

November 2009 was warmer than the long-term average, whereas the temperatures from December until the end of February were considerably lower than the long-term average (Table 19). Frost days were present during the middle and the end of December and all of January as well as February. The minimum air temperature was -14.6°C on 26 January. Sufficient snow cover was only present on a few frost and ice days in December. The crop stands were completely covered with snow in January and February. In the first decade of March night temperatures were below 0°C without snow cover, falling to -11.2°C on 7 March. In April and March two, respectively one, frost day occurred. Considerable fluctuations between maximum and minimum daily air temperature were present particularly on frost days from March to May. The total number of frost and ice days was 67 and 28, respectively, during the entire winter 2009/10. The cold sum of the winter 2009/10 reached 147. Precipitation largely differed from the long-term average, with the period December to April being drier than normal. However, the rainfall total in May largely exceeded the 30-year average.

Table 19: Weather conditions during the intercropping experiments in 2009/10 and 2010/11

	Air temperature (°C)				Frost days[3]		Ice days[4]	Snow cover	Precipitation (mm)	
Month	Mean	Dptr.[1]	Min.	Cold sum[5]	No. (total/ with snow cover)	Mean/ Max. daily air temper-ature differ-ence (°C)	No.	Ht. (cm)	Tot.	Dptr.[1]
2009/ 2010										
Aug.	18.9	+2.0	9.6	0	0/0	-	0	0	19	− 58
Sept.	15.0	+2.0	5.1	0	0/0	-	0	0	27	− 45
Oct.	8.1	−0.8	− 1.3	0	1/0	7.6/7.6	0	0	57	+ 12
Nov.	8.0	+3.8	0.7	0	0/0	-	0	0	78	+ 19
Dec.	0.5	−1.6	−12.4	43	17/7	4.8/8.7[2]	8	1-7	56	− 16
Jan.	− 4.1	−5.4	−14.6	77	19/19	5.2/15.9[2]	12	4-31	8	− 53
Feb.	− 0.8	−2.4	− 8.0	18	19/19	3.7/6.9[2]	8	5-26	14	− 33
Mar.	4.0	+0.1	−11.2	9	8/0	7.1/12.8	0	0	11	− 50
Apr.	8.4	+0.7	− 1.2	0	2/0	12.6/14.7	0	0	19	− 25
May	9.9	−2.5	− 1.1	0	1/0	13.6/13.6	0	0	97	+ 56
Jun.	15.5	+0.5	6.9	0	0/0	-	0	0	73	0
Jul.	20.8	+3.5	7.2	0	0/0	-	0	0	11	− 74
2010/ 2011										
Aug.	17.1	+0.2	9.1	0	0/0	-	0	0	189	+112
Sept.	13.2	+0.2	4.1	0	0/0	-	0	0	94	+ 23
Oct.	9.2	+0.3	0.8	0	0/0	-	0	0	41	− 5
Nov.	4.2	0	− 9.4	16	10/0	6.8/9.5	0	0	98	+ 39
Dec.	− 7.0	−6.1	−14.4	115	30/22	5.2/10.3[2]	23	1-9	24	− 48
Jan.	1.8	+0.5	− 7.5	22	17/6	3.7/7.9[2]	4	1-3	21	− 41
Feb.	0.9	+0.7	−10.1	30	19/3	4.1/9.9	8	1	51	+ 5
Mar.	4.3	+0.4	− 4.8	6	13/0	7.7/11.8	1	0	10	− 51
Apr.	11.7	+4.0	1.1	0	0/0	-	0	0	10	− 34
May	13.4	+1.0	− 0.3	0	1/0	12.2/12.2	0	0	24	− 17
Jun.	16.4	+1.4	5.5	0	0/0	-	0	0	77	+ 5
Jul.	16.8	−0.5	9.5	0	0/0	-	0	0	50	− 35

[1]Departure from 30-year average (1978-2007), [2]with snow cover, [3]Daily minimum temperature < 0°C, [4]Daily maximum temperature < 0°C, [5]Sum of daily mean air temperatures < 0°C.

4.2.3.2 Intercropping experiment 2010/11

In August 2010, the total rainfall at the experimental field amounted to 189 mm, which exceeded the long-term average by 112 mm. Rainfall totals in September were also much higher than normal (Table 19). Therefore sowing of the experiment was delayed to October. The December daily minimum and in the majority of cases the maximum temperatures were below 0°C, which resulted in a -6.1°C temperature departure from the 30-year average. In doing so, the crop stands were seldom fully covered by snow. The lowest air temperature was -14.4°C on 28 December. However, a 7 cm snow cover was present. Several frost days without snow occurred in February and March with the lowest air temperature on 22 February reaching -10.1°C. Late frost appeared as well in May, which resulted in a total of 90 frost, 36 ice days and a cold sum of 189 during the winter 2010/11. Higher-than-average monthly temperatures were observed in spring, most notably in April. At the same time, the period March to May was much drier than in the previous years.

4.2.4 Sampling procedures, measurements, analytical methods and calculations

For the determination of the winter hardiness, winter pea and triticale plants were counted before winter and after the last spring frost in 3 × 1 m per plot. After counting the plants before winter, peas were labelled with wooden picks to avoid the count of later emerged plants at the second counting date. The percentage of winter-killed plants was calculated by dividing the number of plants after winter by the number of plants before winter.

A biomass sampling was performed in the period between pea main flowering and the beginning of fruit development, at BBCH-stage 65-67 in EFB and 72 in James (Meier, 1997). Crops were cut 1 cm above the soil surface from an area of 0.5 m^2 per plot, separated in component crops and dried at 60°C to constant weight.

The lodging resistance of sole and intercropped peas was determined by dividing the stand height at maturity by the stand height at pea main flowering. To ensure accuracy, the length of the pea plants was measured five times per plot using the same positions in the plot at both measurement dates. A lodging resistance index equal or greater than 1 indicates that no lodging occurred.

At maturity, the plants in 1 m^2 per plot were harvested by hand, the number of pods and ears was counted and the grain yields were recorded in order to assess grain yield components. Besides, the grain yield was determined in a central area of 17.5 m^2 in each plot using a combine harvester (Haldrup C-85, Germany). Grain samples were cleaned, separated in component crops and used to determine the 1000 seed weight.

Soil samples were taken from soil depth ranges of 0-30, 30-60 and 60-90 cm in each plot, starting the day after harvest (Table 18), to analyse the N_{min} content.

Plant biomass and grain samples were ground with a sieve of 1 mm (Tecator Cyclotec 1093, Foss, Denmark). The grain P, K and Mg concentration was analysed by ICP-OES

(ISO 11885, 2007; VDLUFA, 2007). Near-Infrared Spectroscopy (NIRS, NIRLab, Büchi, Switzerland) was used to predict crude nutrient, starch and sugar content in grain samples. Soil samples were analysed for soluble soil nitrogen with the calcium chloride extraction method (VDLUFA, 1991). The grain Metabolisable Energy content was assessed using the regression equations for pigs recommended by the German Society of Nutrition Physiology (GfE, 2008). The digestibility of crude nutrients in EFB was calculated using preliminary digestibility percentages for EFB in the pig (A. Berk, 2012, personal communication), whereas digestibility percentages of white-flowered spring peas were taken for James. All parameters are expressed on a dry matter basis (d.m.).

4.2.5 Statistical Analysis

Sowing of the intercropping experiment in the second experimental year was delayed by one month, due to excess rainfall in August and September 2010 (Table 19). Therefore, the statistical analysis was conducted separately for each experimental year. After testing the data for normality and homogeneity of variance, ANOVA and post hoc tests (Tukey) were used to analyse normally distributed data. Data were processed using the Proc MIXED procedure of SAS 9.2. In the case of proportions (winter survival) and counts (number of plants per m^{-2}), the assumptions for the analysis of variance were not fulfilled, whether transformed or not. Therefore, the statistical analysis of these data was performed using Proc GLIMMIX. Means and standard errors were then reported on the inverse linked scale. The GLIMMIX procedure allows data to be analysed with both fixed and random effects and a non-normal outcome variable (Bolker et al., 2008).

4.3 Results

4.3.1 Winter losses

Losses from winter-kill were significantly higher in winter pea cultivar James (30.1 %) than in EFB (9.8 %) in the first experimental year (Table 20). Winter losses of sole and intercropped peas, however, were comparable irrespective of the winter pea cultivar. The crop stand did not significantly affect triticale losses in 2009/10. Triticale sole crops showed a tendentially higher winter loss rate than EFB sole crops and a significantly lower rate than James sole crops. Total intercrop winter losses were comparable to winter losses in triticale sole crops and the corresponding winter pea sole crops. In 2010/11, neither winter pea cultivar nor crop stand affected pea losses due to winter-kill. The James winter loss rate was much lower than in 2009/10, whereas EFB showed comparable values in both experimental years. Sole and intercropped triticale plants did not, in contrast to the first experimental year, suffer from frost. The total crop stand winter losses were significantly higher in pea sole crops than in triticale sole crops. The intercrops took up an intermediate position between the sole crops. With the exception of significantly higher triticale losses after shallow ploughing in 2009/10, damage from frost occurred independent of the ploughing system.

Table 20: Effect of crop stand and ploughing system on the winter-kill rate of winter peas, triticale and total crop stands in 2009/10 and 2010/11

	Winter-kill rate (%)					
	2009/10			2010/11		
Effect	Winter pea	Triticale	Total	Winter pea	Triticale	Total
Crop stand						
EFB SC	8.6 ± 3.3 b		8.6 ± 3.3 c	10.0 ± 2.6 a		10.0 ± 2.6 a
EFB-TR IC	10.9 ± 2.9 b	16.1 ± 4.9 a	14.3 ± 2.5 bc	13.6 ± 6.1 a	0.1 ± 0.1 a	3.9 ± 1.8 ab
James SC	31.7 ± 4.8 a		31.7 ± 4.8 a	8.5 ± 1.4 a		8.5 ± 1.4 a
James-TR IC	28.5 ± 4.9 a	17.6 ± 4.6 a	23.1 ± 3.0 ab	14.5 ± 5.7 a	0.0 ± 0.0 a	4.0 ± 1.6 ab
TR SC		11.3 ± 2.8 a	11.3 ± 2.8 bc		0.3 ± 0.2 a	0.3 ± 0.2 b
Ploughing system						
DP	22.3 ± 3.7 a	7.5 ± 1.2 b	16.4 ± 3.0 a	9.2 ± 2.1 a	0.2 ± 0.1 a	4.9 ± 1.4 a
SP	16.7 ± 3.9 a	22.5 ± 3.5 a	18.5 ± 2.5 a	14.5 ± 4.0 a	0.2 ± 0.1 a	5.7 ± 1.2 a

Values are means ± SEM. Means within each effect and column with different letters are significantly different ($P < 0.05$).

4.3.2 Lodging resistance

In contrast to the experimental factor ploughing system, the crop stand significantly affected the winter pea stand height at flowering and at harvest as well as the lodging resistance index. Pea cultivar EFB had significantly longer shoots than James in both experimental years at flowering (Table 21, Table 22). Intercropping resulted in higher-growing winter peas than sole cropping at pea flowering in 2009/10, whereas the growth length was lower in EFB and similar in James intercrops than in the corresponding sole crops at pea flowering in the second experimental year. EFB exhibited, in contrast to James, severe lodging, resulting in a low crop stand height at harvest and a significantly lower lodging resistance index than for James. However, EFB intercrop stands were significantly higher at harvest and produced a tendentially or significantly better lodging resistance index than EFB sole crops. Growth in length continued in James after main flowering, resulting in higher stand heights at harvest than at flowering and a lodging resistance index above 1.

Table 21: Effect of crop stand and ploughing system on stand height at pea flowering and harvest and lodging resistance of winter peas in 2009/10

	2009/10		
	Stand height (cm)		Lodging resistance index[1]
	Flowering	Harvest	
Crop stand			
EFB SC	80.7 ± 1.6 b	16.6 ± 1.2 c	0.21 ± 0.02 c
EFB-TR IC	105.8 ± 1.9 a	37.7 ± 3.4 b	0.36 ± 0.03 c
James SC	23.3 ± 0.7 d	60.8 ± 1.5 a	2.61 ± 0.08 a
James-TR IC	28.2 ± 0.9 c	58.5 ± 1.5 a	2.07 ± 0.07 b
Ploughing system			
DP	60.2 ± 9.3 a	44.8 ± 5.0 a	1.33 ± 0.28 a
SP	58.7 ± 8.9 a	42.0 ± 4.7 a	1.30 ± 0.27 a

Values are means ± SEM. [1]Lodging resistance index: stand height at harvest / stand height at pea main flowering. A lodging resistance index equal or greater than 1 indicates that no lodging occurred. Means within each effect and column with different letters are significantly different ($P < 0.05$).

Table 22: Effect of crop stand and ploughing system on stand height at pea flowering and harvest and lodging resistance of winter peas in 2010/11

	2010/11		
	Stand height (cm)		Lodging resistance index[1]
	Flowering	Harvest	
Crop stand			
EFB SC	84.9 ± 1.5 a	20.2 ± 1.5 c	0.24 ± 0.02 c
EFB-TR IC	75.4 ± 2.2 b	53.1 ± 2.1 a	0.70 ± 0.02 b
James SC	31.4 ± 0.7 c	38.8 ± 1.9 b	1.24 ± 0.08 a
James-TR IC	31.9 ± 1.1 c	33.5 ± 1.4 b	1.05 ± 0.05 a
Ploughing system			
DP	56.8 ± 6.3 a	37.1 ± 3.4 a	0.81 ± 0.11 a
SP	55.0 ± 6.5 a	35.7 ± 3.2 a	0.81 ± 0.10 a

Values are means ± SEM. [1]Lodging resistance index: stand height at harvest / stand height at pea main flowering. A lodging resistance index equal or greater than 1 indicates that no lodging occurred. Means within each effect and column with different letters are significantly different ($P < 0.05$).

4.3.3 Crop biomass production

In 2009/10, the crop biomass production was highest in EFB-triticale intercrops followed by EFB sole crops and least in triticale and James sole crops (Fig. 8A). Sole and intercropped EFB produced comparable biomasses, whereas the biomass of James was significantly lower in the intercrop than in the sole crop. The biomass production of total crop stands in the second experimental year was significantly greater in EFB and triticale sole crops and in both winter pea-triticale intercrops than in James sole crops (Fig. 8B).

Irrespective of the winter pea cultivar, intercropped peas accumulated less biomass than sole cropped peas. The ploughing system did not affect the winter pea biomass formation in both experimental years. Also, total crop stand biomass production was comparable in both ploughing systems (Fig. 8). The triticale biomass accumulation was significantly lower after shallow ploughing than after deep ploughing in 2009/10 (DP: 2.74 t d.m. ha^{-1}, SP: 1.84 t d.m. ha^{-1}), whereas no significant differences were revealed in the second experimental year.

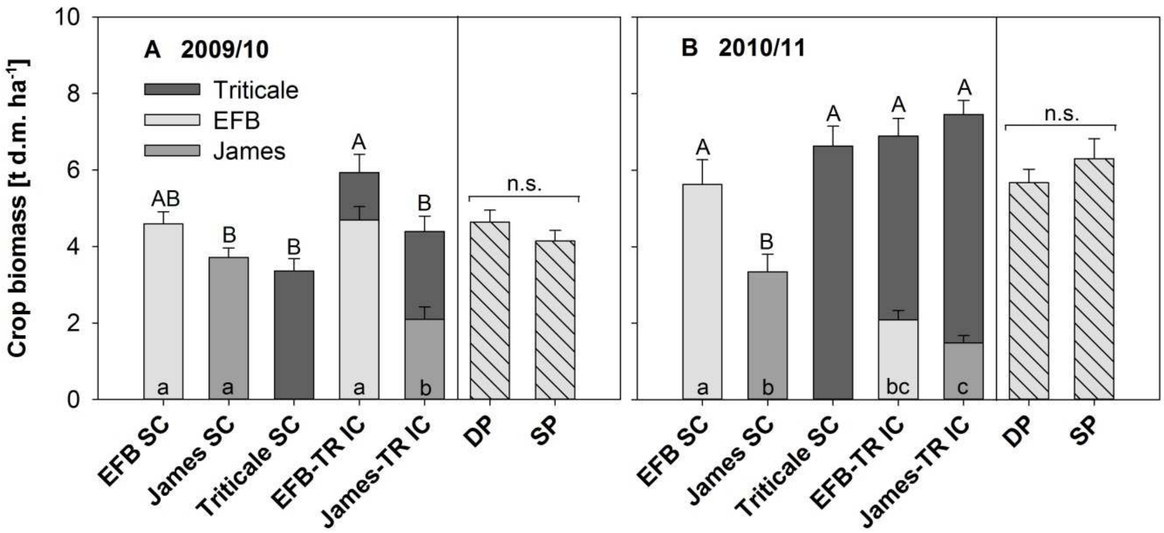

Fig. 8: Effect of crop stand and ploughing system (DP: deep ploughing, SP: shallow ploughing) on crop biomass production of winter pea and triticale sole (SC) and intercrops (IC) in 2009/10 (A) and 2010/11 (B). Values are means and SEM (error bars). Different capital letters indicate significant differences ($P < 0.05$) between crop stands with regard to total crop stand biomass production. Different lowercase letters denote significant differences in winter pea biomass production. n.s.: non-significant.

4.3.4 Winter pea yield components and grain yield performance

In autumn 2009/10, field emergence tended to be better in James (88 plants m^{-2}) than in EFB (82 plants m^{-2}). Therefore, despite significantly higher winter losses in James in 2009/10, the number of plants m^{-2} in spring did not differ significantly between winter pea cultivars (Table 23). Intercropped EFB plants produced a significantly higher number of pods per plant than sole cropped EFB and James as well as intercropped James in 2009/10. Regardless of sole or intercropping, the number of seeds per pod was greater in EFB than in James. James sole and intercrops showed a significantly higher seed mass than the corresponding EFB sole and intercrops. Also, the seed mass of intercropped James was significantly higher than that of sole cropped James in 2009/10. Moreover, winter pea yield components did not differ significantly between ploughing sytems.

Table 23: Effect of crop stand and ploughing system on yield components of winter peas in 2009/10 and 2010/11

		Yield components			
Period	Effect	Plants m^{-2}	Pods $plant^{-1}$	Seeds pod^{-1}	Seed mass (mg)
2009/10	Crop stand				
	EFB SC	74.0 ± 3.5 a	8.6 ± 0.8 b	3.7 ± 0.14 a	94.7 ± 1.2 c
	EFB-TR IC	33.0 ± 2.1 b	28.3 ± 4.1 a	4.0 ± 0.13 a	98.5 ± 0.8 c
	James SC	61.0 ± 5.4 a	11.4 ± 1.6 b	2.4 ± 0.11 b	164.5 ± 2.3 b
	James-TR IC	29.2 ± 1.9 b	10.8 ± 1.9 b	2.4 ± 0.13 b	175.7 ± 2.1 a
	Ploughing system				
	DP	50.3 ± 5.5 a	12.6 ± 1.7 a	3.0 ± 0.2 a	133.7 ± 9.8 a
	SP	47.5 ± 5.5 a	17.0 ± 3.2 a	3.2 ± 0.2 a	133.0 ± 9.5 a
2010/11	Crop stand				
	EFB SC	81.0 ± 4.6 a	6.6 ± 1.2 a	3.9 ± 1.0 ab	107.9 ± 1.8 c
	EFB-TR IC	40.0 ± 2.6 b	6.7 ± 1.2 a	4.6 ± 0.9 a	137.5 ± 1.3 b
	James SC	72.0 ± 9.6 a	4.1 ± 0.5 ab	4.0 ± 0.8 ab	183.2 ± 2.0 a
	James-TR IC	33.5 ± 3.4 b	3.0 ± 0.5 b	2.3 ± 0.5 b	177.4 ± 2.9 a
	Ploughing system				
	DP	55.3 ± 5.3 a	6.1 ± 0.9 a	4.2 ± 0.7 a	150.7 ± 8.3 a
	SP	58.0 ± 7.6 a	4.1 ± 0.5 a	3.3 ± 0.4 a	150.6 ± 8.1 a

Values are means ± SEM. Means within each experimental period, effect and column with different letters are significantly different ($P < 0.05$).

In agreement with the findings in the first experimental year, no varietal difference was found for the number of pea plants m^{-2} in spring 2011 (Table 23). Plant densities in spring 2011, however, were higher than in the first experimental year. The pea yield structure analysis of 2010/11 showed that the highest number of pods $plant^{-1}$ and seeds pod^{-1} were obtained in intercropped EFB. Values for these pea yield components were least in James intercrops and comparable in both winter pea sole crops. Intercropping positively influenced EFB seed mass, whereas sole and intercropped James did not differ significantly in seed mass. The experimental factor ploughing system did not influence pea yield components in 2010/11.

The yield performance was significantly affected by an interaction of crop stand and ploughing system in 2009/10 but not in 2010/11 (Fig. 9). Significantly higher grain yields were obtained for the EFB sole crop after shallow than after deep ploughing in 2009/10, but otherwise no significant differences between ploughing systems were detected for total grain yields. In 2009/10, grain yield of EFB sole crops was significantly lower after deep ploughing and comparable after shallow ploughing compared with intercropped EFB. James, however, yielded less in intercrops than in sole crops in the first experimental year, which was significant after shallow but not after deep ploughing (Fig. 9A). Winter pea sole cropping resulted in higher grain yields than winter pea intercropping and the cultivar EFB showed a better yield performance than James in the second experimental year (Fig. 9B). The yield performance of triticale was significantly lower after shallow ploughing compared with deep ploughing in 2009/10 (DP: 0.87 t d.m. ha^{-1}, SP: 0.60 t d.m. ha^{-1}), whereas no significant differences between ploughing systems were found in 2010/11 (DP: 2.33 t d.m. ha^{-1}, SP: 2.77 t d.m. ha^{-1}).

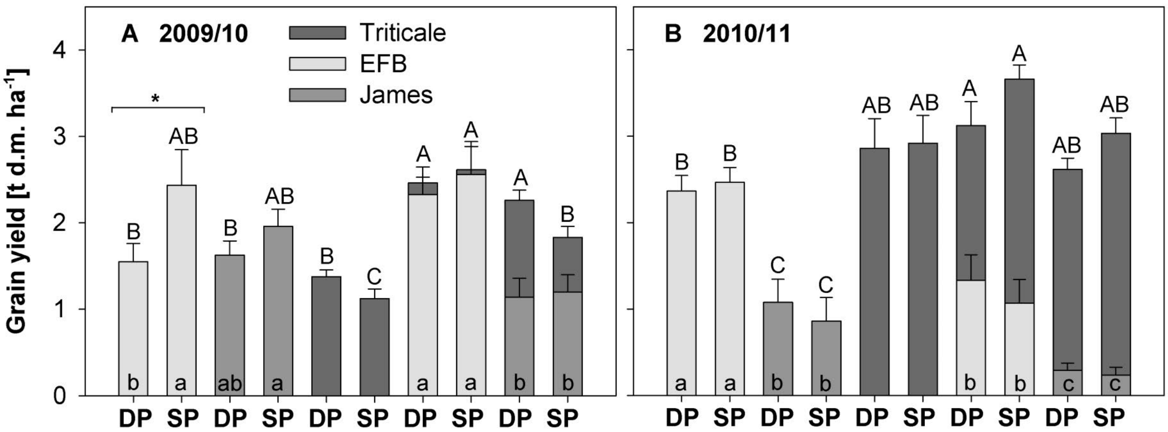

Fig. 9: Grain yields of winter pea and triticale sole and intercrops after deep (DP) and shallow ploughing (SP) in 2009/10 (A) and 2010/11 (B). Values are means and SEM (error bars). Different capital letters indicate significant differences ($P < 0.05$) between crop stands within the same ploughing system concerning total grain yields. Different lowercase letters denote significant differences between winter pea grain yields. Asterisks indicate significant differences between deep and shallow ploughing within the same crop stand.

4.3.5 Grain quality and energetic feed value

4.3.5.1 Chemical composition and macronutrient concentration

The grain chemical composition differed most significantly between winter pea cultivars. Contents of crude protein and crude fibre were higher in winter pea cultivar EFB than in cultivar James, whereas James had significantly higher amounts of crude fat, starch and total sugars (Table 24). Triticale sole crops contained similar or higher proportions of crude fat and starch as well as significantly lower proportions of crude protein, crude fibre, crude ash and sugar than winter pea sole crops. With regard to the chemical constituents crude protein, crude fibre, crude ash and sugar, the content in EFB-triticale intercrops was significantly higher in comparison to James-triticale intercrops. In contrast, James-triticale intercrops were higher in crude fat and starch content. Winter pea sole crops contained higher or comparable amounts of the chemical constituents than the corresponding winter pea-triticale intercrops with the exception of crude fat and starch in EFB sole crops in 2009/10 and starch in James sole crops in both experimental years, which were significantly lower than in the associated winter pea-triticale intercrops.

Table 24: Effect of crop stand on chemical composition of total harvested grains in 2009/10 and 2010/11

		Content (g d.m. kg^{-1})				
	Period	EFB SC	James SC	Triticale SC	EFB-TR IC	James-TR IC
CP[1]	2009/10	237.2 ± 3.1 a	224.9 ± 2.8 a	100.8 ± 1.0 c	239.1 ± 2.4 a	168.1 ± 7.5 b
	2010/11	236.3 ± 2.7 a	208.7 ± 2.5 b	84.3 ± 1.0 e	154.9 ± 6.2 c	103.0 ± 2.0 d
Crude fat	2009/10	16.8 ± 0.2 c	18.7 ± 0.2 b	19.5 ± 0.2 a	16.6 ± 0.2 c	19.1 ± 0.1 ab
	2010/11	17.0 ± 0.2 c	19.5 ± 0.2 ab	19.5 ± 0.4 ab	18.8 ± 0.2 b	19.8 ± 0.3 a
Crude fibre	2009/10	75.7 ± 0.4 a	72.2 ± 0.5 b	24.2 ± 0.4 d	72.5 ± 0.9 b	51.9 ± 1.2 c
	2010/11	79.2 ± 1.1 a	74.5 ± 0.9 a	25.7 ± 0.5 c	43.1 ± 2.4 b	30.6 ± 1.0 c
Crude ash	2009/10	29.5 ± 0.2 a	30.0 ± 0.3 a	19.7 ± 0.1 c	29.4 ± 0.2 a	25.4 ± 0.5 b
	2010/11	31.9 ± 0.3 a	30.2 ± 0.4 b	21.0 ± 0.3 d	25.2 ± 0.5 c	22.4 ± 0.2 d
Starch	2009/10	498.4 ± 2.2 d	523.2 ± 2.0 c	687.2 ± 1.1 a	499.0 ± 2.4 d	595.6 ± 4.3 b
	2010/11	490.4 ± 3.0 d	524.5 ± 2.4 c	676.6 ± 2.5 a	606.7 ± 9.1 b	658.3 ± 3.6 a
Sugar	2009/10	68.4 ± 0.2 b	71.0 ± 0.5 a	48.3 ± 0.9 e	65.4 ± 0.6 c	61.5 ± 1.1 d
	2010/11	68.0 ± 0.6 b	72.5 ± 0.5 a	42.9 ± 0.4 e	53.2 ± 0.8 c	46.5 ± 1.1 d

Values are means ± SEM. [1]CP: crude protein. Means on the same line with different letters are significantly different ($P < 0.05$).

A marked effect of the ploughing system appeared with the grain sugar content (Table 26). Deep ploughing resulted in significantly higher values compared with shallow ploughing for total crop stands as well as for winter peas in both experimental years. The same results were obtained for crude fat values in winter peas. Shallow ploughing, however, produced a significantly higher proportion of crude fibre in seeds of total crops stands in 2009/10 as well as higher total crop stand crude fat and winter pea crude protein values in 2010/11. Apart from that, the effect of deep and shallow ploughing on the grain chemical composition was comparable.

P, K and Mg contents were higher in EFB sole and EFB-triticale intercrops than in the corresponding James sole and James-triticale intercrops (Table 25). Macronutrient contents were comparable between winter pea sole crops and the associated winter pea-triticale intercrops, with the exception that winter pea sole crops had mostly significantly higher K contents. Apart from deep ploughing, which had a positive effect on the K and Mg content concerning total crop stands, no significant effect of the ploughing system was found on the macronutrient content (Table 26).

Table 25: Effect of crop stand on macronutrient content of total harvested grains in 2009/10 and 2010/11

		Content (g d.m. kg^{-1})				
	Period	EFB SC	James SC	Triticale SC	EFB-TR IC	James-TR IC
P	2009/10	4.88 ± 0.09 a	4.47 ± 0.09 b	4.12 ± 0.04 c	4.91 ± 0.14 a	4.28 ± 0.08 bc
	2010/11	4.12 ± 0.17 a	3.09 ± 0.22 b	3.73 ± 0.06 a	3.67 ± 0.06 a	3.64 ± 0.12 ab
K	2009/10	12.35 ± 0.18 a	11.63 ± 0.22 a	6.12 ± 0.08 c	12.25 ± 0.35 a	9.34 ± 0.35 b
	2010/11	12.82 ± 0.32 a	11.55 ± 0.53 b	6.07 ± 0.08 d	8.06 ± 0.25 c	6.52 ± 0.27 d
Mg	2009/10	1.41 ± 0.03 a	1.27 ± 0.03 b	1.33 ± 0.02 ab	1.41 ± 0.05 a	1.28 ± 0.01 b
	2010/11	1.59 ± 0.05 a	1.28 ± 0.10 b	1.56 ± 0.07 a	1.46 ± 0.03 ab	1.33 ± 0.09 ab

Values are means ± SEM. Means on the same line with different letters are significantly different (P < 0.05).

Table 26: Effect of ploughing system on chemical composition of total harvested grains and winter peas in 2009/10 and 2010/11

		Content (g d.m. kg^{-1})			
		2009/10		2010/11	
		DP	SP	DP	SP
Chemical constituents					
Crude protein	Total	188.1 ± 12.8 a	197.5 ± 12.5 a	159.6 ± 13.4 a	161.3 ± 15.3 a
	Winter peas	227.1 ± 3.7 a	233.2 ± 2.9 a	224.1 ± 4.0 b	234.7 ± 4.6 a
Crude fat	Total	18.4 ± 0.3 a	18.0 ± 0.3 a	18.6 ± 0.3 b	19.2 ± 0.3 a
	Winter peas	18.2 ± 0.4 a	17.6 ± 0.3 b	18.3 ± 0.3 a	17.5 ± 0.3 b
Crude fibre	Total	58.1 ± 4.9 b	60.5 ± 4.7 a	52.7 ± 5.3 a	49.6 ± 5.1 a
	Winter peas	73.1 ± 0.6 a	73.9 ± 0.5 a	77.1 ± 0.8 a	76.0 ± 1.0 a
Crude ash	Total	26.5 ± 1.0 a	27.0 ± 0.9 a	26.3 ± 1.1 a	26.2 ± 1.0 a
	Winter peas	29.8 ± 0.2 a	29.6 ± 0.2 a	31.2 ± 0.3 a	31.5 ± 0.3 a
Starch	Total	564.1 ± 17.9 a	557.0 ± 17.8 a	585.7 ± 17.2 a	593.3 ± 17.3 a
	Winter peas	514.4 ± 4.5 a	509.1 ± 4.0 a	507.4 ± 4.6 a	499.5 ± 4.8 a
Sugar	Total	63.5 ± 1.9 a	62.3 ± 2.0 b	58.0 ± 2.9 a	56.4 ± 2.9 b
	Winter peas	70.1 ± 0.6 a	68.5 ± 0.7 b	69.8 ± 0.6 a	68.4 ± 0.8 b
Macronutrients					
P	Total	4.47 ± 0.09 a	4.60 ± 0.09 a	3.65 ± 0.11 a	3.64 ± 0.12 a
	Winter peas	4.58 ± 0.11 a	4.72 ± 0.09 a	3.34 ± 0.16 a	3.64 ± 0.17 a
K	Total	10.11 ± 0.6 a	10.56 ± 0.56 a	9.44 ± 0.70 a	8.71 ± 0.61 b
	Winter peas	11.93 ± 0.18 a	12.11 ± 0.20 a	12.11 ± 0.33 a	11.92 ± 0.26 a
Mg	Total	1.33 ± 0.02 a	1.35 ± 0.02 a	1.53 ± 0.04 a	1.40 ± 0.05 b
	Winter peas	1.32 ± 0.03 a	1.35 ± 0.03 a	1.47 ± 0.05 a	1.58 ± 0.11 a

Values are means ± SEM. Means on the same line within the same experimental period with different letters are significantly different (P < 0.05).

4.3.5.2 Metabolisable Energy content and output

The grain Metabolisable Energy (ME) content was significantly lower in EFB than in James, sole as well as intercropped, in either experimental year (Table 27). Intercropping did not influence the ME content of winter peas except that intercropped EFB had a significantly higher ME content than EFB sole crops in 2010/11. Apart from the EFB-triticale intercrop in 2010/11, triticale sole crops had a significantly lower total ME content than James sole and intercrops and a significantly higher content than EFB sole and intercrops.

Table 27: Effect of crop stand on Metabolisable Energy content and output of winter peas and total harvested grains in 2009/10 and 2010/11

		Metabolisable Energy content ($MJ\ kg^{-1}$)		Metabolisable Energy output ($100\ MJ\ ha^{-1}$)	
Period	Crop stand	Winter peas	Total	Winter peas	Total
2009/10	EFB SC	13.30 ± 0.02 b	13.30 ± 0.02 d	265.2 ± 36.4 ab	265.2 ± 36.4 a
	EFB-TR IC	13.32 ± 0.01 b	13.35 ± 0.01 d	329.5 ± 27.6 a	340.8 ± 27.2 a
	James SC	15.29 ± 0.02 a	15.29 ± 0.02 a	274.1 ± 20.8 ab	274.1 ± 20.8 a
	James-TR IC	15.25 ± 0.02 a	14.68 ± 0.06 b	179.2 ± 21.2 b	301.5 ± 17.3 a
	Triticale SC		14.05 ± 0.01 c		175.5 ± 11.3 b
2010/11	EFB SC	13.25 ± 0.02 c	13.25 ± 0.02 d	320.0 ± 15.6 a	320.0 ± 15.6 b
	EFB-TR IC	13.32 ± 0.02 b	13.45 ± 0.01 c	160.0 ± 25.8 b	456.2 ± 24.3 a
	James SC	15.18 ± 0.02 a	15.18 ± 0.02 a	147.2 ± 27.6 b	147.2 ± 27.6 c
	James-TR IC	15.22 ± 0.02 a	13.67 ± 0.03 b	46.0 ± 7.4 c	376.7 ± 15.3 ab
	Triticale SC		13.46 ± 0.01 c		389.2 ± 29.2 ab

Values are means ± SEM. Means within each experimental period and column with different letters are significantly different ($P < 0.05$).

As far as the ME output of winter peas in 2009/10 is concerned, highest values were obtained in intercropped EFB, followed by winter pea sole crops and intercropped James (Table 27). In 2010/11, sole cropped winter peas showed a better winter pea ME output than intercropped winter peas and EFB outmatched the winter pea cultivar James. In 2009/10, winter pea sole and intercrops gave significantly higher total ME outputs than triticale sole crops, whereas highest ME output was obtained in EFB-triticale intercrops followed by triticale sole as well as James-triticale intercrops in the second experimental year. James sole crops, however, gave the lowest ME output in 2010/11.

Table 28: Effect of ploughing system on Metabolisable Energy content and output of total harvested grains and winter peas in 2009/10 and 2010/11

		2009/10		2010/11	
		DP	SP	DP	SP
Metabolisable Energy content ($MJ\ kg^{-1}$)					
Pigs	Total	14.16 ± 0.18 a	14.12 ± 0.19 a	13.79 ± 0.17 b	13.82 ± 0.17 a
	Winter peas	14.34 ± 0.26 a	14.31 ± 0.26 a	14.22 ± 0.25 b	14.26 ± 0.25 a
Metabolisable Energy output ($100\ MJ\ ha^{-1}$)					
Pigs	Total	258.3 ± 16.7 a	280.5 ± 21.0 a	326.1 ± 25.9 a	345.5 ± 31.8 a
	Winter peas	230.4 ± 19.1 a	287.4 ± 24.3 a	183.1 ± 28.7 a	169.8 ± 30.6 a

Values are means ± SEM. Means on the same line within the same experimental period with different letters are significantly different ($P < 0.05$).

The ploughing system did not influence the ME content and output in 2009/10, whereas significant higher ME contents were found both in winter peas as well as in total harvested grains after shallow ploughing. The ME output in 2010/11, however, was not affected by the ploughing system (Table 28).

4.3.6 N_{min} after harvest and succeeding winter wheat yield

The N_{min} content after harvest of the 2009/10 intercropping experiment was significantly highest in EFB sole crops, followed by EFB-triticale intercrops and least in James-triticale intercrops as well as in triticale sole crops (Table 29). In 2010/11, EFB sole crops provided the significantly highest amount of N_{min}, too. However, there were no significant differences between the other crop stands in the second experimental year. The N_{min} content after harvest did not differ significantly between deep and shallow ploughed plots in either experimental year (Table 29).

Table 29: Effect of crop stand and ploughing system on N_{min} content in the soil (0-90 cm) directly after harvest of the intercropping experiments and grain yield of the succeeding winter wheat

	N_{min} (kg ha^{-1})		Winter wheat yield (t d.m. ha^{-1})	
Effect	2009/10	2010/11	2010/11	2011/12
Crop stand				
EFB SC	57.4 ± 8.2 a	39.2 ± 7.6 a	3.69 ± 0.20 a	2.40 ± 0.19 a
EFB-TR IC	34.4 ± 3.4 b	10.8 ± 1.8 b	3.49 ± 0.09 a	1.61 ± 0.12 b
James SC	21.6 ± 1.4 c	12.0 ± 1.6 b	2.61 ± 0.14 b	2.08 ± 0.27 a
James-TR IC	14.2 ± 3.1 d	8.7 ± 1.1 b	2.15 ± 0.11 bc	1.26 ± 0.13 bc
TR SC	12.5 ± 0.9 d	13.2 ± 4.2 b	1.92 ± 0.18 c	1.00 ± 0.14 c
Ploughing system				
DP	26.2 ± 3.9 a	13.5 ± 2.6 a	2.66 ± 0.18 a	2.05 ± 0.15 a
SP	27.8 ± 5.0 a	20.0 ± 4.2 a	2.88 ± 0.19 a	1.29 ± 0.12 b

Values are means ± SEM. Means within each effect and column with different letters are significantly different ($P < 0.05$).

Highest winter wheat yields were revealed after EFB sole and EFB-triticale intercrops, whereas triticale sole cropping resulted in the lowest succeeding crop yield performance in 2010/11 (Table 29). Winter wheat gave better results after winter pea cultivar EFB than after James both in sole crops and intercrops. Irrespective of the winter pea cultivar, no significant differences occurred between associated winter pea sole and intercrops. The ploughing system did not significantly affect winter wheat grain yields in 2010/11.

The winter wheat yield performance in 2011/12 was lower compared to 2010/11 and the effects of the preceding crops differed from those in the first experimental year (Table 29). Winter wheat yielded significantly more after winter pea sole crops than after winter pea-triticale intercrops and in particular after triticale sole crops. EFB tended to have a better preceding crop effect than winter pea cultivar James in the sole as well as in the intercrop. In contrast to the first experimental year, grain yields were significantly higher after deep than after shallow ploughing.

4.4 Discussion

4.4.1 Winter losses

In summary, the winter 2009/10 was warmer than the winter 2010/11. In contrast to the second experimental year, snow completely covered the crop stands during most frost days and prevented, therefore, exposure to cold temperatures in 2009/10. Besides, the minimum air temperature of -14.6 °C on 26 January in winter 2009/10 corresponds with the -14.4°C measured on 28 December in 2010/11. Late frost occurred in both years until the beginning of May and the daily fluctuations between maximum and minimum air temperature were comparable in both spring seasons. Similar plant losses were found in winter pea cv. EFB in both intercropping experiments (Table 20). However, winter-kill rates in James were higher in 2009/10 than in 2010/11 and triticale only suffered from frost in 2009/10. The differences in winter-kill of semi-leafless winter pea cultivar James as well as of triticale between both experimental years are not associated with the winter conditions during both experimental years. They may therefore be related to the differing sowing dates in both experimental years, which were a result of the wet summer and autumn in 2010 (Table 19). Winter peas and triticale sown in October 2010 were less developed than those sown in September 2009, with James having 6-7 tendrils and 1-2 tendrils developed before the first frost event in autumn 2009 and 2010, respectively. According to Urbatzka et al. (2012), semi-leafless winter peas are frost sensitive when they have more than 5-6 tendrils at the end of winter. Owing to an advanced pre-winter development, flower initiation risks to coincidence with frost events in early spring; hence, early sown winter peas were more susceptible to late frost (Etévé and Derieux, 1982; Knott and Belcher, 1998). The advanced development of the semi-leafless cultivar James before winter due to the September sowing date may have therefore contributed to the higher winter-kill rates in 2009/10. Our observation is in accordance with Urbatzka et al. (2012), who showed that the winter survival of a semi-leafless winter pea cultivar was improved when sowing was performed at the beginning or the end of October instead of the middle of September. In addition, a poor acclimation may be responsible for the James losses in 2009/10, which is often a problem in early-sown winter peas (Murray and Swensen, 1991). The minimum air temperature at the experimental site was not consistently below 10°C before frost occurrence. Cold acclimation in peas, however, occurs when minimum temperatures are within the range 0-10°C (Kephart and Murray, 1989; Murray and Swensen, 1991). Prieur and Cousin (1978) found that even an acclimation at 8°C was not sufficient.

Triticale should have at least 3-4 leaves developed before winter. However, the development of first tillers is recommended for an optimal overwintering (Farack et al., 2006). Tillering stage was reached in both experimental years with triticale showing 4-6 tillers in autumn 2009 and 1-2 tillers before first frost events in autumn 2010. Pre-winter development was probably too advanced in 2009/10 and optimal in 2010/11, which may explain the differences in triticale winter survival.

The significantly higher winter-kill rate of cultivar James compared to cultivar EFB in 2009/10 and the similar plant losses in both cultivars in the second experimental year might be attributed, in part, to differences in pre-winter plant development. At the onset of winter 2009, EFB was less developed than James and possessed only 4-5 tendrils, whereas both pea cultivars showed the same pre-winter development in the second experimental year. The EFB winter-kill rates, ranging from 9 % to 14 % in the present study, are in keeping with those reported by Urbatzka et al. (2012). These results indicate that the normal-leafed cultivar EFB possesses good winter hardiness, which was to some extent better than that of triticale. The better winter survival of normal-leafed winter peas is related to a better protection of the shoot apex from frost by stipules and leaves that are not fully expanded (Etévé, 1985; Murray and Swensen, 1991).

Murray et al. (1985) reported that intercropping winter peas and winter barley or wheat tended to increase the winter survival of winter peas from 66 % to 70-74 % and of winter barley by 10-11 % depending on the pea sowing rate. They also found that wheat plant losses were significantly lower in winter pea-wheat intercrops than in wheat sole crops. The present data, however, do not confirm the efficacy of intercropping for an improvement in winter survival of winter peas or cereals.

The ploughing system did not affect the winter survival with the exception of triticale showing more plant losses after shallow ploughing in 2009/10 (Table 20). This difference might be attributed to a better field emergence and establishment of triticale stands after deep ploughing compared with shallow ploughing.

4.4.2 Lodging resistance

Plants of normal-leafed cultivar EFB were significantly taller than those of cultivar James at pea flowering. Owing to the normal leaf type, EFB exhibited severe lodging after flowering, which resulted in a low lodging resistance index in EFB sole crops (Table 21, Table 22). These results confirm the high susceptibility to lodging of normal-leafed winter peas, which has already been reported in previous studies (Murray and Swensen, 1985; Urbatzka et al., 2011a). Growth in height of semi-leafless cultivar James continued after flowering, particularly in 2009/10. No lodging occurred in James sole or intercrops, which may result from the short plant height and the semi-leafless leaf type. This finding is in contrast to other published data demonstrating as well a high lodging potential in semi-leafless winter pea sole crops (Urbatzka, 2010). The short plant height of James, however, caused severe problems with weed overgrowth. Intercropping resulted in a significantly higher stand height at harvest and increased the lodging resistance of cultivar EFB, which facilitated harvest operations. This result correlates well with the literature (Murray and Swensen, 1985; Urbatzka et al., 2011a). Owing to the good anti-lodge potential of winter pea-wheat intercrops, the light absorption as well as the canopy aeration was improved and the pea fungal disease incidence reduced (Murray and Swensen, 1985). An influence of the ploughing system on the stand height and the pea lodging resistance was not observed.

4.4.3 Crop biomass production

The low field emergence and the plant losses of triticale in winter 2009/10 reduced the projected triticale density by 71 % in sole crops and by 75 % in intercrops, which resulted in low triticale aboveground biomass production. Therefore, pea-triticale intercrops solely tended to exceed the biomass production of the corresponding pea sole crops and triticale sole crops did not differ from winter pea sole crops at pea flowering in 2009/10 (Fig. 8A). Despite half pea plant density in the intercrop, EFB out-yielded the sole crop biomass production by 2 % and intercropped James had a by 7 % higher biomass production compared to the expected value of half of the sole crop biomass production. Intercropped winter peas first of all EFB, thus, profited from the low competitive ability of the sparse triticale stands in 2009/10.

The well-developed triticale in the second experimental year, however, suppressed both winter pea cultivars in the intercrop, resulting in significantly lower biomass values than in the corresponding winter pea sole crops (Fig. 8B). Comparable, and significantly lower, pea shoot biomass values were as well obtained in intercrops of rye and normal-leafed, respectively semi-leafless, winter peas compared with the corresponding winter pea sole crops (Urbatzka, 2010). Chen et al. (2004) demonstrated as well that intercropping winter peas and barley suppresses the biomass production of winter peas. Intercropping James and triticale significantly improved total biomass production, whereas values in EFB-triticale intercrops tended to be higher than in EFB sole crops. Owing to the differences in leaf type and plant height, EFB showed a higher biomass production than James. Our data therefore confirm the suitability of normal-leafed winter peas as winter catch crops (Urbatzka, 2010).

The significantly lower shoot biomass production in triticale after shallow ploughing in 2009/10 stems from higher winter losses and therefore significantly lower plant densities in spring. Apart from that ploughing system did not affect the biomass production.

4.4.4 Yield performance

Winter pea-triticale intercrops out-yielded winter pea sole crops after deep ploughing but not after shallow ploughing in the first experimental year (Fig. 9A). This fact might be attributed to the significantly higher winter losses and therefore lower yield performance of triticale after shallow ploughing. In addition, winter pea-triticale intercrops showed a better yield performance than triticale sole crops, which demonstrates the triticale yield formation problems in 2009/10. Neither the crop biomass production at pea flowering nor the winter pea yield component analysis showed significant differences between shallow and deep ploughing (Fig. 8A, Table 23). Therefore, the reasons for the significantly higher yield performance of EFB sole crops after shallow ploughing remains unclear (Fig. 9A). This finding is in contrast to other published data demonstrating significantly lower spring pea yields after short-term practice of shallow ploughing compared with deep ploughing (Baigys et al., 2006; Pranaitis and Marcinkonis, 2005). The yield performance of intercropped EFB was comparable or significantly higher compared to sole cropped EFB, whereas James sole crops showed a tendentially or significantly higher yield performance than intercropped James in 2009/10 (Fig. 9A). The higher competitive ability of normal-leafed compared to semi-leafless peas in pea-cereal intercrops is in accordance with Urbatzka et al. (2011a), who ascribed this fact to the indeterminate growth type and the high biomass production in normal-leafed winter peas. Nonetheless, both winter pea cultivars yielded more than the expected value of half of the corresponding winter pea sole crops. This indicates that not only biomass production but also yield formation in winter peas, most notably in EFB, profited from poor triticale stands in 2009/10. In pea-dominated intercrops, normal-leafed winter peas were found to be more competitive than cereals due to their indeterminate growth and the high shoot length, which may explain the findings in the present study (Murray and Swensen, 1985).

With the exception of EFB sole crops, the winter pea yield performance was lower in 2010/11 than in first experimental year, which was mainly due to a low number of pods plant^{-1}. Besides, grain yields were found to be higher in normal-leafed cultivar EFB than in James. Intercropped winter peas showed significantly lower grain yields than the corresponding winter pea sole crops. Yet, winter pea cultivar EFB approached the, on the basis of the sole crop, anticipated yield in the intercrop as opposed to James. The droughty conditions in spring 2011 (Table 19) reduced the productivity of the winter peas by decreasing the number of pods per plant^{-1}, whereas triticale was not affected. A possible explanation for this difference is a better developed root system in triticale that allowed subsoil moisture to be accessed. The suppression of winter peas in the intercrop is therefore attributable to a higher competitive ability of the triticale. The lower yield performance of sole as well as of intercropped James compared to EFB originates from the coincidence of flowering with spring drought due to the earlier flowering date in James. Despite the problems in intercropped winter pea yield formation in the second experimental year, winter pea-triticale intercrops yielded significantly more than the associated winter pea sole crops. Our research has therefore proven that intercrops compensate to a certain extent for the total failure of one, or the partial failure of all, companion crops, which is a possible explanation for the stability of intercropping systems (Morse et al., 1997). Urbatzka (2010) has shown as well that EFB and semi-leafless winter pea-cereal intercrops significantly out-yielded the corresponding winter pea sole crops. Yield performance of EFB sole and intercrops is in close agreement with those obtained by Urbatzka et al. (2011a).

4.4.5 Grain quality and energetic feed value

The differing chemical composition of the examined winter pea cultivars EFB and James can be attributed to differences in flower colour. The coloured-flowered winter pea cultivar EFB was found to have higher levels of crude protein and crude fibre and lower amounts of crude fat, starch and sugar than the white-flowered cultivar James (Table 24). Our data is concordant with those of previous studies (Bastianelli et al., 1998; Canbolat et al., 2007; Urbatzka et al. 2011a). Gdala et al. (1992), however, found higher crude protein content in white-flowered peas compared with coloured-flowered peas. Different sample sizes for white and coloured-flowered peas as well as a large varietal variation are possible explanations for these different results. The higher crude fibre content in coloured-flowered peas is, according to Bastianelli et al. (1998), in part due to their smaller seed size. Another possible explanation is a higher hull proportion in coloured-flowered peas compared to white-flowered peas (Pastuszewska et al., 2004). The significantly lower seed mass in EFB compared to James (Table 23) supports this assumption. The chemical composition of the intercrops was as well affected by the differing winter pea flower colour with EFB-triticale intercrops having higher crude protein and crude fibre as well as lower crude fat and starch contents than James-triticale intercrops. Contrary to winter pea sole crops, EFB-triticale intercrops were found to have significantly higher grain sugar contents than James-triticale intercrops. This may be associated with a lower triticale grain yield and the low sugar content in triticale.

Previous studies have reported contradictory findings concerning the level of P in white- and coloured-flowered peas. Igbasan et al. (1997) found both lower and higher values in coloured-flowered peas, whereas no significant differences were observed by Bastianelli et al. (1998) in peas of differing flower colour. In contrast to these earlier findings, significantly higher P, K and Mg values were observed in the coloured-flowered cultivar EFB compared with James (Table 25). Accordingly to the sole crops, EFB-triticale intercrops showed a higher macronutrient content than James-triticale intercrops. These different results suggest that varietal characteristics rather than flower colour were the contributing factor. Intercropping, however, did not significantly affect the macronutrient content in winter peas.

Digestibility experiments have demonstrated that the ME content of coloured-flowered peas is significantly lower than that of white-flowered peas (Canbolat et al., 2007; Grosjean et al., 1998; Hlödversson, 1987). Owing to the higher crude fibre content and the presence of condensed tannins, coloured-flowered peas have a lower apparent ileal and faecal digestibility of crude protein and organic matter in pigs than white-flowered peas (Gdala et al., 1992; Abrahamsson et al., 1993; Grosjean et al., 1998). In agreement with the findings in these previous studies, we found a significantly lower ME content for the coloured-flowered winter pea cultivar EFB compared with the white-flowered winter pea cultivar James (Table 27). Thus, significantly lower ME contents were revealed for EFB-triticale intercrops than for James-triticale intercrops. Owing to the higher ME content in triticale, EFB-triticale intercrops improved the total energetic feed value compared with EFB sole crops. Unlike EFB, James-triticale intercrops had a lower ME content than James sole crops due to the lower triticale ME content. The higher crude protein content may be partially responsible for the significantly higher ME content in intercropped EFB than in sole cropped EFB in 2010/11.

It is because of the yield formation problem in triticale and the higher yield performance of EFB that winter pea sole crops and winter pea-triticale intercrops, independent of the pea cultivar, obtained comparable ME output results in 2009/10 (Table 27). Yet, the ME output was highest in EFB-triticale intercrops, which is congruent with the results in the second experimental year. There were as well no differences in the ME output between EFB and James-triticale intercrops in the second experimental year, which is explained by the dominating triticale proportion in the intercrop. The significantly higher ME output in winter pea-triticale intercrops than in winter pea sole crops is mainly caused by a better yield performance. Despite significantly higher crude protein contents in intercropped than in sole cropped winter peas and a higher ME content in intercropped EFB, the winter pea ME output was significantly higher in winter pea sole crops. This fact may be attributed to the significantly higher winter pea sole crop grain yields.

The ploughing system had little bearing on the chemical composition and the energetic feed value in winter pea and triticale sole and intercrops. Shallow ploughing clearly resulted in significantly lower grain sugar content than deep ploughing (Table 26). Besides, the winter pea crude fat content was higher after deep ploughing, whereas levels in triticale were found to be higher after shallow ploughing. This explains the comparable, respectively significantly higher, crude fat levels in the total crop stand analysis. The problematic weather conditions in 2010/11 may be responsible for the significantly higher winter pea crude protein and the lower K and Mg contents in total crop stands after shallow ploughing. The significantly higher ME content in winter pea as well as in total harvested grains in 2010/11 originates from the significantly higher crude protein content in winter peas and the higher crude fat and starch content in total harvested grains. Nevertheless, ME outputs were not affected by the ploughing system.

4.4.6 Preceding crop effect

EFB sole crops resulted in the significantly highest winter wheat yield and were therefore found to be the best preceding crops (Table 29). The highest amount of N_{min} in the soil after harvest was detected in EFB sole crops. EFB sole crops provided, thus, more nitrogen to the succeeding crop compared with the other crop stands, which may explain the good wheat yield performance. These results are in close agreement with those obtained by Urbatzka et al. (2009). Differences in N_{min} after harvest and winter wheat yield performance, demonstrating a good preceding crop effect of EFB-triticale intercrops in 2009/10 and minor beneficial effects in 2010/11, can be attributed to the differing intercrop composition. Due to the poor triticale stands in 2009/10, winter pea EFB had a high proportion in the EFB-triticale intercrops and showed a biomass production comparable to the EFB sole crops. In contrast, triticale dominated EFB-triticale intercrops in 2010/11. Sole crops and intercrops of semi-leafless winter pea cultivar James caused both lower N_{min} contents in the soil and winter wheat yields than the corresponding crop stands with the normal-leafed cultivar EFB. This fact is related to the poor growth and biomass production of James particularly in 2010/11. Winter pea sole crops and winter pea-triticale intercrops, however, contributed to a better winter wheat performance than triticale sole crops. The ploughing system affected neither the amount of N_{min} in the soil after crop harvest nor the winter wheat yield performance in 2010/11. Despite comparable amounts of N_{min} after harvest as well as in spring (data not shown), shallow ploughing resulted in a significantly lower wheat yield performance in 2011/12 (Table 29). We might, therefore, suppose drought in spring 2012 to impair water supply more in shallow ploughed than in deep ploughed plots. A higher weed infestation after shallow ploughing, however, was not observable.

4.5 Conclusions

The results of our study indicate that only the cultivation of the normal-leafed winter pea EFB ensures a good winter survival. Although EFB sole crops were found to have the best preceding crop effect, sole cropping cannot be recommended due to complete lodging after flowering. Intercropping, however, improves the lodging resistance of normal-leafed winter peas and allows for optimal harvest operations. In contrast, sole cropping of semi-leafless winter pea cultivar James is possible. The intercropping of semi-leafless winter pea cultivar James and triticale may be advantageous due to a low weed suppressive ability of James sole crops. A comparison of the differing results in both experimental years, however, indicates that James may benefit from a reduction of the triticale plant density in the intercrop. Semi-leafless, white-flowered winter pea sole and intercrops have a better energetic feed value, whereas biomass production, yield performance, grain macronutrient content and succeeding crop yield were higher for normal-leafed, coloured-flowered winter pea sole and intercrops. In spite of limitations for the use in monogastric rations, normal-leafed, colour-flowered winter peas are a more stable and therefore agronomically better alternative to spring peas than semi-leafless, white-flowered winter peas.

In general, shallow ploughing resulted in comparable or better results than deep ploughing, particularly with regard to winter peas. On the basis of the short-term results of our study, we conclude that the cultivation of peas is practicable after shallow ploughing. Long-term results and closer examinations, however, are necessary to find the reasons for the few negative effects of shallow ploughing on the grain quality, e.g., sugar content, the triticale biomass and yield formation in 2009/10 as well as the wheat yield performance in 2010/11, which are not made clear by the present study.

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5 Effect of intercropping winter peas of differing leaf type and time of flowering on annual weed infestation in deep and shallow ploughed soils and on pea pests

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Abstract

The performance of organic crop production largely depends on preventive and cultural control strategies for weeds and pests. Field experiments were carried out in Northern Germany to study the effect of intercropping a normal-leafed, coloured-flowered (cv. E.F.B. 33) or a semi-leafless, early flowering and white-flowered winter pea (cv. James) and triticale on the infestation with annual weeds, pea aphids and pea moths in comparison to the respective sole crops. In addition, shallow ploughing (10-12 cm) vs. deep ploughing (25-27 cm) was investigated with regard to an infestation with annual weeds. The higher weed suppressive ability of the normal-leafed winter pea cv. E.F.B. 33 compared with the semi-leafless winter pea cv. James was due to lower light transmission to the weed canopy level. The weed infestation was in most cases comparable between E.F.B. 33 sole and intercrops. Intercropping James, however, significantly reduced the weed infestation compared to the respective sole crop. The ploughing system had no significant effect on the weed infestation in winter pea and triticale sole or intercrops. Winter pea sole crops were found to have higher pea aphid density, incidence of infested plants and cumulative aphid-days than the corresponding winter pea-triticale intercrops. The proportion of pea moth larvae-damaged peas was similar or significantly higher in winter pea-triticale intercrops than in winter pea sole crops. Thus, intercropping winter peas and triticale is a possible cultural method to reduce an infestation with annual weeds or pea aphids. No beneficial effect of intercropping, however, was found with regard to a reduction of pea moth damages. Shallow ploughing did not increase the weed infestation in crops differing in their ability to suppress annual weeds.

Keywords: organic farming, ploughing system, weed suppression, *Acyrthosiphon pisum* Harris, cumulative aphid-days, *Cydia nigricana* Fabricius

5.1 Introduction

Weed and pest management largely influences crop performance and organic farmers rely first of all on cultural and other preventive management strategies. Effective weed and pest management therefore is a challenge and often a weakness in organic farming. Intensive tillage, e.g. deep mouldboard ploughing, is known as an effective preventive weed management strategy in organic farming (Kouwenhoven et al., 2002). The need to reduce the environmental impact of agricultural management practices and to improve soil quality has increased the interest in a reduction of tillage intensity, e.g. shallow ploughing. Shallow ploughing was found to decrease fuel consumption and CO_2 release from the soil, and to increase soil aggregate stability and topsoil microbial activity (Børresen and Njøs, 1994; Chen and Huang, 2009; Curci et al., 1997; Kouwenhoven et al., 2002; Reicosky and Archer, 2007; Vian et al., 2009). However, the results of most studies indicate that shallow ploughing results in an increase in annual, and in particular perennial, weed infestation in organic and conventional farming (Børresen and Njøs, 1994; Brandsæter et al., 2011; Håkansson et al., 1998). Pranaitis and Marcinkonis (2005) reported that the grain yield of semi-leafless peas (*Pisum sativum* L.) decreased with decreasing ploughing depth which was attributable to an increase in weed infestation.

Normal-leafed peas have a better weed suppressive ability than semi-leafless pea cultivars and their yield performance is therefore less affected by weed competition (Spies et al., 2011). Owing to the low lodging resistance, aeration and harvest of normal-leafed pea crop stands is often problematic. An intercropping with cereals improves the lodging resistance of normal-leafed winter peas (Urbatzka et al., 2011) and the weed suppressive ability of semi-leafless peas (Begna et al., 2011; Corre-Hellou et al., 2011; Poggio, 2005), which deserves special attention in reduced tillage systems under organic management.

Pea aphids (*Acyrthosiphon pisum* Harris) cause direct damage to pea plants by sucking plant sap. Honeydew excretion by pea aphids facilitates colonisation of saprophytic moulds on the plant surface (Biddle, 1985). Much more critical, however, is their ability to vector plant viruses (Brisson and Stern, 2006; Seidenglanz et al., 2011). Aphid feeding on peas causes a decrease in yield performance and nitrogen-fixing activity (Hinz, 1991; Maiteki and Lamb, 1985; Sirur and Barlow, 1984). The pea moth (*Cydia nigricana* Fabricius) larva feeds on the developing pea seeds in the pod and a high infestation reduces grain yield and quality (Huusela-Veistola and Jauhiainen, 2006). Although pea moth related damages are more relevant in green pea and pea seed production than in grain pea production for feeding purposes, a reduction of a moth infestation in grain peas is important to reduce the risk for neighbouring pea fields (Huusela-Veistola and Jauhiainen, 2006). The severity of pea aphid and moth infestations and thereby related damages are dependent on environmental and weather conditions as well as on the coincidence of pest occurrence and sensitive pea growth stages (Huusela-Veistola and Jauhiainen, 2006; McVean et al., 1999; Schultz and Saucke, 2005). McVean et al. (1999) and Thöming et al. (2011) suggested that peas should be sown early and only early-maturing cultivars should be used for pea production as one preventive management strategy to avoid coincidence and therefore high pea aphid and moth infestation levels. Owing to the fact that time of flowering and maturity is earlier than in spring peas, cultivation of winter peas could be advantageous to minimize pea aphid and moth damages in grain pea production. Moreover, the data that do exist indicate that intercropping peas and cereals can be effective in reducing an infestation with some pea pests, e.g. pea aphids (Bedoussac et al., 2008; Bedoussac, 2009; Seidenglanz et al., 2011).

The aim of this study was to: (1) evaluate the effects of ploughing system and intercropping on the annual weed infestation in semi-leafless and normal-leafed winter peas and their underlying causes, (2) determine whether winter pea cultivars differing in leaf type, as well as in time of flowering and maturity, vary in their susceptibility to pea aphid and moth attacks and (3) examine the impact of pea sole and pea-triticale intercropping on an infestation with pea aphids and moths.

5.2 Material and methods

5.2.1 Site characteristics, experimental design and crop management

The field experiments were conducted at the experimental station of the Thünen Institute of Organic Farming at Trenthorst, Northern Germany (53°46’N, 10°30’E, 43 m a.s.l.) in the seasons 2009/10 and 2010/11. According to the World Reference Base for Soil Resources, the soil type at the experimental site was classified as a Stagnic Luvisol and the soil texture as a loam. Post-sowing soil characteristics are presented in Table 30. The 30-year mean annual precipitation at the nearest National Meteorological Service weather station in

Lübeck-Blankensee (53°52’N, 10°42’E) is 706 mm with a mean temperature of 8.8°C. The weather conditions during the experimental years were recorded at the experimental site and are given in Table 31. Triticale (2009/10, *Triticosecale* Wittmack) and oilseed rape (2010/11, *Brassica napus* L.) were the previous crops at the experimental site.

Table 30: Characteristics of the topsoil (0-20 cm) at the experimental site in 2009/10 and 2010/11

	2009/10	2010/11
pH ($CaCl_2$)	7.0	6.5
P (CAL, mg kg^{-1})	92	96
K (CAL, mg kg^{-1})	133	147
Mg ($CaCl_2$, mg kg^{-1})	169	121
N_t (%)	0.12	0.14
C_t (%)	1.10	1.38

Table 31: Air temperature and precipitation during the 2009/10 and 2010/11 experimental period and departure from 30-year average

Month	2009/10				2010/11			
	Air temperature (°C)		Precipitation (mm)		Air temperature (°C)		Precipitation (mm)	
	Average	Dptr.[1]	Total	Dptr.[1]	Average	Dptr.[1]	Total	Dptr.[1]
August	18.9	+2.0	19	−58	17.1	+0.2	189	+112
September	15.0	+2.0	27	−45	13.2	+0.2	94	+ 23
October	8.1	−0.8	57	+12	9.2	+0.3	41	− 5
November	8.0	+3.8	78	+19	4.2	0	98	+ 39
December	0.5	−1.6	56	−16	− 7.0	−6.1	24	− 48
January	− 4.1	−5.4	8	−53	1.8	+0.5	21	− 41
February	− 0.8	−2.4	14	−33	0.9	+0.7	51	+ 5
March	4.0	+0.1	11	−50	4.3	+0.4	10	− 51
April	8.4	+0.7	19	−25	11.7	+4.0	10	− 34
May	9.9	−2.5	97	+56	13.4	+1.0	24	− 17
June	15.5	+0.5	73	0	16.4	+1.4	77	+ 5
July	20.8	+3.5	11	−74	16.8	−0.5	50	− 35

[1]Dptr.: Departure from 30-year average (1978-2007).

The experimental factor ploughing system consisted of deep (DP, stubble tillage: precision cultivator, soil depth 8-10 cm; primary tillage: mouldboard plough to a soil depth of 25-27 cm) and of shallow ploughing (SP). Stubble and primary tillage in the shallow ploughing system were performed with a skim plough (Stoppelhobel, Zobel-Stahlbau, Germany) to a soil depth of 4-6 cm and 10-12 cm, respectively. Long-term mouldboard ploughing to a soil depth of 25-30 cm was performed at the experimental site before the start of the experiment.

The factor crop stand included five treatments: the semi-leafless, white-flowered winter pea cultivar James and the normal-leafed, coloured-flowered cultivar E.F.B. 33 (shortened

EFB) were grown as sole crops (SC, James SC, EFB SC, 80 germinable kernels m^{-2}) and in intercrops (IC) with triticale (cv. Grenado, James-TR IC, EFB-TR IC). The intercrop consisted of 40 germinable kernels winter pea and 150 germinable kernels triticale m^{-2}. Component crops were arranged in alternate rows with a 12.5-cm row distance. A triticale sole crop (Triticale SC, 300 germinable kernels m^{-2}) was grown for weed infestation comparison purposes.

The experimental layout was a split-plot design with four replicates. Ploughing systems were arranged as main plots and crop stands as subplots. The plot size was 2.75 × 15 m. Sowing was performed on 10 September 2009 and 11 October 2010. As a result of the high precipitation in late summer and autumn 2010 (Table 31), sowing was delayed by one month in the second experimental year.

Crop management occurred in accordance with European organic farming standards (Commission Regulation (EC) No. 889/2008). No mechanical weed control was performed in the experiments. The most prevalent annual weed species in 2009/10 were *Lamium purpureum* L. and *Stellaria media* (L.) Vill., whereas *Galium aparine* L. dominated the weed community in the second experimental year. The weed species composition at the experimental fields and their order of dominance are listed in Table 32.

Table 32: Proportion of annual weed species in total weed ground coverage and weed species order of dominance averaged over all crop stands and ploughing systems at the experimental fields in 2009/10 and 2010/11

	2009/10		2010/11	
Scientific name	% of total weed coverage	Order of dominance	% of total weed coverage	Order of dominance
Capsella bursa-pastoris (L.) Medic.	8.5	4	6.4	7
Chenopodium album L.	0	-	0.3	11
Galeopsis tetrahit L.	0	-	0.3	11
Galium aparine L.	0.2	9	24.6	1
Geranium dissectum L.	0	-	0.9	9
Geranium rotundifolium L.	0.8	7	0	-
Lamium purpureum L.	37.6	1	13.4	4
Myosotis arvensis (L.) Hill.	3.1	6	8.3	6
Matricaria chamomilla L.	5.0	5	11.4	5
Poa annua L.	0.3	8	1.6	8
Polygonum persicaria L.	0	-	0.1	-
Stellaria media (L.) Vill./Cyr.	35.8	2	17.5	2
Veronica hederifolia L.	0	-	14.4	3
Vicia hirsuta (L.) Gray	0.1	10	0	-
Viola arvensis Murr.	8.6	3	0.8	10

5.2.2 Sampling procedures, measurements, counts and calculations

Ground coverage of weeds was estimated five times per plot using rectangular frames with an area of 0.5 m^2 at the end of stem elongation in EFB corresponding to the inflorescence emergence in James (Table 33). Annual weed biomass samplings were performed in June (pea flowering/beginning of pod development) and July (pea ripening/maturity) from an area of 0.5 m^2 and 1 m^2 per plot, respectively. The sampling dates and the corresponding crop growth stages are given in Table 33. Annual weeds were cut 1 cm above the soil surface and dried at 60°C to constant weight. The fresh weight and the dry matter of the weed samples were measured to estimate the water content of the weed biomass. The aboveground crop biomass was as well determined at the June biomass sampling date and the proportion of weeds in the total aboveground biomass was calculated. Weed and pea biomass samples were milled (0.5 mm, Foss Tecator 1093, Denmark) and analysed to total nitrogen (N) content (CNS elemental analyser, HEKAtech, Germany).

Table 33: Dates of weed ground coverage estimation and biomass samplings with the corresponding crop growth stages (BBCH) in 2009/10 and 2010/11

	2009/10				2010/11			
		Growth stage				Growth stage		
		EFB	James	Triticale		EFB	James	Triticale
Weed ground coverage	22 April	39	55	30	4 May	39	51	31
Weed and crop biomass sampling 1	15 June	65	72	65	14 June	67	72	71
Weed biomass sampling 2	19 July	88	89	87	16 July	83	89	83

Simultaneous photosynthetically active radiation (PAR) measurements above the crop stand and on the weed canopy level were carried out using a SS1-SunScan Canopy Analysis System and a reference BF5 Sunshine Sensor (Delta-T Devices, United Kingdom). Five measurements per plot were taken across the rows on a weekly basis starting at the end of winter pea stem elongation. The proportion of total PAR transmitted to the weed canopy level was calculated by relating the value measured on the weed canopy level to the incident PAR above the crop stand.

The density of live pea aphids (number per shoot tip) was counted and the incidence (proportion of infested plants) was determined during the entire infestation period twice or three times a week in deep ploughed plots according to the EPPO standards (EPPO, 2005).

The pea BBCH growth stages were recorded at each assessment. Cumulative aphid-days were calculated following Ruppel (1983).

Winter pea grain samples of a plot combine harvest from an area of 17.5 m^2 were used to determine the pea moth infestation level. In doing so, four times 200 grains per plot were screened for symptoms of attack.

5.2.3 Statistical Analysis

Owing to the differing sowing dates, the statistical analysis was conducted separately for both experimental years. Winter pea cropping system and cultivar were analysed as combined factor crop stand, in order to allow a comparison with triticale sole crops concerning the infestation with annual weeds. ANOVA followed by Tukey's post hoc was performed by using the MIXED procedure of SAS 9.2. Weed coverage data were transformed using arcsine square root transformation, whereas data for weed biomass and weed N uptake were log transformed to achieve normality. Proc NLMIXED was used to fit nonlinear regression models. A negative binomial model was fitted to the aphid density data using Proc GLIMMIX to account for overdispersion in both experimental years (Littell et al., 2006; Liu and Cela, 2008; O'Hara and Kotze, 2010). A binomial distribution and the logit link in Proc GLIMMIX were used for the analysis of the pest incidence data (Madden et al., 2002; Piepho, 1999). Due to the fact that aphid counting and the PAR measurements were made on non-equal time intervals, unequal repeated measure analysis was performed (Littell et al., 2006).

5.3 Results

5.3.1 Weeds

5.3.1.1 Weed ground coverage, weed biomass and weed-crop biomass relationship

The experimental factor crop stand had a significant effect on the weed ground coverage in both experimental years. The weed ground coverage was highest in James sole crops and least in triticale sole crops and did not differ significantly between EFB and James in either sole crops or in intercrops (Table 34). Intercropping winter peas and triticale tended to reduce the weed ground coverage in 2009/10 and resulted in significantly lower weed ground coverage values in 2010/11.

Also, the proportion of weeds in total aboveground biomass and the weed biomass in 2009/10 were significantly affected by the experimental factor crop stand. Additionally, the analysis of variance showed a significant sampling date × crop stand interaction for the weed biomass data in 2010/11. The proportion of weeds in total aboveground biomass was significantly greater in James sole crops than in the other examined crop stands in both experimental years (Table 34). James-triticale intercrops exhibited significantly lower proportions of weeds in total aboveground biomass than James sole crops. There were no significant differences between EFB sole crops, triticale sole crops and winter pea-triticale intercrops in 2009/10. Unlike in 2009/10, EFB sole cropping resulted in a significantly higher proportion of weeds in total aboveground biomass compared with triticale sole cropping and intercropping in 2010/11.

Table 34: Effect of crop stand on the weed infestation in 2009/10 and 2010/11

		Weed ground coverage (%)	Weed biomass in total aboveground biomass (%)	Weed biomass (g d.m. m^{-2})	
	Crop stand	April/May	June	June	July
2009/10	EFB SC	44.0 ± 2.4 ab	1.7 ± 0.6 b	7.4 ± 2.4 d	9.1 ± 3.7 c
	EFB-TR IC	33.4 ± 2.0 bc	1.0 ± 0.3 b	6.0 ± 1.7 d	6.0 ± 2.9 c
	James SC	53.4 ± 4.9 a	21.0 ± 3.2 a	96.4 ± 13.6 a	76.4 ± 19.6 a
	James-TR IC	43.6 ± 4.9 ab	8.4 ± 2.4 b	37.4 ± 11.8 b	32.0 ± 3.7 b
	Triticale SC	26.4 ± 2.4 c	4.2 ± 1.0 b	13.2 ± 2.7 c	24.4 ± 5.3 b
2010/11	EFB SC	16.6 ± 0.9 a	14.2 ± 2.5 b	85.9 ± 10.1 b	21.1 ± 9.6 b
	EFB-TR IC	7.4 ± 0.5 b	6.1 ± 1.0 c	47.4 ± 4.3 c	25.6 ± 3.2 b
	James SC	18.0 ± 1.4 a	39.2 ± 6.5 a	186.3 ± 21.2 a	202.3 ± 20.2 a
	James-TR IC	6.3 ± 0.5 b	4.9 ± 0.7 c	37.1 ± 5.3 c	34.5 ± 6.6 b
	Triticale SC	5.5 ± 0.3 b	6.9 ± 1.2 c	49.8 ± 10.0 c	23.8 ± 4.0 b

Values are means ± SEM. Means within each column and experimental year with different letters are significantly different ($P < 0.05$).

The significantly highest weed biomass accumulation was determined in James sole crops in both experimental years (Table 34, Fig. 10). The EFB sole and intercrops were found to have significantly lower weed biomass values than James and triticale sole as well as intercrops in 2009/10. Besides, there was no significant difference between EFB sole and EFB-triticale intercrops concerning the weed biomass accumulation at the first sampling as well at the second sampling in 2009/10, whereas James-triticale intercropping resulted in a significantly lower weed biomass accumulation compared with James sole cropping at both sampling dates in the same year.

The weed infestation in 2010/11 was higher than in the previous experimental year (Table 34, Fig. 10). EFB sole crops showed a significantly lower biomass accumulation than James sole crops in 2010/11 (Table 34). In contrast, no varietal difference was revealed in winter pea-triticale intercrops. Intercropping winter peas and triticale reduced the biomass accumulation at the first sampling date independent of the pea cultivar. At the second sampling date, however, a significant lower weed biomass accumulation in the intercrop than in the sole crop was solely present for cultivar James. The weed biomass accumulation in triticale sole crops was significantly lower than that in EFB sole crops at the first sampling date and comparable at the second sampling date. Moreover, no significant differences occurred between triticale sole crops and winter pea-triticale intercrops at both sampling dates in 2010/11.

Triticale was found to have a lower biomass accumulation at pea flowering in 2009/10 (Triticale SC: 335.8, EFB-TR IC: 123.5, James-TR IC: 184.4 g d.m. m^{-2}) than in 2010/11 (Triticale SC: 663.2, EFB-TR IC: 480.7, James-TR IC: 596.7 g d.m. m^{-2}). Therefore, the total crop biomass accumulation of triticale sole crops and winter pea-triticale intercrops was considerably lower than that in 2010/11. There was a relationship between crop and weed aboveground biomass accumulation at the June sampling date (Fig. 10). Weed aboveground biomass exponentially decreased as the crop aboveground biomass increased, most notably in the second experimental year.

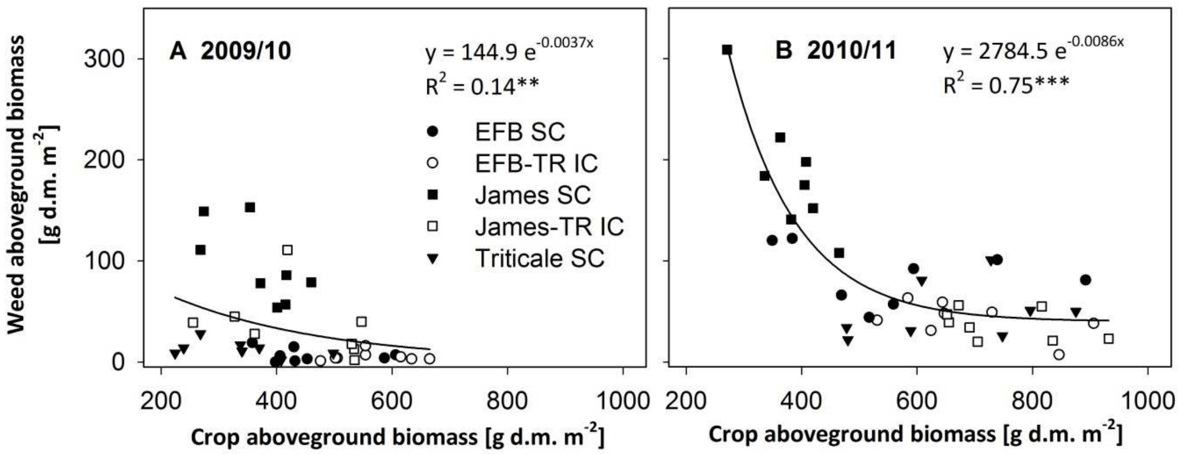

Fig. 10: Relationship between weed and crop aboveground biomass at the June sampling date in 2009/10 (A) and 2010/11 (B) independent of ploughing system. ** and *** indicate that exponential regression is significant at $P < 0.01$ and $P < 0.0001$.

There was neither a significant interaction comprising the experimental factor ploughing system nor a significant ploughing system main effect for weed infestation parameters. Weed ground coverage, proportion of weeds in total aboveground biomass and weed biomass accumulation after shallow and deep ploughing thus revealed comparable results (Table 35). Also, total crop aboveground biomass accumulation did not differ significantly between shallow and deep ploughing (data not shown).

Table 35: Effect of ploughing system on weed parameters in 2009/10 and 2010/11

	2009/10		2010/11	
	DP	SP	DP	SP
Weed ground coverage (%)	37.4 ± 3.0 a	43.0 ± 3.0 a	10.9 ± 1.3 a	10.3 ± 1.4 a
Weed biomass in total aboveground biomass (%)	6.5 ± 2.1 a	8.0 ± 2.0 a	15.0 ± 2.9 a	13.5 ± 4.1 a
Weed biomass (g d.m. m^{-2})	26.5 ± 5.4 a	35.1 ± 6.6 a	75.3 ± 11.2 a	67.9 ± 11.7 a
Weed biomass N content (%)	1.72 ± 0.08 a	1.63 ± 0.07 a	1.48 ± 0.06 b	1.68 ± 0.07 a
Weed biomass N removal (kg ha^{-1})	3.9 ± 0.8 a	5.0 ± 0.9 a	10.8 ± 1.6 a	10.4 ± 1.6 a
Weed biomass dry matter content (%)	27.4 ± 2.2 a	27.7 ± 2.0 a	22.8 ± 0.8 a	20.7 ± 0.7 b

Values are means of one rating/sampling date (weed ground coverage, weed biomass in total aboveground biomass) or two sampling dates (weed biomass, N content, N uptake and dry matter content) ± SEM. Means on the same line within the same experimental year with different letters are significantly different ($P < 0.05$).

5.3.1.2 Weed biomass N content and N uptake

The N content of the weed biomass was significantly affected by a crop stand main effect in 2009/10 and a sampling date × crop stand interaction in 2010/11. The highest weed N content was detected in EFB sole crops in both experimental years (Table 36). At the first sampling date in June, weeds in EFB-triticale intercrops were found to have significantly lower weed N contents than EFB sole crops, whereas no significant differences in weed N content occurred between EFB sole and intercrops at the July sampling date. Also, the weed biomass in James sole crops possessed a significantly lower N content than that in EFB sole crops. Unlike in 2009/10, the weed biomass N content in James sole and intercrops did differ significantly in 2010/11 with lower values in the intercrop at the June and higher values at the July sampling date. Triticale sole cropping resulted in a tendentially or significantly lower weed biomass N content than EFB sole or intercropping. No significant differences were found between triticale and James sole crops in 2009/10 or between triticale sole crops and James-triticale intercrops in both experimental years. The ploughing system did not affect the weed biomass N content in 2009/10, whereas significantly higher values were found after shallow ploughing in 2010/11 (Table 35).

Table 36: Effect of crop stand on weed biomass N content and N uptake at two sampling dates in 2009/10 and 2010/11

		Weed biomass			
		N content (% d.m.)		N uptake (kg ha^{-1})	
	Crop stand	June	July	June	July
2009/10	EFB SC	2.56 ± 0.09 a	1.82 ± 0.23 a	1.8 ± 0.6 cd	1.3 ± 0.4 b
	EFB-TR IC	1.95 ± 0.07 b	1.59 ± 0.13 ab	1.2 ± 0.3 d	0.9 ± 0.5 c
	James SC	1.65 ± 0.11 c	1.23 ± 0.09 b	15.0 ± 1.4 a	9.0 ± 2.1 a
	James-TR IC	1.54 ± 0.05 c	1.35 ± 0.08 b	5.7 ± 1.8 b	4.0 ± 0.4 a
	Triticale SC	1.73 ± 0.04 c	1.32 ± 0.07 b	2.3 ± 0.5 c	3.2 ± 0.7 ab
2010/11	EFB SC	2.33 ± 0.11 a	1.94 ± 0.06 a	19.5 ± 1.9 b	4.1 ± 1.9 b
	EFB-TR IC	1.51 ± 0.12 bc	1.94 ± 0.06 a	6.5 ± 1.1 c	4.9 ± 0.6 b
	James SC	1.63 ± 0.09 b	1.11 ± 0.06 c	29.7 ± 2.6 a	22.7 ± 2.9 a
	James-TR IC	1.30 ± 0.04 cd	1.40 ± 0.07 b	4.8 ± 0.7 c	4.8 ± 0.9 b
	Triticale SC	1.23 ± 0.10 d	1.37 ± 0.08 b	5.9 ± 1.1 c	3.2 ± 0.6 b

Values are means ± SEM. Means within each experimental year and column with different letters are significantly different ($P < 0.05$).

The statistical analysis of the weed N uptake in aboveground biomass revealed a significant crop stand main effect in 2009/10 and a significant sampling date × crop stand interaction in 2010/11. James sole crops showed the highest weed N uptake of all crop stands and significantly higher values than EFB sole crops in both experimental years (Table 36). Moreover, the weed N uptake was significantly higher in James-triticale intercrops than in EFB-triticale intercrops in 2009/10, whereas no significant differences were found between winter pea-triticale intercrops in 2010/11. Triticale sole crops took up an intermediate position between crop stands with James and those with EFB in 2009/10. In 2010/11, however, there were no significant differences between triticale sole and winter pea-triticale intercrops with regard to weed N uptake. The ploughing system had no effect on the weed N uptake in either experimental year (Table 35).

5.3.1.3 Weed biomass dry matter content

A sampling date × crop stand interaction and a crop stand main effect significantly affected the dry matter content of the weed biomass in 2009/10 and 2010/11, respectively. The dry matter content of the weed biomass did not differ significantly between winter pea sole and intercrops in 2009/10, whereas winter pea-triticale intercrops had significantly higher values than winter pea sole crops in 2010/11 (Table 36). Crop stands with James showed a higher weed biomass dry matter content than those with cultivar EFB. Furthermore, the weed biomass in triticale sole crops was comparable to the level in James-triticale intercrops except for the July sampling date in 2009/10. Neither a significant main effect nor an interaction containing the experimental factor ploughing system had an impact on the dry matter content in 2009/10. In contrast, deep ploughing resulted in a significantly higher weed biomass dry matter content than shallow ploughing in 2010/11 (Table 35).

Table 37: Effect of crop stand on weed biomass dry matter content at two sampling dates in 2009/10 and 2010/11

		Weed biomass dry matter content (%)	
	Crop stand	June	July
2009/10	EFB SC	10.9 ± 0.5 b	37.3 ± 3.7 ab
	EFB-TR IC	9.7 ± 1.7 b	31.7 ± 2.6 b
	James SC	23.2 ± 0.9 a	43.7 ± 2.1 a
	James-TR IC	22.6 ± 1.9 a	42.9 ± 1.1 a
	Triticale SC	22.1 ± 2.0 a	33.8 ± 2.1 b
2010/11	EFB SC	15.4 ± 0.5 c	14.6 ± 1.5 c
	EFB-TR IC	23.6 ± 1.1 ab	21.0 ± 0.6 b
	James SC	21.6 ± 0.5 b	19.9 ± 0.6 b
	James-TR IC	24.2 ± 1.0 a	26.6 ± 1.4 a
	Triticale SC	25.1 ± 1.2 a	25.7 ± 2.1 a

Values are means ± SEM. Means within each experimental year and column with different letters are significantly different ($P < 0.05$).

5.3.1.4 Transmission of incident photosynthetically active radiation to weed canopy level

The proportion of incident photosynthetically active radiation (PAR) transmitted to the weed canopy level was significantly affected by a measurement date × crop stand interaction in both experimental years and by a crop stand × ploughing system interaction in 2009/10. The PAR transmission to the weed canopy level was significantly higher with winter pea James than with EFB in sole as well as in intercrops throughout the complete period of measurement in 2009/10 (Fig. 11A). James sole crops were found to have significantly higher values than James-triticale intercrops until the end of flowering in James (BBCH 67, 17 May), but thereafter lower PAR transmission was measured in James sole crops. There was no significant difference between EFB sole and intercrops at the beginning of the PAR measurement in 2009/10. Subsequently, PAR transmission was significantly lower in EFB sole crops than in EFB intercrops. This trend continued until the end of May, respectively the inflorescence emergence (BBCH 51) in EFB. Thereafter, sole and intercropped EFB crop stands showed a comparable PAR transmission. The PAR transmission to the weed canopy in triticale sole crops was between the level of James and EFB crop stands until the middle of May. After the beginning of booting, triticale sole cropping resulted in the highest PAR transmission compared with all other examined crop stands.

The 2010/11 data deviate to a large extent from data gathered in the first experimental year. The PAR transmission was as well highest in James sole crops until the end of May (BBCH 65) and tendentially or significantly higher than in EFB sole crops at all measurement dates (Fig. 11B). Winter pea intercrops and triticale sole crops, however, did not differ significantly during the initial phase of measurement. Moreover, significantly lower PAR transmission was revealed in these three crop stands compared with the winter pea sole crops until the beginning of May. Thereafter, the course of the PAR transmission in intercrops paralleled the trend in triticale sole crops with EFB-triticale intercrops demonstrating the lowest and triticale sole crops the highest value. Contrary to the relatively continuous trend in winter pea sole crops, the PAR transmission in triticale sole and winter pea-triticale intercrops fluctuated all through June. At the same time, EFB sole cropping resulted in the lowest and James sole cropping mostly in the highest PAR transmission to the weed canopy level.

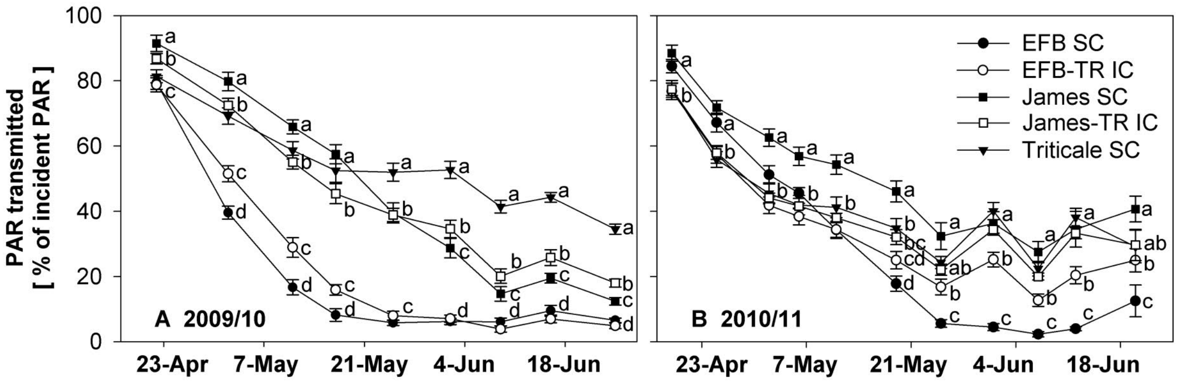

Fig. 11: Proportion of PAR transmitted to the weed canopy level in sole crops (SC) and intercrops (IC) of winter peas and triticale in 2009/10 (A) and 2010/11 (B) averaged over both ploughing systems. Values are means ± SEM (error bars). Different letters indicate significant differences ($P < 0.05$) between crop stands at the same measurement date.

The significant crop stand × ploughing system interaction in 2009/10 was caused by a significantly higher PAR transmission in triticale sole crops after shallow ploughing (52.7 %) than after deep ploughing (43.4 %). In contrast, the ploughing system had no effect on the PAR transmission in all other crop stands. In 2010/11, any effect comprising the experimental factor ploughing system significantly affected the PAR transmission to the weed canopy level.

5.3.2 Pests

5.3.2.1 Pea aphid density and incidence

In the first experimental year, pea aphids were observed on June 2 at the beginning of flowering in EFB (BBCH 60) and at flowering declining in James (BBCH 67). The number of pea aphids on sole and intercropped EFB increased until the declining of EFB flowering (BBCH 67), but thereafter decreased continuously (Fig. 12A). The proportion of infested EFB plants in sole and intercrops showed comparable trends to the pea aphid density data in EFB (Fig. 12E). The highest proportion of infested EFB plants was detected 26 days post infestation, analogous to the highest aphid density. Shortly after the detection of first aphids on EFB, the number of pea aphids and the proportion of infested plants were significantly lower when intercropping than sole cropping was performed. At the maximum infestation level, EFB sole crops were found to have 71 % aphid-infested plants with 21 aphids per shoot tip, whereas 8 aphids per shoot and 44 % infested plants were detected in EFB-triticale intercrops. James aphid infestation peaked 6 days post infestation in intercrops and 8 days after the detection of first aphids in sole crops at the end of flowering (BBCH 69) respectively the beginning of pod development (BBCH 71) (Fig. 12C, G). No further aphids were detected 22 days and 26 days post infestation in sole and intercropped James, respectively. Intercropping James and triticale significantly reduced the density and incidence of pea aphids compared with James sole crops. The maximum number of aphids per James shoot tip was by 6 aphids lower than in EFB sole crops, whereas no difference was found between the maximum density in intercropped EFB and James. Pea aphids were found on 80 % of sole cropped and on 65 % of intercropped James plants at the infestation peak, which was higher than with winter pea cultivar EFB.

Low aphid infestation levels were found in 2010/11, with a maximum number of 3 aphids per shoot tip in both pea cultivars 23 days post infestation at full flowering in EFB (BBCH 65) and the beginning of pod development in James (BBCH 72) (Fig. 12B, D). The pea aphid incidence fluctuated between 0 % and 26 % in EFB sole crops respectively 8 % in EFB intercrops (Fig. 12F). A similar range of values was found for James sole and intercrops (Fig. 12H). Aphid infestation period was simultaneous in both winter pea

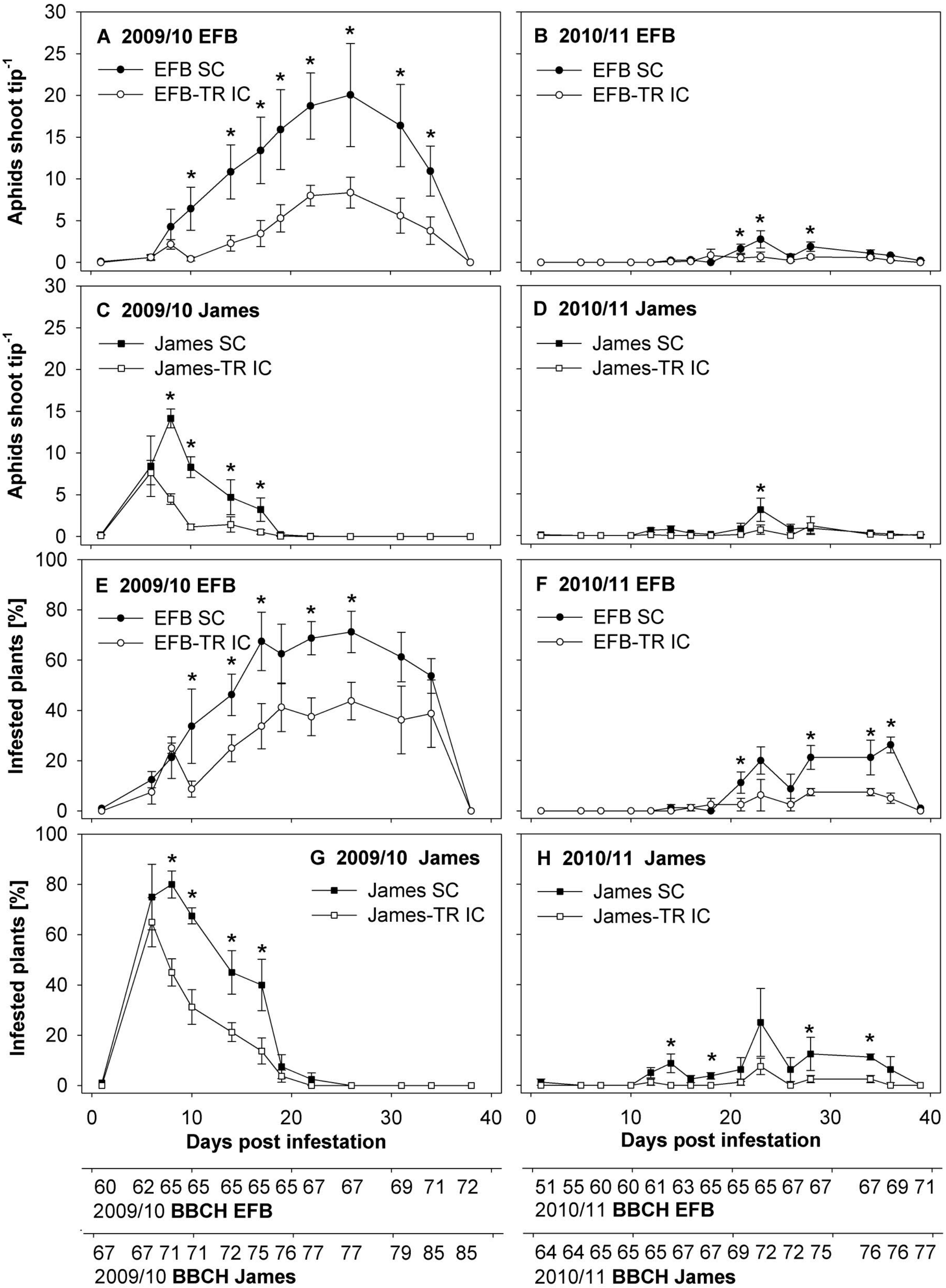

Fig. 12: Density (number of aphids per shoot tip, A-D) and incidence (proportion of infested pea plants, E-H) of pea aphids in 2009/10 (A, C, E, G) and 2010/11 (B, D, F, H) in sole and intercropped winter peas with the corresponding growth stages of James and EFB. First aphids were detected on June 2, 2010 and May 19, 2011. Values are means ± SEM (error bars). Asterisks indicate significant differences ($P < 0.05$) between sole and intercrops.

cultivars. Despite a low infestation level, there were significantly higher numbers of pea aphids per shoot tip and more infested plants in winter pea sole crops than in intercrops at most counting dates.

5.3.2.2 Cumulative aphid-days

Cumulative aphid-days were significantly higher in EFB sole crops and intercrops than in the corresponding James crop stands in 2009/10 (Table 38). In addition, intercropping winter peas and cereals significantly reduced cumulative aphid-days. Compared to the first experimental year, cumulative aphid-day values were considerably lower in 2010/11. The experimental factor crop stand did not significantly affect the values in the second experimental year. There was, however, the tendency of lower cumulative aphid-days in winter pea-triticale intercrops than in winter pea sole crops.

Table 38: Effect of crop stand on cumulative aphid-days in 2009/10 and 2010/11

	Cumulative aphid-days	
Crop stand	2009/10	2010/11
EFB SC	400 ± 79 a	29 ± 2 a
EFB-TR IC	139 ± 20 b	12 ± 4 a
James SC	128 ± 11 b	23 ± 9 a
James-TR IC	56 ± 3 c	11 ± 4 a

Values are means ± SEM. Means within each column with different letters are significantly different ($P < 0.05$).

5.3.2.3 Pea biomass N content

The pea biomass N content at the June biomass sampling was significantly higher in sole cropped than in intercropped winter peas in both experimental years, with the exception that sole cropped James solely tended to have higher values than intercropped James in 2010/11 (Table 39). There was no significant difference in pea biomass N content between winter pea cultivars in 2009/10, whereas sole and intercropped EFB were detected to have significantly higher values than the corresponding crop stands with James in 2010/11.

5.3.2.4 Pea moth larvae damaged peas

A significantly higher proportion of pea moth larvae-damaged winter peas was detected in winter pea cultivar EFB, sole or intercropped, than in cultivar James in both experimental years (Table 40). There was no difference in proportion of damaged peas between sole and intercrops in 2009/10. Intercropping winter peas and triticale in 2010/11, however, significantly increased the proportion of damaged peas. Furthermore, winter pea cultivar EFB showed comparable values in both experimental years, whereas James was found to have a considerably higher proportion of damaged peas in 2010/11.

Table 39: Effect of crop stand on pea biomass N content at the June biomass sampling in 2009/10 and 2010/11

	Pea biomass N content (%)	
Crop stand	2009/10	2010/11
EFB SC	3.00 ± 0.09 a	2.78 ± 0.04 a
EFB-TR IC	2.78 ± 0.07 b	2.60 ± 0.05 b
James SC	3.10 ± 0.04 a	2.51 ± 0.04 bc
James-TR IC	2.60 ± 0.04 b	2.39 ± 0.04 c

Values are means ± SEM. Means within each column with different letters are significantly different ($P < 0.05$).

Table 40: Effect of crop stand on the proportion of pea moth larvae-damaged peas

	Pea moth larvae damaged peas (%)	
Crop stand	2009/10	2010/11
EFB SC	32.3 ± 3.2 a	32.4 ± 1.1 b
EFB-TR IC	37.6 ± 2.3 a	37.4 ± 1.6 a
James SC	7.4 ± 1.7 b	18.2 ± 1.0 d
James-TR IC	4.3 ± 0.9 b	23.0 ± 1.2 c

Values are means ± SEM. Means within each column with different letters are significantly different ($P < 0.05$).

5.4 Discussion

5.4.1 Weed infestation

The weed infestation level differed considerably between both experimental years. Annual weeds covered a higher proportion of the soil in spring in the first experimental year compared with 2010/11 (Table 34). However, the weed biomass accumulation in 2010/11 mostly exceeded the level of the first experimental year. This may be due to differences in sowing date, weather conditions and in weed species composition at the experimental fields (Table 31, Table 32). *L. purpureum* and *S. media*, the most dominant weed species in 2009/10, were already well-developed and covered a large part of the soil before winter, whereas few scattered weeds were present at the 2010/11 experimental field before winter and in early spring. *L. purpureum*, however, began to senesce at the end of May, which resulted in high weed biomass dry matter content at the July sampling date (Table 37). Owing to the droughty conditions in spring 2011, weed growth and development was reduced until the onset of rainfall in the middle of May 2011, but increased considerably thereafter. This was most notable for the predominant weed species *G. aparine*, which resulted in severe weed problems. Thus, an early weed infestation, with a decrease towards maturity, was present at the experimental fields in 2009/10, whereas a late-season weed infestation dominated in the second experimental year.

Weed biomass accumulation and N uptake, as well as the proportion of weed biomass in total aboveground biomass, were significantly higher in James than in EFB sole crops (Table 34, Table 36, Fig. 10). The normal-leafed winter pea cultivar, thus, better suppressed weeds than the semi-leafless cultivar, which correlates well with the literature for spring and winter peas (Spies et al., 2011; Urbatzka, 2010; Urbatzka et al., 2011). EFB sole crops were found to have a lower PAR transmission to the weed canopy level than James sole crops (Fig. 11), which may be related to the higher biomass accumulation in EFB (Fig. 10). The better weed suppressive ability of the normal-leafed winter pea EFB may therefore be associated with lower light availability for weeds. The weed ground coverage at the end of April 2010, respectively the beginning of May 2011, however, did not differ significantly between semi-leafless winter pea cultivar James and normal-leafed cultivar EFB (Table 34). The PAR transmission to the weed canopy level in James sole crops marginally or significantly exceeded the level of EFB sole crops at the same time (Fig. 11). PAR transmission values, however, were at a high level in both winter pea sole crops, which may be responsible for the slight varietal difference with regard to weed ground coverage.

The high weed biomass production in James sole crops in the second experimental year (Table 34) was related to a complete crop stand overgrowth with *G. aparine*, which indicates a good soil nitrogen supply. This was due to the short plant height of James being within a range of 23 to 31 cm at flowering. The weed growth aggravation towards maturity may as well have contributed to the increase in weed biomass in James sole crops from the June to the July sampling date in 2010/11, which stands in contrast to all other crop stands. The tall growing cultivar EFB exhibited severe lodging after flowering in sole crops. However, weed overgrowth in lodged crop stands of sole cropped EFB was observable neither in 2009/10 nor in 2010/11 and the weed biomass accumulation remained at the same level (2009/10) or decreased between the June and the July sampling date (2010/11, Table 34).

Intercropping winter pea James and triticale as well as sole cropping triticale resulted in a significantly lower weed biomass accumulation, proportion of weed biomass in total aboveground biomass and weed N uptake than James sole cropping (Table 34, Table 36).

Moreover, James-triticale intercrops showed lower weed ground coverage values than James sole crops (Table 34). These results confirm the efficient weed suppressive ability of pea-cereal intercrops that has been shown in previous studies for intercrops of semi-leafless winter as well as spring peas and cereals (Begna et al., 2011; Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001; Urbatzka, 2010). Despite higher weed pressure towards maturity in 2010/11, resulting in higher weed biomass accumulation and N uptake in James sole crops compared to the first experimental year, values in James-triticale intercrops had a comparable level in both experimental years (Table 34, Table 36). This may be related to problems in winter triticale emergence, establishment and winter survival in 2009/10, which involved poor sole and intercropped triticale stands with only 30 % of the projected plant density and a by 49-74 % lower aboveground biomass accumulation than in 2010/11 (Fig. 10).

Corre-Hellou et al. (2011) suggested that the higher weed suppression in semi-leafless pea-barley intercrops compared to pea sole crops is mainly due to higher nitrogen competition in case of low soil N availability. The authors also found that high soil N availability contributes to an increase in crop leaf area. They concluded that weed suppression is under these conditions attributable to a strong light competition. Apart from the June biomass sampling in 2010/11, the weed biomass N content of James-triticale intercrops was comparable or significantly higher than in James sole crops (Table 36). In addition, triticale sole cropping resulted solely in a significantly lower weed biomass N content than James sole cropping at the first sampling date in 2010/11. Apart from that, comparable or significantly higher values were detected in the weed biomass from triticale sole crops. These results indicate that nitrogen competition does not sufficiently explain the high weed suppressive ability in James-triticale intercrops and triticale sole crops.

The PAR transmission to the weed canopy level was significantly higher in James sole crops than in James-triticale intercrops and triticale sole crops until the end of May, but did thereafter mostly not differ from or exceed the level of James sole crops (Fig. 11). Thus, in the case of the early weed pressure in 2009/10, the high weed suppressive ability of James-triticale intercrops and triticale sole crops may have predominately originated from a stronger light competition than in James sole crops. The non-significant difference in PAR transmission to the weed canopy level between James sole crops and James-triticale intercrops after the end of May in 2010/11 (Fig. 11B) demonstrates that shading cannot be responsible for the significantly lower late-season weed infestation in James-triticale intercrops in the second experimental year. The weed biomass dry matter content did not differ significantly between James sole crops and James-triticale intercrops at either the June or the July biomass sampling in 2009/10. In contrast to 2009/10, weed biomass in James-triticale intercrops was found to have significantly higher dry matter content than that of James sole crops in the second experimental year (Table 37). Our results suggest that the good weed suppressive ability of James-triticale intercrops was due to a higher water competition compared to James sole crops. This observation is in accordance with results of Mohler and Liebman (1987) for spring pea-barley intercrops. The presumably higher crop-weed competition for water in James-triticale intercrops than in James sole crops in 2010/11 may have resulted from the droughty conditions in spring 2011 (Table 31) inhibiting the biomass formation in James but not in triticale.

Despite the low triticale aboveground biomass accumulation in 2009/10, the weed infestation in EFB-triticale intercrops was comparable to the low weed infestation level in EFB sole crops and significantly lower than in the triticale sole crops (Table 34, Fig. 10A). Owing to the absent competition between winter peas and triticale in the intercrop, the crop biomass accumulation in EFB-triticale intercrops obtained the level of the biomass accumulation in EFB sole crops (Fig. 10A). For this reason, EFB-triticale intercrops paralleled the PAR transmission course of EFB sole crops on a higher level until the end of May, but thereafter reached the low level of EFB sole crops (Fig. 11A). The tendency of lower weed biomass values in the intercrop may therefore be explained by higher crop-weed nitrogen competition than in the sole crop, which resulted in a lower weed biomass N content (Table 36).

Intercropping EFB and triticale significantly reduced the annual weed infestation compared to EFB sole cropping at the June biomass sampling in 2010/11, whereas no significant differences were found at the July sampling date in the second experimental year (Table 34). The effective weed suppressive ability of EFB-triticale intercrops in June can be attributed, in part, to a significantly lower PAR transmission (Fig. 11B). In addition, the weed biomass N content was significantly lower and the dry matter content significantly higher in the EFB-triticale intercrop than in the EFB sole crop (Table 36). We might therefore suppose higher nitrogen and water competition in the intercrop to be important factors for the low weed biomass accumulation in EFB-triticale intercrops at the June sampling date, too. The PAR transmission in EFB sole crops showed a strong decreasing trend towards maturity resulting in a significantly lower PAR transmission level than in EFB-triticale intercrops after the middle of May (Fig. 11B). Moreover, the weed biomass nitrogen content was found to be identical in EFB sole and intercrops at the July biomass sampling date (Table 36). The similar weed biomass accumulation in EFB sole and EFB-triticale intercrops in July may thus be attributed to a change in PAR transmission and nitrogen availability in both crop stands.

Most studies suggest that a decrease in ploughing depth is correlated with an increase in annual, and in particular perennial, weed infestation (Børresen and Njøs, 1994; Brandsæter et al., 2011; Gruber and Claupein, 2009; Kouwenhoven et al., 2002; Pranaitis and Marcinkonis, 2005). Despite differences in weed composition and weed pressure at the experimental sites in 2009/10 and 2010/11, deep and shallow ploughing did not differ significantly in annual weed ground coverage, biomass accumulation and N uptake or in the proportion of weed biomass in total aboveground biomass in both experimental years (Table 35). Our data therefore differ from those reported by others. Interestingly the ploughing system neither affected crop stands with low weed suppressive ability, e.g. James sole crops nor crops stands possessing good weed suppression, as for instance EFB-triticale intercrops. Even the significantly higher PAR transmission in triticale sole crops in 2009/10 in consequence of a lower emergence and a higher winter kill rate of triticale after shallow ploughing did not influence the annual weed infestation. The weed biomass N and the dry matter content were affected by the ploughing system in 2010/11 but not in 2009/10 (Table 35). The significantly higher weed biomass N content and the significantly lower dry matter content after shallow ploughing in 2010/11 did not, however, occur coupled with an increase in weed biomass. These results indicate that a reduction of the ploughing system did not alter the germination environment or considerably change the nutrient and water availability for annual weeds.

5.4.2 Pea pests

5.4.2.1 Pea aphid infestation

The occurrence of pea aphids and the duration of the infestation were closely related to the pea flowering period. Flowering occurred earlier in James than in EFB, most notably in

2009/10 (Fig. 12). That is the reason why the aphid infestation of winter pea James began at James main flowering and peaked between the end of flowering and the beginning of pod development, whereas first aphids on EFB were observed at the beginning of EFB flowering and the maximum infestation level was found to be in the period between EFB main and declining flowering (Fig. 12). Owing to the late appearance of pea aphids in 2009/10, the infestation period was shorter in James than in EFB. The shorter infestation period coupled with a lower aphid density resulted in significantly lower cumulative aphid-days in sole cropped James than in sole cropped EFB (Table 38). These results indicate that early flowering winter peas will be damaged to a lesser extent than late-flowering winter peas. McVean et al. (1999) suggested as well that spring pea sowing time should be as early as possible to avoid the coincidence of flowering and high aphid occurrence. The comparable density and incidence of pea aphids as well as the non-significant difference in cumulative aphid-days between winter pea cultivars in 2010/11 (Table 38, Fig. 12) resulted from the low occurrence of pea aphids and the slightly later flowering date in James. Low aphid density and incidence in 2010/11 might be attributed to spring drought. Maiteki et al. (1986) also found low pea aphid densities under drought conditions in spring and early summer.

Peak aphid density was lower in sole cropped James than in sole cropped EFB, whereas the proportion of infested pea plants tended to be higher in James sole crops compared to EFB sole crops in 2009/10 (Fig. 12). Owing to the less available space on tendrils than on leaflets, the development of aphid colonies is more restricted on semi-leafless than on normal-leafed peas (Soroka and Mackay, 1990). As a consequence, James might have supported fewer pea aphids which involved a higher number of infested plants. The earlier decline of the aphid infestation in James sole crops in 2009/10 occurred in conjunction with an increase in air temperature. This observation is in accordance with other authors, who suggested that adverse environmental conditions affect pea aphids to a greater extent on semi-leafless or leafless peas than on normal-leafed peas (Buchman and Cuddington, 2009; Legrand and Barbosa, 2000; Soroka and Mackay, 1990).

In agreement with the findings of Seidenglanz et al. (2011) for spring peas, pea aphids appeared at the same time in winter pea sole and intercrops (Fig. 12). These data did not support the hypothesis that triticale acts as a barrier and prevents an aphid attack of intercropped winter pea cultivars with short plant height at flowering like James.

Intercropping, however, significantly reduced pea aphid density and incidence as well as cumulative aphid-days most notably with the high infestation level in 2009/10 (Fig. 12, Table 38). Similar results have been demonstrated by Bedoussac (2009) for semi-leafless winter pea-durum wheat intercrops.

Patriquin et al. (1988) compared the number of *Aphis fabae* in faba bean (*Vicia faba* L.) sole crops and faba bean-cereal intercrops under organic conditions. They found that the aphid density and the leaf N content were significantly higher in sole crops than in intercrops. The authors concluded that colonisation as well as reproduction of aphids may be reduced by the nitrogen competition in intercrops. We found mostly significantly lower biomass N contents in intercropped winter peas during the infestation period with pea aphids (Table 39), which confirms these previous observations in faba bean-cereal intercrops. Thus, the lower pea aphid infestation in winter pea-triticale intercrops might be attributed to a lower nitrogen status in intercropped winter peas. Previous studies, however, have reported contradictory findings pertaining to the effect of pea nitrogen supply on the pea aphid reproduction under greenhouse conditions. Moravvej and Hatefi (2008) showed that the aphid reproduction increased with increasing nitrogen content in pea leaves, whereas Buchman and Cuddington (2009) did not find a relationship between pea nitrogen supply and aphid reproduction. Another possible explanation for the differing aphid infestation in sole and intercropped winter peas could be a difference in aphid feeding behaviour due to a variation in plant nitrogen status. Ponder et al. (2000) found that aphids took longer to reach the phloem sap and showed a shorter feeding period on barley under nitrogen limited than under non-nitrogen limited conditions.

Aphid density and incidence was found to decrease earlier in James-triticale intercrops than in James sole crops in 2009/10 (Fig. 12C, G). This observation is in accordance with Seidenglanz et al. (2011), who reported that aphid colonies decreased earlier in semi-leafless spring pea-cereal intercrops than in pea sole crops. The authors concluded that an earlier occurrence and a higher number of predators may be responsible for this earlier decline. A considerable decrease in pea yield performance is ascribable to aphid feeding injuries on flowers and pods (Maiteki and Lamb, 1985). An earlier decline in pea aphid colonies at the end of pea flowering can thus be assumed to prevent yield losses in peas. In contrast to the findings for the semi-leafless cultivar James, a simultaneous decline of pea aphids was observed in EFB-triticale intercrops and EFB sole crops (Fig. 12A, E). This fact might be attributed to the more open canopy in the semi-leafless winter pea cultivar James, which offers less protection from predators.

5.4.2.2 Pea moth infestation

The pea moth infestation level is dependent on weather conditions and the coincidence between pea moth flying period and susceptible plant growth stages (Huusela-Veistola and Jauhiainen, 2006). Thöming and Saucke (2012) reported that mated pea moth females prefer the flowering and the late bud stage in pea. Previous studies have indicated that the cultivation of early flowering and maturing peas avoids or reduces this temporal coincidence and therefore the risk of a high pea moth infestation (Schultz and Saucke, 2005; Thöming et al., 2011; van Emden and Service, 2004). The proportion of pea moth damaged peas was significantly higher for winter pea cultivar EFB than for James, independent of the crop stand (Table 40). This fact might be attributed to the earlier time of flowering and maturity in James than in EFB. The flowering stage in EFB started at the end of May in both experimental years, whereas flowering in James was delayed by two weeks in 2010/11. This explains the similar infestation levels in EFB in both experimental years and the higher pea moth damages of cultivar James in 2010/11.

Intercropping winter peas and triticale had no effect on the pea moth damage level in 2009/10 (Table 40). On the contrary, both winter pea-triticale intercrops were found to have a significantly higher proportion of damaged peas than the corresponding sole crops. We might suppose the differing actual intercropping composition with a pea dominated intercrop in the first and a triticale dominated intercrop in the second experimental year to be responsible for this difference. Our results are consistent with Wnuk (1998), who found no beneficial effect of intercropping spring peas and phacelia (*Phacelia tanacetifolia* Benth.) or white mustard (*Sinapis alba* L.) with regard to pea moth damages on pods.

5.5 Conclusions

Intercropping normal-leafed or semi-leafless winter peas and triticale shows great promise in reducing an infestation with annual weeds and pea aphids. A decrease in pea moth damages could, however, not be achieved by intercropping winter peas and triticale. The weed suppressive ability was significantly higher with normal-leafed winter pea EFB than with semi-leafless cultivar James. Pea pest occurrence and infestation levels were highly dependent on pea flowering time. As a result, the early flowering winter pea cv. James had a distinct advantage over the later-flowering winter pea cv. EFB. Future studies are needed to separate the flowering time from the leaf type effect with regard to a pea aphid infestation. Moreover, it is necessary to evaluate the relationship between pea nitrogen status, phloem sap concentration as well as composition and pea aphid infestation in sole and intercropped peas under field conditions. The ploughing system did not affect the annual weed infestation either in sole or in intercrops. On the basis of these results, we conclude that shallow and deep ploughing are therefore both feasible in the cultivation of organic winter pea and triticale sole or intercrops with respect to annual weeds. Whole crop rotations will have to be examined in order to define the long-term effect of a reduction in ploughing depth with regard to an infestation with annual and perennial weeds.

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6 General Discussion

Recent developments in grain legume cultivation, as well as the necessity to maintain soil fertility, to provide sufficient animal feed and to decrease the environmental impact of agriculture, have heightened the need for improvements in domestic grain legume yield performance, stability and quality as well as for an adoption of reduced tillage systems in organic farming. Against this background, experiments were performed to determine and assess the effects of pea crop stand (sole vs. intercropping spring or winter peas and cereals) and ploughing system (deep vs. short-term shallow ploughing) on annual weed infestation, winter survival, lodging resistance, crop biomass, yield performance and grain quality in a stockless organic farming system. Another purpose of this work was to investigate the effect of mechanical soil loading on the performance of spring pea and oat sole or intercrops after deep and shallow ploughing. Of additional concern has been the impact of intercropping winter peas and triticale on pea pests.

6.1 Annual weed infestation

The first and second objectives of this thesis were to assess the effects of sole vs. intercropping and of shallow vs. deep ploughing on the annual weed infestation in semi-leafless or normal-leafed spring or winter pea cultivation and to identify the factors accounting for the differing weed infestation in pea sole crops, pea-cereal intercrops and cereal sole crops. In agreement with the findings in previous studies for spring as well as for winter peas (Harker et al., 2008; Spies et al., 2011; Urbatzka, 2010), normal-leafed winter peas were observed to have a better weed suppression than semi-leafless winter peas, which was attributable to a lower PAR transmission to the weed canopy level in normal-leafed pea crop stands (Chapter 5). Owing to this good weed suppression, the weed infestation in normal-leafed winter pea sole crops did mostly not differ from that in normal-leafed winter pea-triticale intercrops. Semi-leafless spring and winter pea-cereal intercrops, however, suppressed weeds to a greater extent than sole cropped semi-leafless peas (Chapter 2, 3, 5). These findings are concordant with those of previous studies (Begna et al., 2011; Corre-Hellou et al., 2011; Hauggaard-Nielsen et al., 2001) and corroborate the good weed suppressive ability of pea-cereal intercrops. There is evidence to indicate that a below-ground crop-weed interaction involving nitrogen and water competition as well as oat root exudation of weed suppressing allelochemicals are key factors for the good weed suppressive ability of pea-oat intercrops (Chapter 3).

It has been stated that short- and long-term shallow ploughing increases the perennial (Børresen and Njøs, 1994; Brandsæter et al., 2011; Håkansson et al., 1998) as well as the annual weed infestation (Gruber and Claupein, 2009; Herzog and Bosse, 1976). The results of this research deviate to some extent from these earlier findings. The effect of the ploughing system on the weed infestation was found to be site-specific. Moreover, the weed infestation after shallow and deep ploughing in spring-sown crops differed from that in winter-sown crops at the Trenthorst site (Chapter 2, 3, 5). Shallow ploughing caused a higher annual weed infestation in most spring-sown crops at the Trenthorst site, whereas the effect of ploughing system on the weed infestation at the Köllitsch site highly depended on the crop stand (Chapter 2). These site specific differences may be related to the differing weed species composition at the experimental sites. Unlike in the spring pea intercropping experiment (Chapter 2), the annual weed infestation in semi-leafless and normal-leafed winter pea and triticale sole or intercrops did not differ significantly between shallow and deep ploughing at the Trenthorst site (Chapter 5). Primary tillage was performed simultaneously at the experimental sites with spring and winter-sown crops in Trenthorst. Moreover, there was a considerable overlap of the most dominant weed species at the experimental fields. The differing point in time of secondary tillage, however, may, in part, explain this difference. Consequently, shallow ploughing does not generally result in an increase in weed infestation even in weak weed competitive crops such as semi-leafless peas.

The third objective of this thesis was to answer the questions whether pea sole cropping after shallow ploughing results in higher weed infestation than pea sole cropping after deep ploughing and whether intercropping peas and cereals is able to compensate for this higher weed infestation after shallow ploughing. The results of the 2009 Köllitsch experiment prove in part this hypothesis, but solely the 2010 Köllitsch data provide complete support for the hypothesis that pea sole cropping after shallow ploughing would result in a significantly higher weed infestation than pea sole cropping after deep ploughing, whereas intercropping peas and cereals would involve a comparable weed infestation independent of the ploughing system but on a lower level than in pea sole crops (Chapter 2). Apart from that, pea-cereal intercrops reduced the weed infestation in shallow and deep ploughed fields to the same degree, resulting in a significantly higher weed infestation in intercrops after shallow ploughing. The answer to be given to the third objective must therefore be that the cultivation of peas with a cereal partner provides advantages pertaining to annual weed control after shallow ploughing, even though the weed control effect is dependent on site-specific factors, e.g. weed species composition or weed pressure.

6.2 Pea pests

The fourth objective of this thesis was to find out whether and how intercropping winter peas and triticale reduces pea pest problems. The results show that winter pea-triticale intercropping reduces an infestation with pea aphids (Chapter 5), which is consistent with the findings of Bedoussac (2009) for winter pea-durum wheat intercrops. The presence of the cereal partner, however, did not delay the occurrence of aphids on intercropped peas; hence, cereals do not necessarily act as a barrier against an infestation with pea aphids. The data, however, suggest that intercropped winter peas were less attractive to colonizing aphids due to a lower nitrogen content in the biomass and thus a differing phloem sap composition. Semi-leafless winter pea cultivar James showed an earlier decline of the number of pea aphids and the proportion of infested plants in the first experimental year. This result is in keeping with a previous study, which reported that an earlier occurrence and a higher number of predators may be responsible for the earlier decline of pea aphid colonies in semi-leafless spring pea-cereal intercrops (Seidenglanz et al., 2011). In contrast to pea aphids, the results do not confirm the efficacy of winter pea-triticale intercropping for a reduction of an infestation with pea moths (Chapter 5).

Provided that the pea aphid infestation was severe, the early flowering, semi-leafless winter pea cultivar James showed a lower peak aphid number and a shorter infestation period compared to the later flowering, normal-leafed winter pea cultivar EFB (Chapter 5). Moreover, pea moth larvae-related damages on peas were also observed to be significantly lower in the winter pea cultivar with the advanced flowering and harvest date. The lower infestation with important pea pests in winter pea cultivar James can be assumed to indicate that earlier pea flowering and maturity provide advantages with regard to a reduction in pea pest infestation. These findings provide support for the assumption that earliness in pea development reduces the temporal coincidence between pest occurrence and susceptible plant growth stages, finally resulting in less damage (McVean et al., 1999;

Schultz and Saucke, 2005; Thöming et al., 2011; van Emden and Service, 2004). Owing to the earlier flowering date and time of maturity, a cultivation of winter peas may therefore offer benefits concerning pea pest infestation compared to spring peas. The effect of leaf type on an infestation with pea pests, e.g. aphids, remained unclear.

6.3 Winter survival and lodging resistance

The fifth objective of this thesis was to determine whether intercropping winter peas of differing leaf type and triticale can lower crop winter losses and improve winter pea lodging resistance in different ploughing systems. The data did not confirm the efficacy of intercropping for a reduction in winter losses of winter peas (Chapter 4). The cereal partner did thus not sufficiently protect peas from frost. Murray et al. (1985) have shown that intercropping winter peas and cereals increases the winter survival of the cereal partner. In contrast to these earlier findings, no beneficial effect of intercropping on triticale winter survival was observed in the present experiments. Winter-kill rates of normal-leafed winter pea cv. EFB were significantly lower than those of semi-leafless winter pea cv. James and similar to those of triticale in 2009/10. A difference in plant development at the onset of winter in the first experimental year with EFB being less developed than James, may be a possible explanation for the differing winter survival rates of the examined winter pea cultivars in 2009/10. These results show as well that winter peas were not generally more frost sensitive than cereals. The comparable winter survival of sole and intercropped EFB and James in 2010/11 is presumably closely related to an identical pre-winter development. Despite comparable environmental conditions during winter, James winter-kill rates in 2009/10 were considerably higher than in 2010/11. Unlike in the second experimental year, James showed 6-7 tendrils at the onset of winter in 2009/10. The semi-leafless cultivar thus already exceeded the recommended developmental stage of 5-6 tendrils before winter (Urbatzka et al., 2012), suggesting that James was highly frost sensitive due to an advanced pre-winter development in 2009/10. The weather-related delay of sowing by one month in the second experimental year was responsible for the differences in pre-winter development between both experimental years. The ploughing system did not affect winter survival in winter peas. Thus, overwintering conditions for winter peas were identical in deep and shallow ploughed fields.

Regardless of the ploughing system, normal-leafed winter pea cultivar EFB exhibited severe lodging after flowering as opposed to semi-leafless cultivar James facilitating weed overgrowth, delaying harvest due to a slower canopy drying, exacerbating harvest operations with the risk of yield losses (Chapter 4). As a consequence, sole cropping of normal-leafed winter peas cannot be recommended. Intercropping normal-leafed winter peas and triticale increased the lodging resistance, which is concordant with data for normal-leafed winter pea-cereal intercrops of previous studies (Murray and Swensen, 1985; Urbatzka et al., 2011).

6.4 Crop biomass and yield performance

The sixth objective of this thesis was to evaluate the effects of sole vs. intercropping peas and cereals and of deep vs. shallow ploughing on biomass accumulation and yield performance of component crops and succeeding winter wheat. Intercropping spring or winter peas and cereals resulted, provided that no cereal biomass and yield formation problems appeared, in higher total biomass accumulation and total grain yields compared to pea sole crops (Chapter 2, 4). Nevertheless, biomass accumulation and yield performance of intercropped peas was lower than that of sole cropped spring peas or rather lower than the value expected on the basis of winter pea sole crops. This was most notable with semi-leafless peas and under environmental conditions providing better growth conditions for the cereal partner than for spring or winter peas. These results compare favourably with those reported in the literature (Kontturi et al., 2011; Neumann et al., 2007). The data suggest that normal-leafed winter peas compete better with cereal partners and were partly able to better exploit their yield potential in intercrops with triticale than in sole crops.

The obtained pea yields, particularly those of the examined semi-leafless cultivars, were relatively low. This might have been a result of the intentionally chosen crop rotation pattern ignoring the recommendations of a five to six year interval between pea crops. Spring pea sole crops were the pre-preceding crops in the spring and winter pea intercropping experiments. A short interval between pea crops or a continuous pea production has been shown to reduce soil microbial quality, increase fusarium root rot and thus decrease pea yield performance (Nayyar et al., 2009).

The winter wheat yield performance did not differ significantly between winter pea sole crops and winter pea-triticale intercrops as preceding crops in the first experimental year, whereas sole cropping winter peas in 2010/11 resulted in significantly higher winter wheat yields than intercropping winter peas and cereals (Chapter 4). This may be related to the differing intercrop composition with winter pea dominated intercrops in 2009/10 and triticale dominated intercrops in 2010/11, which was due to problems with triticale field emergence and winter survival in 2009/10 and spring drought impairing the competitive ability of peas against the companion crop triticale in 2010/11. Sole and intercrops of normal-leafed winter pea cultivar EFB left higher amounts of mineralised N in the soil after harvest and were observed to have a better preceding crop effect than the corresponding sole and intercrops of semi-leafless cultivar James.

Crop biomass accumulation was comparable between ploughing systems in winter pea and triticale sole or intercrops (Chapter 4). Moreover, short-term shallow ploughing did not negatively affect the yield performance of sole and intercropped spring or winter peas (Chapter 2, 4). The higher weed infestation in spring pea sole crops after shallow ploughing was thus not associated with a decrease in biomass accumulation or yield performance. The findings of the experiments presented are in contrast to other published data demonstrating significantly lower pea grain yields after short-term shallow ploughing, when compared with deep ploughing (Baigys et al., 2006; Pranaitis and Marcinkonis, 2005). In addition, total grain yields in pea-cereal intercrops did not differ significantly between shallow and deep ploughing (Chapter 2, 4). Two years of different ploughing practice did not influence yield performance of winter wheat in 2010/11 following the first winter pea experiment, whereas winter wheat yields in 2011/12 were significantly lower in shallow ploughed plots and this irrespective of whether winter pea and triticale sole or intercrops were grown as preceding crops (Chapter 4). This yield decline may be related to spring drought in 2012, which may have restricted yield formation in shallow ploughed plots to a higher extent than in deep ploughed plots. The reasons for this decrease after shallow ploughing in the second succeeding crop experiment, however, are not made clear by this thesis and future experiments will have to show the impact of water supply on yield performance in different ploughing systems.

The seventh objective of this thesis was to assess the effects of mechanical soil loading during seedbed preparation or sowing and its interaction with different ploughing systems on yield performance of spring pea and oat sole or intercrops. Despite some bearing on physical soil parameters, mechanical soil loading simulating traffic-induced compaction during seedbed or sowing operations did not contribute to a decrease in yield performance in either sole crops or in pea-oat intercrops in 2009 (Chapter 2). Dry soil conditions during mechanical soil loading implementation, in particular at site Köllitsch, and the low precipitation rate in the 2009 growing season, may have contributed to the fact that mechanical soil loading had no effect on the crop performance in 2009. Sole and intercropped peas reacted negatively to the mechanical soil loading in 2010 resulting in a significant decrease in pea yield performance. Intercropping did thus not mitigate negative effects of mechanical soil loading on the pea yield performance. In contrast, mechanical soil loading did not influence oat yield performance in 2010. These findings provide support for the assumption that legumes are notably sensitive to compacted soils and more sensitive to poor soil structure than cereals (Batey, 2009; Jayasundara et al., 1998). The 2010 experiments at both sites provide support for the hypothesis that the degree to which mechanical soil loading decreases yield performance is related to the ploughing system. Mechanical soil loading after deep ploughing significantly reduced total grain yields, whereas no significant differences were present after shallow ploughing (Chapter 2). The fact that the yield performance in shallow ploughed plots was less affected by a mechanical soil loading than in deep ploughed plots may be related to the higher soil strength in the untilled soil layer after shallow ploughing. These results indicate that a reduction in ploughing depth increases the soil load bearing capability and thus reduces the risk for a subsoil compaction and yield decreases. Previous studies comparing the effect of mechanical soil loading after deep ploughing and after shallow ploughing or other reduced tillage systems in organic or conventional farming have reported similar results (Bakken et al., 2009; Herzog and Bosse, 1976; Wiermann et al., 2000; Yavuzcan et al., 2005).

6.5 Grain quality and energetic feed value

The eighth objective was to analyse the effects of crop stand, winter pea flower colour, ploughing system, mechanical soil loading and their interactions on grain quality and energetic feed value of peas and cereals. The crude protein content was generally found to be comparable in sole and in intercropped spring peas, whereas intercropped oats showed remarkably higher crude protein contents compared to oat sole crops (Chapter 2). The presence of the legume pea and the lower cereal plant density in the intercrop thus allowed intercropped oats greater availability for soil N. These results correlate well with the literature (Hauggaard-Nielsen et al., 2001; Hauggaard-Nielsen et al., 2008; Lauk and Lauk, 2008; Neumann et al., 2007). As a result, protein yields of pea-oat intercrops were comparable or greater than those of pea sole crops, dependent on oat yield performance (Chapter 2). Intercropped spring peas, however, showed considerably lower protein yields than spring pea sole crops due to lower grain yield performance. In addition, in the majority of cases, the energetic feed value of winter and spring peas did not differ significantly between sole and intercropped peas (Chapter 2, 4). The significantly lower Metabolisable Energy content of intercropped spring peas at Trenthorst in 2010 or the higher content in intercropped EFB in 2010 compared to the respective sole crops is believed to be a result of a significantly lower, respectively higher, crude protein content. Despite higher crude protein contents, significantly higher energetic feed value of intercropped oats was only found at Trenthorst. The determination of the Metabolisable Energy output revealed higher values for winter pea-triticale intercrops compared to winter pea sole crops (Chapter 4). A better yield performance of James-triticale intercrops and accordingly higher Metabolisable Energy contents coupled with better grain yields in the case of EFB-triticale intercrops can be held responsible for the better total Metabolisable Energy output of winter pea-triticale intercrops.

Grain chemical composition and energetic feed value differed significantly between semi-leafless, white-flowered and normal leafed, coloured-flowered winter peas. Grains of the coloured-flowered winter pea cultivar EFB were richer in crude protein but lower in starch, crude fat and sugars compared to the white-flowered winter pea cultivar James (Chapter 4). Moreover, coloured-flowered winter pea sole crops and intercrops contained more phosphorus, potassium and magnesium than white-flowered winter pea cultivar James and triticale sole or intercrops. EFB sole and intercrops showed a lower Metabolisable Energy content than the corresponding sole and intercrops with James and the triticale sole crops. The Metabolisable Energy content of the semi-leafless, white-flowered spring pea was also higher than that of the coloured-flowered winter pea. These results are concordant with those of previous studies (Canbolat et al., 2007; Grosjean et al., 1998; Hlödversson, 1987; Bastianelli et al., 1998). The lower energetic feed value of coloured-flowered peas, e.g. EFB, can be ascribed to their higher fibre content, which is partly explained by their smaller seed size (Bastianelli et al., 1998). Besides, EFB and other coloured-flowered winter peas have been shown to contain higher amounts of condensed tannins and trypsin inhibitors than white-flowered peas (Urbatzka et al., 2011). The digestibility of crude protein and organic matter in monogastrics is reduced due to high fibre content and the presence of secondary metabolites in coloured-flowered peas (Gdala et al., 1992; Grosjean et al., 1998; Abrahamsson et al., 1993). Moreover, Canbolat et al. (2007) suggested the higher tannin content in coloured-flowered peas to be responsible for a significantly lower gas production indicating lower rumen fermentation compared to white-flowered peas. Thus, in order to prevent negative effects on feed conversion and animal performance, the use of unprocessed coloured-flowered peas is limited particularly with regard to monogastrics. Dehulling of coloured-flowered peas, however, increases the energetic feed value due to a reduction in fibre and tannin content (Perrot, 1995).

Only minor effects of the ploughing system were found on the grain chemical composition, the macronutrient content and the Metabolisable Energy content (Chapter 2, 4). This observation is in accordance with Bakken et al. (2009), who reported that the grain protein content of organic cereals did not generally differ between short-term shallow ploughed and deep ploughed fields. Shallow ploughing, however, resulted in a significantly lower crude fat content in winter peas as well as a lower grain sugar content in sole and intercrops of winter pea and triticale independent of the experimental year. Protein yields and the Metabolisable Energy output did not vary between ploughing systems, with the exception of higher protein yields in spring pea-oat intercrops and oat sole crops after shallow ploughing in consequence of a higher oat yield performance.

A clearly negative impact of the mechanical soil loading on the grain chemical composition or the energetic feed value was revealed solely for the pea crude protein content at Köllitsch in 2010. In agreement with the results of the yield performance in 2010, sole and intercropped pea protein yields, total protein yields and the pea protein content significantly decreased with an increase in mechanical soil loading after deep ploughing, whereas no significant differences were revealed after shallow ploughing. In conclusion, a significant decrease in pea grain quality due to current mechanical soil loading intensities during sowing operations could be avoided by a reduction of the ploughing depth under organic farming conditions.

6.6 Conclusions and future perspectives

This thesis shows benefits and limitations of intercropping spring or winter peas and cereals. Intercropping peas and cereals resulted in a good weed suppressive ability, a lower pea aphid infestation, an increase in lodging resistance, and had advantages concerning grain yield performance and quality. However, the present results show as well a remarkable variability in the performance of pea-cereal intercrops, which stems from competition effects between peas and cereal partners. This variability is at the same time an advantage (compensation of crop failure) as well as a disadvantage (unsteady grain yield composition and quality as well as residual nitrogen effects on the succeeding crop). Given the variability of intercrops, there is the necessity to combine cultivars that are highly adapted. Despite a selection of agronomically suited pea and cereal cultivars, the development and performance of peas often differ in sole and intercrops; hence, cultivars bred under sole crop conditions are not necessarily well adapted for the use in intercropping systems. It is thus necessary that advanced breeding lines are selected both under sole crop conditions and in intercrop environments. A special breeding program for intercropping systems, however, is not realistic. From the results of the winter pea-triticale intercropping experiments, it can be concluded that a lower triticale sowing density in the intercrop might provide advantages concerning a reduction in interspecific competition with semi-leafless winter peas. Intensive research is needed to improve mixtures of semi-leafless or normal-leafed winter peas and cereals or other companion crops in intercropping systems.

A short-term reduction in ploughing depth had only minor, non-uniform effects on the agronomic performance of spring or winter pea and cereal sole or intercrops and the succeeding crop. The effect of the ploughing system on the annual weed infestation was inconsistent as well, showing higher or similar values compared to deep ploughing. Yet, intercropping spring peas and oats has been shown to compensate for a higher annual weed infestation after shallow ploughing at one of the two experimental sites. Crops were partly less affected by a mechanical soil loading in shallow than in deep ploughed fields due to a higher bearing capability. Consequently, a cultivation of semi-leafless or normal-leafed spring and winter peas after short-term shallow ploughing seems to be possible under organic farming conditions without high perennial weed infestation. Intercropping peas and cereals, however, may be of particular suitability for the cultivation of peas in reduced tilled soils, e.g. due to a good annual weed suppressive ability. One problem inherent in a study of this kind is the effect of tillage on perennial weeds. A next step would therefore be to include perennial weeds in the investigation of ploughing system effects. Only long-term experiments may ultimately answer the question about the utility of reduced ploughing depth in organic farming systems particularly with regard to nitrogen availability and weed infestation.

Climate-change models predict a decrease in precipitation and soil moisture coupled with an increase in air temperature for the June-August period in Central Europe (Rowell and Jones, 2006). For this reason, the cultivation of peas with an early flowering time and maturity, such as winter peas, could provide agronomic benefits. The normal-leafed, coloured-flowered winter pea cultivar EFB has been shown to have a good winter survival as well as a better yield performance and weed suppressive ability than the examined semi-leafless winter pea cultivar James. Nonetheless, the energetic feed value of the coloured-flowered winter pea cultivar was limited due to a high crude fibre content and presumably the presence of secondary plant compounds. Early flowering and maturing winter peas seemed to have an advantage over winter peas with a late flowering time and maturity concerning a reduction in important pea pests. Thus, important future breeding aims should be a reduction in seed coat percentage and a selection of cultivars with low secondary plant compound content to improve the feed value of coloured-flowered winter peas. In addition, an advance in flowering and harvest date could help to reduce an infestation with important pea pests. Also, the effect of pea leaf type, flowering date and their interactions on an infestation with pea pests is poorly understood and has to be studied in detail. Pea sowing date is a key issue for winter survival and yield performance in winter peas. Knowledge about cold acclimation in winter peas is limited and further improvements in winter survival are needed; hence future studies will be necessary to determine the environmental conditions for an efficient cold acclimation in winter peas and pea plant developmental stages that allow for a good winter survival and consequently optimal sowing dates in different environments.

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Summary

The present work aimed at evaluating the intercropping of spring or winter peas and cereals as well as at determining the suitability of shallow ploughing in organic pea cultivation with regard to annual weed infestation, winter losses, lodging resistance, biomass accumulation, yield performance, grain chemical composition and energetic feed value. Another intent of this work was to investigate the impact of mechanical soil loading during seedbed preparation or sowing in deep (mouldboard plough, 25-30 cm) and shallow ploughed (skim plough, 7-12 cm) soils on yield performance and grain quality of spring pea and oat sole or intercrops. Of additional concern has been the impact of intercropping winter peas and triticale on pea pest infestation.

For these purposes, four-factorial field experiments with the factors crop stand (spring pea and oat sole or intercropping), ploughing system (deep and shallow ploughing), mechanical soil loading (0, 26, 45 kN rear wheel load) and site (Köllitsch, Eastern Germany and Trenthorst, Northern Germany) were conducted in 2009 and 2010. The intercropping of the winter pea cultivars E.F.B. 33 (shortened EFB, normal-leafed, coloured-flowered) and James (semi-leafless, white-flowered) after shallow and deep ploughing was examined in field experiments at Trenthorst in 2009/10 and 2010/11. The winter pea intercropping experiments were followed by winter wheat (2010/11, 2011/12) to test the previous crop effect. A pot experiment and a bioassay were conducted complementary to the spring pea intercropping experiments to determine causes of a possibly differing weed suppressive ability in pea and oat sole or intercrops.

〉 The weed infestation strongly depended on pea leaf type, with semi-leafless pea crop stands being more infested than those of normal-leafed peas. Semi-leafless spring and winter pea-cereal intercrops suppressed weeds to a greater extent than sole cropped semi-leafless peas, whereas the weed infestation in normal-leafed winter pea sole and intercrops did not, in general, differ significantly. Results of the field and pot experiments, as well as of the bioassay, indicate that a stronger below-ground crop-weed interaction involving nitrogen or water competition and oat root exudation of weed suppressing allelochemicals are possible causes of a better weed suppression in pea-oat intercrops than in pea sole crops. The effect of the ploughing system on the annual weed infestation was highly dependent on crop stand and site, with spring pea

sole cropping after shallow ploughing resulting in a higher weed infestation compared to deep ploughing at both sites. Pea-oat intercrops, however, were found to have a similar weed infestation in both ploughing systems at Köllitsch, but a significantly higher weed infestation after shallow ploughing at Trenthorst. In contrast to the spring pea experiments, the weed infestation in semi-leafless and normal-leafed winter pea sole and intercrops did not differ significantly between shallow and deep ploughing.

〉 Intercropping winter peas and triticale reduced an infestation with pea aphids (*Acyrthosiphon pisum* Harris), whereas no beneficial effect of intercropping was observed pertaining to a reduction of pea moth (*Cydia nigricana* Fabricius) larvae-damaged peas.

〉 Winter-kill rates of the normal-leafed winter pea cv. EFB were significantly lower than those of the semi-leafless cv. James in 2009/10 (EFB: 10 %, James: 30 %), whereas identical values were observed in both winter pea cultivars (12 %) in 2010/11. Intercropping winter peas and triticale did not decrease winter-kill rates of winter peas. Also, the ploughing system had no significant effect on pea winter losses.

〉 In contrast to the semi-leafless winter pea cv. James, normal-leafed cv. EFB exhibited severe lodging after flowering. Intercropping normal-leafed winter peas and triticale, however, increased the lodging resistance. The ploughing system did not significantly affect winter pea lodging resistance.

〉 Spring or winter pea-cereal intercrops were observed to have higher biomass accumulation and total grain yields compared to the respective pea sole crops subject to the condition that no cereal biomass and yield formation problem appeared. The cereal partner suppressed intercropped peas, which was most notable with semi-leafless peas and under environmental conditions providing better growth conditions for the cereal partner. Shallow ploughing resulted in a comparable or a significantly better yield performance in sole and intercropped peas and cereals compared to deep ploughing. The mechanical soil loading did not influence the yield performance of spring pea and oat sole or intercrops in 2009, presumably due to dry soil conditions during mechanical soil loading implementation. In contrast to oat, mechanical soil loading with a rear wheel load of 26 and 45 kN reduced pea grain yields in 2010 by 12.1 % and 20.8 %, respectively. In addition, total grain yields decreased with increasing mechanical soil loading after deep ploughing in 2010, whereas no significant differences were found after shallow ploughing.

〉 Winter wheat after the preceding EFB sole and intercrops over yielded (2010/11: 3.59, 2011/12: 2.01 t d.m. ha^{-1}) winter wheat after the preceding James sole and intercrops (2010/11: 2.38, 2011/12: 1.67 t d.m. ha^{-1}). The winter wheat yield performance did not differ significantly between the preceding winter pea-triticale intercrops and the respective pea sole crops in 2010/11. Winter wheat grain yields in 2011/12, however, were significantly lower after winter pea-triticale intercrops independent of the winter pea cultivar. In addition, there were no significant differences between shallow and deep ploughing with respect to succeeding winter wheat yield performance in 2010/11, whereas shallow ploughing in 2011/12 resulted in significantly lower winter wheat grain yields (1.29 t d.m. ha^{-1}) than deep ploughing (2.05 t d.m. ha^{-1}).

〉 Coloured-flowered winter pea cv. EFB was found to have higher grain crude protein, crude fibre, P, K and Mg as well as a lower starch, sugar and crude fat contents compared to the white-flowered winter pea cv. James. The Metabolisable Energy content of white-flowered winter (15.24 MJ kg^{-1}) and spring peas (15.70 MJ kg^{-1}) was significantly higher when compared with the coloured-flowered winter pea cv. EFB (13.30 MJ kg^{-1}). The grain chemical composition and the energetic feed value of spring or winter peas did not depend on pea crop stand, whereas the oat grain crude protein content responded positively to an intercropping with spring peas. The ploughing system had only minor effects on the grain chemical composition and the energetic feed value. Comparable to the yield performance, the mechanical soil loading did not affect the grain quality in 2009. Pea grain crude protein content, pea protein yield and total protein yield decreased with an increasing mechanical soil loading after deep ploughing in 2010, whereas no significant differences were revealed after shallow ploughing.

In conclusion, despite of a partially higher weed infestation, short-term shallow ploughing resulted in a comparable or better agronomic performance and grain quality of sole and intercropped peas, and mitigated the risk of a decrease in pea performance caused by a mechanical soil loading during seedbed or sowing operations. Owing to their benefits, e.g. the good weed suppressive ability, pea-cereal intercrops are of particular suitability for the cultivation of peas in reduced tilled soils in organic farming.

Zusammenfassung

Ziel der vorliegenden Arbeit war es, den Mischfruchtanbau von Sommer- oder Wintererbsen und Getreidearten zu bewerten und die Eignung einer flachwendenden Bodenbearbeitung im ökologischen Erbsenanbau hinsichtlich annuellem Unkraut-aufkommen, Auswinterung, Standfestigkeit, Biomassebildung, Ertragsleistung, Korn-inhaltsstoff-Zusammensetzung und energetischem Futterwert zu ermitteln. Weiterhin war im Rahmen dieser Arbeit beabsichtigt, den Einfluss einer mechanischen Bodenbelastung während der Saatbettbereitung oder der Saat auf die Ertragsleistung und Kornqualität von Sommererbsen und Hafer in Reinsaat oder im Gemenge in tief- (Pflug, 25-30 cm) und flachwendend (Stoppelhobel, 7-12 cm) bearbeiteten Böden zu untersuchen. Von weiterem Belang war der Einfluss des Mischfruchtanbaus von Wintererbsen und Triticale auf den Schädlingsbefall an Erbsen.

Zu diesem Zweck wurden vierfaktorielle Feldversuche mit den Versuchsfaktoren Anbauform (Sommererbsen und Hafer in Reinsaat oder im Gemenge), Pflugsystem (flach- und tiefwendende Bodenbearbeitung), mechanische Bodenbelastung (0 t, 2,6 t und 4,6 t Hinterradlast) und Standort (Köllitsch, Ostdeutschland und Trenthorst, Norddeutschland) in den Jahren 2009 und 2010 durchgeführt. Der Mischfruchtanbau der Wintererbsen-Sorten E.F.B. 33 (kurz EFB, normalblättrig, buntblühend) und James (halbblattlos, weißblühend) wurde in Feldversuchen am Standort Trenthorst in den Versuchsjahren 2009/10 und 2010/11 nach flach- und tiefwendender Bodenbearbeitung untersucht. Im Anschluss an die Mischfruchtversuche mit Wintererbsen wurde Winterweizen angebaut (2010/11, 2011/12), um die Vorfruchtwirkung zu prüfen. Ein Gefäßversuch und ein Bioassay wurden ergänzend zu den Mischfruchtversuchen mit Sommererbsen durchgeführt, um die Ursachen eines möglicherweise unterschiedlichen Unkrautunterdrückungsvermögen in Reinsaaten und Gemengen von Sommererbsen und Hafer bestimmen zu können.

〉 Das <u>Unkrautaufkommen</u> hing in hohem Maße vom Blatttyp der Erbse ab, wobei Bestände mit halbblattlosen Erbsen stärker verunkrautet waren als normalblättrige Erbsenbestände. Mischfruchtbestände von halbblattlosen Sommer- und Wintererbsen unterdrückten Unkräuter stärker als Reinsaatbestände von halbblattlosen Erbsen, wohingegen das Unkrautaufkommen in Reinsaat- und Mischfruchtbeständen von

normalblättrigen Wintererbsen in der Regel nicht signifikant unterschiedlich war. Die Ergebnisse der Feld- und Gefäßversuche sowie des Bioassays weisen darauf hin, dass eine stärkere unterirdische Interaktion zwischen Kulturpflanzen und Unkräutern bedingt durch eine Konkurrenz um Stickstoff und Wasser sowie eine Abgabe von Unkraut unterdrückenden allelopathischen Substanzen über Wurzelexsudation beim Hafer mögliche Gründe für eine bessere Unkrautunterdrückung in Sommererbsen-Hafer-Gemengen im Vergleich zu Erbsen-Reinsaaten sind. Der Einfluss des Pflugsystems auf das annuelle Unkrautaufkommen war in hohem Maße vom Kulturpflanzenbestand und dem Standort abhängig, wobei der Anbau von Sommererbsen-Reinsaaten nach flachwendender Bodenbearbeitung an beiden Standorten zu einem höheren Unkrautaufkommen im Vergleich zur tiefwendenden Bodenbearbeitung geführt hat. Das Unkrautaufkommen in Erbsen-Hafer-Gemengen war am Standort Köllitsch in beiden Pflugsystemen vergleichbar, am Standort Trenthorst jedoch nach flachwendender Bodenbearbeitung signifikant höher. Im Gegensatz zu den Sommererbsen-Versuchen waren keine signifikanten Unterschiede im Unkrautaufkommen zwischen der flach- und der tiefwendenden Bodenbearbeitung in den Rein- und Mischsaaten von halbblattlosen und normalblättrigen Wintererbsen festzustellen.

〉 Der Mischfruchtanbau von Wintererbsen und Triticale führte zu einer Reduzierung des Befalls mit der <u>Grünen Erbsenblattlaus</u> (*Acyrthosiphon pisum* Harris), wohingegen keine befallsreduzierende Wirkung des Mischfruchtanbaus gegenüber dem <u>Erbsenwickler</u> (*Cydia nigricana* Fabricius) festgestellt wurde.

〉 Die <u>Auswinterungsraten</u> der normalblättrigen Wintererbsen-Sorte EFB lagen im Versuchsjahr 2009/10 signifikant unter denen der halbblattlosen Wintererbsen-Sorte James (EFB: 10 %, James: 30 %), während im zweiten Versuchsjahr bei beiden Wintererbsen-Sorten mit 12 % identische Werte festgestellt wurden. Der Mischfruchtanbau von Wintererbsen und Triticale führte nicht zu einer Reduzierung der Auswinterungraten der Wintererbsen. Das Pflugsystem hatte ebenfalls keinen signifikanten Einfluss auf die Auswinterung der Wintererbsen.

〉 Im Gegensatz zur halbblattlosen Wintererbsen-Sorte James traten bei der normalblättrigen Wintererbsen-Sorte EFB nach der Blüte starke Lagererscheinungen auf, wobei die <u>Standfestigkeit</u> von EFB durch einen Mischfruchtanbau von

Wintererbsen und Triticale deutlich verbessert wurde. Das Pflugsystem hat die Standfestigkeit der Wintererbsen nicht signifikant beeinflusst.

〉 Die Mischfruchtbestände von Sommer- oder Wintererbsen und Getreidearten wiesen unter der Voraussetzung, dass keine Biomasse- und Ertragsbildungsprobleme beim Getreide auftraten, eine höhere Biomasseproduktion und höhere Gesamterträge im Vergleich zu den entsprechenden Erbsen-Reinsaaten auf. Der Getreidepartner unterdrückte die Erbsen in den Mischfruchtbeständen. Dies was insbesondere bei halbblattlosen Erbsen und unter Umweltbedingungen festzustellen, die für das Wachstum des Getreidepartners förderlicher waren. Die flachwendende Bodenbearbeitung führte im Vergleich zur tiefwendenden Bodenbearbeitung zu einer vergleichbaren oder einer signifikant besseren Ertragsleistung der Rein- und Mischfruchtbestände von Erbsen und Getreide. Die mechanische Bodenbelastung hat die Ertragsleistung der Kulturen im Jahr 2009 vermutlich aufgrund von trockenen Bodenbedingungen zum Zeitpunkt der Durchführung der mechanischen Bodenbelastung nicht beeinflusst. Eine mechanische Bodenbelastung mit 2,6 oder 4,6 t Hinterradlast führte im Jahr 2010, im Gegensatz zum Hafer, zu einer Reduzierung der Erbsen-Erträge um 12,1 bzw. 20,8 %. Die zunehmende mechanische Bodenbelastung bewirkte im Jahr 2010 zudem eine kontinuierliche Abnahme der Gesamterträge nach tiefwendender Bodenbearbeitung, wohingegen nach flachwendender Bodenbearbeitung keine signifikanten Unterschiede festgestellt wurden.

〉 Der Winterweizen, der nach den Rein- und Mischsaaten von EFB angebaut wurde (2010/11: 35,9; 2011/12: 20,1 dt TM ha^{-1}), war dem Winterweizen nach den Rein- und Mischsaaten von James (2010/11: 23,8; 2011/12: 16,7 dt TM ha^{-1}) ertraglich überlegen. Zwischen den Wintererbsen-Triticale-Mischsaaten und den entsprechenden Wintererbsen-Reinsaaten konnten im Jahr 2010/11 keine signifikanten Unterschiede hinsichtlich der Ertragsleistung der Nachfrucht Winterweizen festgestellt werden. Im Jahr 2011/12 fielen die Winterweizen-Erträge nach den Wintererbsen-Triticale-Mischsaaten hingegen unabhängig von der Wintererbsen-Sorte signifikant geringer aus. Im Jahr 2010/11 wurde kein signifikanter Unterschied der Winterweizen-Ertragsleistung in flach- und tiefwendend bearbeiteten Böden festgestellt, wohingegen die Ertragsleistung der Nachfrucht Winterweizen im Jahr 2011/12 nach flachwendender Bodenbearbeitung (12,9 dt TM ha^{-1}) signifikant unter derjenigen der tiefwendenden Bodenbearbeitung (20,5 dt TM ha^{-1}) lag.

〉 Die buntblühende Wintererbsen-Sorte EFB wies höhere Rohprotein-, Rohfaser-, P-, K- und Mg- sowie geringere Stärke-, Zucker- und Rohfettgehalte im Korn im Vergleich zur weißblühenden Wintererbsen-Sorte James auf. Der metabolische Energiegehalt der weißblühenden Winter- (15,24 MJ kg^{-1}) und Sommererbsen (15,70 MJ kg^{-1}) lag signifikant über demjenigen der buntblühenden Wintererbsen-Sorte EFB (13,30 MJ kg^{-1}). Die Korninhaltsstoff-Zusammensetzung und der energetische Futterwert der Sommer- und Wintererbsen waren von der Anbauform der Erbsen unabhängig, wohingegen der Mischfruchtanbau von Erbsen einen positiven Effekt auf den Rohproteingehalt des Hafers hatte. Das Pflugsystem hatte nur geringe Auswirkungen auf die Korninhaltsstoff-Zusammensetzung und den energetischen Futterwert. Die Kornqualität wurde ebenso wie die Ertragsleistung nicht von der mechanischen Bodenbelastung im Jahr 2009 beeinflusst. Der Rohprotein-Gehalt der Erbsen und die Erbsen- sowie Gesamtproteinerträge nahmen mit zunehmender Bodenbelastung im Jahr 2010 nach tiefwendender Bodenbearbeitung jedoch kontinuierlich ab, wohingegen keine signifikanten Unterschiede nach flachwendender Bodenbearbeitung festgestellt wurden.

Die kurzfristige flachwendende Bodenbearbeitung führte trotz eines teilweise höheren Unkrautaufkommens somit zu einer vergleichbaren oder besseren pflanzenbaulichen Leistung und Kornqualität von Erbsen aus Reinsaat- und Mischfruchtbeständen und reduzierte das Risiko einer Abnahme der Leistungsfähigkeit des Erbsenanbaus bedingt durch eine mechanische Bodenbelastung während der Saatbettbereitung oder Saat. Der Mischfruchtanbau von Erbsen und Getreide ist aufgrund seiner vorteilhaften Effekte, wie etwa dem guten Unkrautunterdrückungsvermögen, in besonderem Maße für den Erbsenanbau bei reduzierter Bodenbearbeitung unter ökologischen Anbaubedingungen geeignet.

Danksagung

> ***"Quando se viaja em direção a um objetivo é muito importante prestar atenção no caminho. O caminho é que sempre nos ensina a melhor maneira de chegar, e nos enriquece, enquanto o estamos cruzando.***
> *Wenn man auf ein Ziel zugeht, ist es äußerst wichtig, auf den Weg zu achten. Denn der Weg lehrt uns am besten, ans Ziel zu gelangen, und er bereichert uns, während wir ihn zurücklegen.*
>
> *Paulo Coelho*[§] "

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[§] Coelho, P., 1987. O diário de um Mago. Editora Rocco Ltda., Rio de Janeiro / Coelho, P., 1999. Auf dem Jakobsweg, Tagebuch einer Pilgerreise nach Santiago de Compostela. Diogenes Verlag, Zürich.

Erklärung

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Bad Sooden-Allendorf, den 10. April 2014

Annkathrin Gronle