Development of concepts for expanding the use of no-tillage farming in organic agriculture

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Omnium autem rerum,
ex quibus aliquid acquiritur,
nihil est agricultura melius,
nihil uberius,
nihil dulcius,
nihil homine libero dignius.

Marcus Tullius Cicero
(106 – 43 BC)

Abstract

Intensive tillage by means of mouldboard ploughing can be highly effective for weed control in organic farming, but it also carries an elevated risk for rapid humus decomposition and soil erosion. Conservation tillage techniques offer considerably reduced soil erosion and improved soil structure but they are rarely used in organic farming systems due to the increased weed pressure. To develop organic systems that are less dependent on tillage this study evaluated the non-legume cover crops spring rye (*Secale cereale* L.), black oat (*Avena sativa* L.), sunflower (*Helianthus annuus* L.), white mustard (*Sinapis alba* L.), buckwheat (*Fagopyrum esculentum* Moench) and hemp (*Cannabis sativa* L.) for their ability to suppress weed growth, reduce plant available nitrogen in the soil and produce large amounts of biomass with slow N mineralisation, without and with the incorporation of organic fertiliser (horn grist, 50 kg N ha^{-1}) before seeding. Resulting from these preliminary trials the spring rye was chosen as cover crop before no-till, reduced tillage and plough tillage cropping of legume cash crops monocropped and intercropped with cereal grains. The legume cash crops winter and spring faba bean (*Vicia faba* L.), field pea (*Pisum sativum* L.) and spring narrow-leafed lupin (*Lupinus angustifolius* L.), monocropped and intercropped with winter wheat (*Triticum aestivum* L.; winter crops) and oats (*Avena sativa* L.; spring crops) were evaluated for their dry matter production and grain yield as well as for their ability to suppress weeds. An additional study determined if the transition to the no-till system could be carried out through no-till seeding of summer annual legume cover crops faba bean, normal leafed field pea, narrow-leafed lupin, grass pea (*Lathyrus sativus* L.), and common vetch (*Vicia sativa* L.) monocropped and intercropped with sunflower after the harvest of cereal grain cash crops. The objectives of the studies were: (i) to examine six non-legume cover crops (rye, oats, sunflower, mustard, buckwheat and hemp) for their suitability for cover cropping preceding no-till sown legume cash crops through evaluation of their ability to produce biomass and reduce plant available inorganic soil N resources by N accumulation and assessment of long term N immobilisation in plant compartments with a high C : N ratio through simulated N mineralisation, (ii) to determine if the total biomass production and N accumulation can be increased by incorporating organic fertiliser before seeding, (iii) to assess the suitability of three different legume species (field pea, faba bean and narrow-leafed lupin) for no-till cash crop systems by examination of their grain production after no-till, reduced tillage and plough tillage, (iv) to determine the capacity of intercropped plant stands of legume cash crops and

cereal grains to enhance the weed suppression and the total grain yield, (v) to investigate if autumn seeding compared to spring seeding of grain legumes can enhance the weed competition of legume cash crops, (vi) to determine if the transition to the no-till system can be alternatively realised through no-till seeding of legume cover crops or if tillage is needed for sufficient weed suppression and cover crop production.

The non-legume cover crop biomass production ranged from 0.95 to 7.73 Mg ha^{-1}, with fertiliser increasing the total biomass at locations with low N status. Sunflower consistently displayed large biomass and N accumulation at all locations and fertiliser variations, although not always significantly more than other species. Most shoot-N was stored in sunflower leaf material, which can be easily mineralised making it less suited as cover crop before no-till sown spring grain legumes. Rye, which produced slightly less biomass, but accumulated more N in the stem biomass, would be better suited than sunflower in this type of system. The N mineralisation simulation from rye biomass indicated long N immobilisation periods potentially improving weed suppression within no-till sown legume cash crops.

The legume cash crop winter field pea (normal leafed variety), displayed in the no-till system grain yields of up to 3.39 Mg ha^{-1} which was similar to the plough tillage system. For spring faba bean and field pea the yield in the reduced tillage system amounted to 2.92 and 3.29 Mg ha^{-1}, respectively which was similar to the plough tillage system, but did not exceed 2.15 Mg ha^{-1} in the no-tillage system. Narrow-leafed lupin consistently displayed yields below 0.65 Mg ha^{-1} in the no-tillage system. Normal leafed winter field pea appeared to be best suited for the transition period to an organic no-tillage system due to the autumn seeding and its high competitive ability. Spring faba bean and field pea can be successfully grown in the reduced tillage system. Intercropping can increase the total grain yield and weed competition as long as sufficient soil nitrogen resources are plant available.

The no-tillage sown monocropped and intercropped legume cover crop total shoot dry matter, shoot N accumulation and N_2 fixation differed with year, location, tillage system and species due to variations in weather, inorganic soil N resources and weed competition. Biomass production reached up to 1.65 and 2.19 Mg ha^{-1} (both intercropped field peas), and N_2 fixation up to 53.7 and 60.5 kg ha^{-1} (both common vetches) in the no-till and reduced tillage system, respectively. In the no-till system consistently low sunflower performance compared with the legumes prevented significant intercropping effects. Under central European conditions no-till cover cropping appears to be practicable if weed density is low at seeding. The interactions between year, location, tillage system and species demonstrate the difficulties in cover crop species selection for organic conservation tillage systems.

This study demonstrated two approaches for the transition to no-till seeding in organic agriculture. Before no-till sown legume cash crops the N immobilisation of available inorganic soil N resources would be most successful with cereal grains that show high C : N ratios in their plant material to reduce weed infestation from emerging weeds in legume cash crops. No-till seeding of legume cash crops with high weed suppressive abilities appears to be possible. Legume cover cropping could be carried out if weed density at seeding is low. This study´s results indicated that the complete transition to an organic no-till system is probably not practicable due to the different weed suppressive abilities of cash crops and the increasing weed pressure after the omission of tillage. Nevertheless, certain cash and cover crops can be sown without tillage and the integration of short term no-tillage phases growing grain legumes could make organic farming more sustainable.

Abbreviations

a.s.l	above sea level
BO	Bockelwitz (trial location)
cv.	cultivar
C	Carbon
DM	dry matter
DWD	Deutscher Wetterdienst (German Meteorological Service)
GR	Groß Radisch (trial location)
IC	intercropped
KÖ	Köllitsch (trial location)
LfULG	Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (Saxon State Office for Environment, Agriculture and Geology)
MC	monocropped
N	Nitrogen
PI	Pillnitz (trial location)
RG	Reinhardtsgrimma (trial location)
SBS	Staatsbetrieb Sachsenforst (Saxon State-Owned Forestry Enterprise)
STICS	Simulateur mulTIdisciplinaire pour les Cultures Standard

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1. Chapter: Introduction

1.1 No-till seeding in organic farming

Sustainable organic farming is based on the principle of soil fertility preservation. This stands in contrast to the widespread use of deep inversion plough tillage for primary tillage in organic farming systems (Wilhelm et al., 2011). The continued use of the mouldboard plough is due to its proven efficiency for weed control (Gruber and Claupein, 2009). However, this labour and energy intensive technique reduces the soil's aggregate stability and organic matter content (Schjønning and Rasmussen, 1989; Hermawan and Cameron, 1993) leading to soil erosion. No-till practices on the contrary can diminish soil erosion to tolerable rates (Montgomery, 2007), stabilise soil aggregates and increase soil organic carbon close to the soil surface while reducing the annual CO_2 emissions (Carter, 1992; Madari et al., 2005; He et al., 2009; Ussiri and Lal, 2009).

Nonetheless, to date, the adaption of organic no-tillage systems is negligible under the temperate climate conditions of central Europe. In this region the average annual precipitation range (Germany 551.6 – 1018.1mm) (Becker, 2013) is higher than in the semi-arid and arid regions of North America and Central Asia in which the conventional no-tillage systems are widely used. No-tillage practices can increase the soil water storage (Fabrizzi et al., 2005) but potential yield increases due to the water preservation are limited in central Europe so that the adaption rate will only increase if economic or environmental benefits arise. Economic benefits from reduced fuel consumption and lower labour costs due to omitted tillage are often already offset in the transition period to the no-tillage system by yield reductions (Reicosky and Saxton, 2007) as a result of poor crop emergence, increased weed pressure and reduced N mineralisation.

The omission of tillage typically increases the abundance of perennial weeds (Streit et al., 2000; Tørresen et al., 2003) which is a main drawback in organic no-till systems that do not allow continuous cropping, as it is the case in arable fields in Central Europe. Plant mulches from cover crops and heavy straw covers have shown weed suppressive abilities and could be a key technology for a successful transition to an organic no-tillage system (Massucati and Köpke, 2010).

1.2 Strategies for the implementation of no-tillage practices in organic agriculture

The production of large amounts of mulch material has to be ensured by choosing the right strategy depending on the point in the crop rotation and the related status of N availability as well as the N requirements of the following crop.

Transitioning to organic no-tillage at the end of a yearly crop cycle by omitting stubble tillage can increase perennial weed growth (Pekrun and Claupein, 2006) especially in cases of high N availability. To improve the conditions in the transition period it is advisable to remove very competitive perennial weeds after harvest by plough tillage and suppress emerging weeds through the establishment of cover crops, which produce a weed suppressing soil cover in which the spring cash crops are directly sown. Today, cover crops in Central Europe are predominantly used to reduce soil erosion and nitrogen (N) leaching. For this purpose cover crops need to develop quickly and cover the ground, ideally producing ≥2.0 Mg ha^{-1} above ground dry matter and accumulate ≥60 kg N ha^{-1}. The ability of cover crops to suppress weeds and reduce their germination and growth through low N availability is a new core task which is particularly important for grain legume cash crops in organic no-tillage systems.

Cover crop plants can reduce weed growth through light interception, above and below ground competition and uptake of available inorganic nutrient resources particularly nitrate N (Kruidhof et al., 2008; Spies et al., 2011). For systems with subsequent legume cash crops weeds can be suppressed by the thick residue mulch that retains accumulated N, intercepts light and has, in some species, allelopathic properties (Barnes and Putnam, 1983; Putnam and DeFrank, 1983; Teasdale and Mohler, 2000).

1.3 Characteristics of cover crop materials

For a long lasting effect in legume cash crops the composition of cover crop residues should delay residue decomposition and N mineralisation. Parameters for the biochemical composition or residue quality can include the content of carbon (C), N, carbohydrates, cellulose, hemicelluloses, lignin and polyphenols as well as the proportion of carbon to nitrogen (C : N ratio) in the plant materials (Bending et al., 1998; Trinsoutrot et al., 2000; Corbeels et al., 2003; Abiven et al., 2005). The influence of most of the parameters on N mineralisation varies but it has been shown that the N mineralisation correlates well with the residue C : N ratio (Trinsoutrot et al., 2000).

A high quality residue has a high C : N ratio which results in slow decomposition and N mineralisation, while low quality residues with low C : N ratios are mineralised in a short period of time. Plant parts differ in their C : N ratio depending on their phenological growth stage (Steer et al., 1985), making the compartmentalisation important for the evaluation of the residue quality. The C : N ratio of stem material increases as they develop and mature due to the relocation of N during the generative growing phase into inflorescence and seeds. The result is that the C : N ratio is usually highest in the stem material and lowest in the leaf and inflorescences. For a slow residue decomposition and N mineralisation it is therefore not only important to select for species with a large C : N ratio for the whole plant, but to select for cover crops that produce large amounts of stem material with a high C : N ratio before reaching maturity. The C : N ratio in legume plant material is usually much lower than in non legumes (Smith and Sharpley, 1990), thus it can be beneficial to use non legume cover crops for reduced N mineralisation and better retention of residues on the soil surface. The non legume species rye, oats, sunflower, mustard, buckwheat and hemp have been evaluated as cover crops through the determination of their total biomass production (Stivers-Young, 1998; Creamer and Baldwin, 2000; Clark, 2007; Miyazawa et al., 2010; Forentìn et al., 2011). Rye, oats and mustard have been in use as cover crops in organic farming in Central Europe. Sunflower, buckwheat and hemp are considered to be promising new cover crops.

Cereal cover crops can use the plant available soil nitrogen (N) resources to produce large quantities of plant material with a wide carbon (C) to N ratio (Ruffo and Bollero, 2003) which can result in a N immobilisation and reduced weed growth. Additionally rye mulch has shown the ability to reduce the weed emergence and the weed biomass under no-tillage conditions (Barnes and Putnam, 1983). For the transition to an organic no-tillage system the mulch layer should be established with a cover crop in late summer right after the last stubble tillage.

Low inorganic soil N, as a result of slow N mineralisation, can have negative effects on both non-legume weeds and cash crops. Grain legume cash crops are able to substitute for low inorganic soil N by symbiotic N_2 fixation which makes them suitable for the transition period to an organic no-till system. Diametrically opposed to high N demand by non legume cash crops high inorganic soil N resources (in particular nitrate) are undesired for grain legume cash crops because they limit the symbiotic N_2 fixation. For peas it has been shown by Voisin et al. (2002) that soil nitrate contents have to fall below the threshold value of <56 kg N ha^{-1} to initiate symbiotic N_2 fixation. In their experiments, peas in their vegetative and beginning of seed filling state, began to display reduced symbiotic N_2 fixation at soil nitrate contents of >3 and >14 kg N ha^{-1} (0-0.4 m soil layer), respectively. Cover crops should therefore produce large amounts of biomass to accumulate and immobilise as much inorganic soil N as possible. In a succeeding pea cash crop this could help to maximise the percentage of the total crop N derived from symbiotic N_2 fixation. Large amounts of residues are also needed for sufficient weed suppression (Teasdale et al., 1991), while low soil nitrate availability could additionally reduce the germination of weeds like *Chenopodium album* L. that require nitrate to break their seed dormancy. This could be advantageous for grain legumes especially in their early growing period in which their slow initial development (Giunta et al., 2009), makes them susceptible to weed competition (Nelson and Nylund, 1962).

1.4 Advancements in seeding technology

While the weed suppression increases with mulch quantity (Teasdale and Mohler, 2000) the crop seed placement is impaired by heavy residue layers. With no-till disk machines seeds can end up positioned on top of hairpinned residues while shank type openers are not practicable under very heavy residue conditions due to poor residue flow leading to plugging problems of the seeding unit. The embedding of seeds in hairpinned residues can result in reduced crop emergences in dry conditions due to poor seed-soil contact (Baker and Saxton, 2007). Therefore special no-tillage seeding techniques have to be used for thick cover crop residue layers. The inverted T-cross slot openers (Fig. A 1-2a-b), were developed for the use in high residue environments (Baker, 2007) and can improve the seed placement under those conditions by placing the seed into horizontal slots below the residue covered soil surface, creating water vapour rich conditions that favourably affect germination (Fig. A 3; Wuest, 2002; Baker, 2007).

1.5 Timing of legume cash crop seeding and use of intercrops

Even with weed suppressing plant mulch present and crop seed placement with advanced seeding technology the crop-weed competition can still be shifted in favour of weed growth due to the slow early development of large seeded grain legumes.

The establishment of the winter legumes in autumn allows a faster spring development and biomass production compared with legumes that are sown in spring. Additionally the early crop-weed competition of the legumes can be further improved by cereal grains that are sown with the legumes. Such intercropped (IC) plant stands are able to use the faster canopy development (Giunta et al., 2009) and the early elevated soil N uptake of the IC cereals

(Jensen, 1996) to increase the crop-weed competition of the IC crop stands compared with the monocropped (MC) legumes. This can considerably reduce the weed biomass production compared with MC legume plant stands as was shown for winter wheat and winter faba bean by Bulson et al. (1997).

Winter wheat is well adapted to the winter conditions in central Europe and can be intercropped with both the winter faba bean and field pea. Both of these legumes have shown the capability to overwinter under central European conditions (Arbaoui et al., 2008; Urbatzka et al., 2012). However they are also susceptible to frost damage if there is no protective snow cover. Experiments in the harsh winter conditions of North America have shown that long stubble can significantly increase the winter wheat survival due to the increased snow depth and higher soil temperatures (Larsen et al., 1988). For the winter legumes a similar result could be achieved with cover crop residues which increase snow trapping and protect the winter legumes in the no-tillage system.

In spring the advanced winter legume development will only be a competitive advantage against the weeds if sufficient quantities of legumes overwinter. In years with a low overwintering percentage the spring sown legumes could reach higher yields and show a better weed suppression than the winter legumes.

Depending on the point in crop rotation and the soil N status cover cropping might require additional fertilisation for non-legume cover crops or the use of legume cover crops.

1.6 No-till sown legume cover crops

In some conditions it can therefore be advisable to transition to the no-till system after grain cash crop harvest in summer with the establishment of no-till seeded cover crops. This can reduce the weed competition for the cover crop because the available N resources for weeds have been depleted by the cash crop, whereas perennial weeds that are favoured by the omission of tillage (Moonen and Barberi, 2004), were cut in the harvest process. The no-till seeding of cover crops can also reduce the annual weed population density as weed seeds are not incorporated into the soil and germination from the weed seed bank is not induced by tillage (Bilalis et al., 2001). During the cover cropping period, the weed growth will be reduced through cover crop-weed competition for light, water and nutrients.

In organic no-till systems late season cover crops have to be terminated in their growth to enable seeding and development of the cash crops. The cover crop termination by frost is therefore an essential component in an organic no-till system approach because the termination by tillage or herbicides is not possible and alternative methods like mowing or rolling can delay the cash crop seeding and pose the risk of regrowth. The termination of cover crops during winter is also advantageous in dry years because it allows the soil water resources to be replenished over winter while frost resistant cover crops would continue their resource usage throughout spring, with possibly detrimental effects for the subsequent cash crop (Clark, 2007).

Growing a cover crop mixture of legumes and a non-legume, like rye, can further deplete available soil N sources for weeds, reducing their growth and increasing the legume N_2 fixation efficiency (Brainard et al., 2012). The additional biomass production of the non-legume can increase the total intercropped biomass over the monocropped biomass production. The use of rye can be problematic in an organic no-till system when insufficient winter kill delays the cash crop seeding, because for the successful termination by the alternative use of a roller-crimper, rye has to reach anthesis (Mirsky et al., 2009). Alternatively sunflowers can be used and as a warm season crop they will be terminated by frost. Sunflowers are well suited as an intercrop partner due to the complementary characteristics to legumes, such as early ground shading. Successful conventional sunflower cropping in a well fertilised no-till system has shown their suitability for conservation tillage (Halvorson et al., 1999).

Low inorganic soil N resources after the harvest of cereals can be compensated by legumes through N_2 fixation (Reiter et al., 2002). The N_2 fixation can be a competitive advantage over the weeds and increase the available N resources for the subsequent cash crop, which will be provided through decomposing legume residue (McVay et al., 1989). This could, to some extent, compensate for the decreased mineralisation in the no-till system.

1.7 General objectives and thesis layout

Research in the transition period into organic no-till systems has been sparse in Central Europe and no successful concept has been established to this day. Therefore it was the objective of the present study to develop an approach to enable the use of no-till seeding in organic farming systems. Due to limited availability of direct weed control measures without soil disturbance in organic farming our new approach used a combination of non-legume cover crops to immobilise available soil N resources and suppress weeds through thick mulch covers subsequent to legume cash crops. The transition into the no-till system by no-till seeding of legume cover crops was additionally trialled. It is expected from this study that the results will be a valuable contribution for the development of a more sustainable organic no-tillage system.

The objectives of this study were:

(i) To examine six non-legume cover crops (rye, oats, sunflower, mustard, buckwheat and hemp) for their suitability for cover cropping preceding no-till sown legume cash crops through evaluation of their ability to produce biomass and reduce plant available inorganic soil N resources by N accumulation and assessment of long term N immobilisation in plant compartments with a high C : N ratio through N mineralisation with the STICS crop model.

(ii) To determine if the total biomass production and N accumulation can be increased by incorporating organic fertiliser before seeding.

(iii) To assess the suitability of three different legume species (field pea, faba bean and narrow-leafed lupin) for no-till cash crop systems by examination of their grain production after no-till, reduced tillage and plough tillage.

(iv) To determine the capacity of intercropped plant stands of legume cash crops and cereal grains to enhance the weed suppression and the total grain yield.

(v) To investigate if autumn seeding can enhance the weed competition of legume cash crops.

(vi) To determine if the transition to the no-till system can be alternatively realised through no-till seeding of legume cover crops or if tillage is needed for sufficient weed suppression and cover crop production.

The present dissertation consists of five Chapters. The non-legume cover crop trials are described in Chapter 2 followed by Chapter 3 with an implementation of preliminary trial results described in Chapter 2. In trials described in Chapter 3 the non-legume cover crop rye is used as a cover crop ahead of no-till sown legume cash crops monocropped and intercropped with cereal grains. In additional trials described in Chapter 4 legume cover crops were used to approach the introduction into organic no-tillage directly after harvest of a cereal grain cash crop.

2. Chapter: The Suitability of Non-legume Cover Crops for Inorganic Soil Nitrogen Immobilisation in the Transition Period to an Organic No-till System

2.1 Introduction

The evaluation of cover crops through determination of their biomass production and weed suppression is common. However, for the use in the transition period to an organic no-till system the cover crops need to reduce the plant available N in the soil and produce large amounts of biomass with slow N mineralisation. Therefore a novel approach should be used to evaluate potential cover crops by their proportion of stem, leaf and inflorescence with regards to total cover crop biomass, the C : N ratio of the plant compartments and the related N mineralisation. The total and partitioned cover crop biomass and N accumulation as well as the individual C : N ratio of plant partitions can each be used to evaluate the quantity and quality performance of different plant species. However, the production of large amounts of biomass combined with a large N accumulation does not necessarily lead to an extended period of low N availability. For a more specific cover crop selection based on their overall properties, all factors can be combined in a model simulation like the residue decomposition model of the STICS (Simulateur mulTIdisciplinaire pour les Cultures Standard) model (Brisson et al., 1998). The simulated proportional net N mineralisation of separated leaf and stem material could help to identify species specific N mineralisation behaviour of the plant compartments while the combined simulation of the different materials from one species would account for material interactions during mineralisation. Cover crop species often differ in their leaf and stem biomass production and in the amount of N that is accumulated in these plant compartments. Their characteristics vary as well and it is important to simulate the net N mineralisation from the individual residues to predict the amount of released N over winter potentially influencing the early weed competition and the onset of symbiotic N_2 fixation in the succeeding legume cash crop. These new methods could help to identify cover crops more precisely for the transition to organic no-tillage systems.

The growth of non legume cover crops can be impaired by the low availability of inorganic soil N. This shortage could be compensated by the incorporation of organic fertilisers before the seeding of the cover crops, which improves the N supply and could lead to increased cover crop biomass production. The larger dry matter production could result in improved residue cover and weed suppression in the early cash crop phase.

It was the objective of our trials with non-legume cover crops to test the following hypotheses: (i) The cover crop species rye, oats, sunflower, mustard, buckwheat and hemp differ in their partitioning of biomass, N accumulation and C : N ratio in stem material as well as in combined leaf and inflorescence material. (ii) The use of fertiliser before seeding increases the total biomass production and N accumulation of the non legume cover crops. (iii) Cover crop species differ in the ability to reduce plant available inorganic soil N during growth and in their potential to immobilise the accumulated N over winter and spring. As a result, these species vary in their suitability as cover crops preceding no-till sown legume cash crops.

2.2 Materials and Methods

2.2.1 Experimental study site and field trial setup

Field trials were conducted from July to October 2008 in three different environments (three site-years): at the long term organically farmed research field of the University of Applied Sciences Dresden at Pillnitz (PI; 51°00'N, 13°53'E, 116 m a.s.l.), at a long-term certified organic farm at Groß Radisch (GR; 51°15'N, 14°41'E, 240 m a.s.l.), and the organic research field of the Teaching and Research Farm Köllitsch (KÖ; 51°30'N, 13°06'E, 84 m a.s.l.), Germany (at GR based on and at PI and KÖ equivalent to Council Regulation (EC) No 834/2007 (European Union, 2007). The three sites were selected to represent different climate conditions, in particular a different distribution of precipitation during the cover cropping phase. The preceding crops before the cover cropping period were spring barley, winter triticale and winter wheat at the PI, GR and KÖ location, respectively. At the GR and KÖ locations the grain was harvested in early August 2008 and the straw was transported off the field. At PI the spring barley was chopped with a flail mower on the 18 June due to insufficient plant development; residues remained in the field.

The design of the field trial was a completely randomised split plot with four replications. The main plot factor was N fertilisation (no fertiliser and fertiliser (horn grist, 50 kg N ha^{-1}) incorporated directly before seeding. Each main plot was divided into eight sub plots (30 m^2 – 3 m wide and 10 m long), with one plot each for spring rye (*Secale cereale* L., local cultivar from St. Leonhard, Austria), black oat (*Avena sativa* L., cv. Auteuil), sunflower (*Helianthus* *annuus* L., cv. Methasol), white mustard (*Sinapis alba* L., cv. Signal), buckwheat (*Fagopyrum esculentum* Moench, cv. Spacinska) and hemp (*Cannabis sativa* L., cv. Bialobrzeskie) with seeding rates (viable seeds): 300, 350, 90, 150, 200 and 150 seeds m^{-2}, respectively), no cover crop (weeds only) and bare soil fallow without vegetation (managed through periodical flame weeding, every 14 days). The seeding rates were in the upper range of local customary seeding rates to achieve rapid ground cover and soil protection as well as weed suppression. Plots without cover crop were used to examine weed growth potential and weed competition by evaluated cover crop species. Bare soil fallow was included in the study as a control to determine the influence of cover cropping on the soil N mineralisation during the cover cropping period.

Two days before seeding, the plough tillage (0.25 m) and the seedbed preparation with a rotary harrow (0.08 m) was carried out at the GR and KÖ location (Table 2.1). At GR, the field was additionally rolled before seeding. At PI, the residue incorporation by plough tillage and seedbed preparation was performed one week (26 June 2008) after barley growth was terminated with a flail mower. At the day of seeding, the fertiliser (fertilised plots only) in the form of horn grist (DCM - Deutsche CUXIN Marketing GmbH, Germany) at a rate of 50 kg N ha^{-1} was incorporated at a depth of 0.05 m with a plot seeder (Type HEGE 80, Wintersteiger, Austria). The seeding of the cover crops (row spacing 0.15 m) was carried out with the same plot seeder at a depth of 0.03 m. The no cover crop (weeds) and fallow plot without vegetation received one pass with the empty plot seeder. The cover crop field emergence was determined two to three weeks after seeding with four repetitions per plot (four randomly selected rows one metre long).

2.2.2 Sample collection and analysis

Soil samples were collected directly after seeding (ten sample points for each main plot) and after cover crop biomass sampling in October (four sample points for each subplot). At both PI and KÖ, the soil samples were taken from 0 to 1.2 m (four equal core sections at 0.3 m), while at GR the sampling depth was limited to the soil layer from 0 to 0.6 m (two equal core sections at 0.3 m) due to high stone content in the soil layer below 0.6 m. Core samples of the same depth-level were homogenised and stored in cold storage coolers in the field, followed by deep freezing to -18°C the day of sample collection until the final analyses. Within one hour of defrosting, soil extracts with 0.01 M $CaCl_2$ were prepared, and NO_3^-N and NH_4^+N concentrations were examined using a Continuous Flow Analyzer (SAN++, Skalar

Table 2.1. Site specific soil information, experimental and simulation details.

Site	Pillnitz (PI)	Groß Radisch (GR)	Köllitsch (KÖ)
Soil type (FAO classification)[a]	Calcaric Cambisol	Eutric Gleysol	Arenic Fluvisol
Soil texture	Sandy Loam	Slightly Loamy Sand	Loamy Sand
Soil pH (0.01 M $CaCl_2$)	6.0	5.4	5.5
Soil P (CAL; mg kg^{-1})[b]	41	23	26
Soil K (CAL; mg kg^{-1})[b]	146	134	66
Soil Mg (0.01 M $CaCl_2$; mg kg^{-1})	78	63	115
Tillage and seedbed preparation	26 June 2008	9 August 2008	11 August 2008
Fertiliser incorporated[c]	29 July 2008	11 August 2008	13 August 2008
Cover crop sowing date	29 July 2008	11 August 2008	13 August 2008
Field emergence determined	19 August 2008	24 August 2008	27 August 2008
Harvest	25 October 2008	30 October 2008	31 October 2008
Start of Simulation	25 October 2008	30 October 2008	31 October 2008
End of Simulation	13 March 2009	18 March 2009	19 March 2009

[a] Soil type according to IUSS Working Group WRB, (2006).
[b] Calcium Acetate Lactate (CAL) extraction method after Schüller (1969).
[c] Only in fertiliser plots.

Analytical B.V., Breda, Netherlands) based on the VDLUFA method A 6.1.4.1 (Thun and Hoffmann, 1991) and DIN ISO 14255 : 1998-11 (DIN Deutsches Institut für Normung e.V., 1998), respectively. Soil sampling depth varied between GR and the other two locations as described so that only the samples up to 0.6 m soil depth were used for the comparative analysis of all trial sites.

At the biomass harvest in October an area of 2.04 m^2 of each plot was cut by hand and the plant cover was separated into cover crops and weeds. The above ground gross fresh weight of cover crops and weeds was determined directly after harvest in the laboratory using a laboratory scale (SI 6002, Denver-Instrument). Samples of 200 to 400 g were dried in a drying cabinet at 105°C to constant weight for the dry matter weight calculations. To determine the C and N content in cover crop stem, leaf and inflorescence material additional plants were harvested from each plot. Ten representative plant shoots per plot were sampled for sunflower, mustard, buckwheat and hemp while twenty plant shoots per plot were sampled for rye and oats. For each plant, the shoot, leaves and inflorescence were separated from the stem by hand. The leaf and inflorescence material were combined and were declared as leaf material. The stem and leaf material fresh weight were determined and the plant parts were dried for the dry matter weight calculations in a drying cabinet at 60°C. The dried plant parts were finely ground (< 0.2 mm) with an ultra centrifugal mill (ZM 1000, Retsch, Germany). Analysis for %C and %N was performed with an elemental analyser (TruSpec Macro, LECO, USA) in compliance with the VDLUFA method 4.1.2 (Bassler, 1976) and DIN ISO 10694 : 1996-08 (DIN Deutsches Institut für Normung e.V., 1996) respectively.

2.2.3 Statistical Analyses

The data for field emergence, stem and leaf material (separated as well as combined) of cover crop shoot dry matter, N accumulation, C : N ratio; weed shoot dry matter and N accumulation and the inorganic soil N for the soil layer 0 to 0.6 m were subjected to analysis of variance (ANOVA) using the MIXED procedure (SAS v. 9.3 SAS Institute, Cary, NC). Statistical analyses were performed over three locations – site years (PI, GR and KÖ) using a linear mixed model with location, fertilisation and species as fixed and replicates as random effects. The fit of the model was tested using residual plots of the pooled data and, when necessary, data transformations (Piepho, 2009) were used to achieve required assumptions for linear regression analyses (Ireland, 2010).

The cover crop field emergences, cover crop C : N ratio of stem and leaf material, stem percentage of the total biomass (stem%) and %N in stem biomass did not require any transformation while the logarithmic transformation was applied to all other data sets. Homogeneity of variance was tested and in case of heterogeneous variances the model was fitted for partitioned variances (Littell et al., 2011). The degrees of freedom were determined based on the Kenward-Roger method. Least square means were calculated and mean comparisons were carried out with the Tukey-Kramer test ($\alpha = 0.05$) within the SAS procedure MIXED.

2.2.4 Simulation of N mineralisation

The residue decomposition module of the STICS model (Brisson et al., 1998) was utilised to predict the N mineralisation from residues produced by the different cover crops. The decomposition model considers three pools: the cover crop residues, the microbial biomass decomposing the residues and the humified organic matter (Brisson et al., 1998; Nicolardot et al., 2001). Daily changes in these pools are related to their C : N ratio and the amount of carbon in these pools. During the decomposition of the cover crop residue, carbon is either emitted as CO_2 or incorporated in microbial biomass. Crop residue N that is not used for the growth of microbial biomass is released to the pool of inorganic N. This pool also acts as a source of inorganic N for the development of microbial biomass. Decomposing microbial biomass releases C and N which is partly included in humified organic matter, partly emitted as CO_2 or, in the case of N, released as inorganic N. This flow of C and N is characterised by the model through (i) the plant residue decomposition rate constant (k) and the accumulation of C from residue in the microbial biomass (Y), (ii) the decay rate constant of the microflora (λ) and the amount of microbial C humification (coefficient h), (iii) the C : N ratios of the three pools $C : N_{Residue}$, $C : N_{Microbial\ biomass}$ and $C : N_{Humus}$ (Fig. 2.1) (Brisson et al., 2009; Nicolardot et al., 2001). The permanent mineralisation of humified organic matter consistently releases additional mineral N that is not included in the present simulation which only considers the net N mineralisation from cover crop residue. The net N mineralisation from the cover crops is also influenced by external parameters: the soil (inorganic soil N contents), climate (temperature and precipitation) as well as by the placement of residues (at the surface or at a certain depth of incorporation). Nicolardot et al. (2001) evaluated and validated the decomposition model (Brisson et al., 1998) with mature and immature crop materials in soil incubation experiments, revealing significant correlations of the microbial biomass C : N, the constant of residue decomposition (k), the coefficient for the humification of the decaying microbial biomass (h), with the C : N ratio of residues. In additional soil incubation experiments Justes et al. (2009) confirmed these relationships and further evaluated and parameterised the model for immature autumn grown cover crops with a wide range of C : N ratios. Under field conditions the decomposition model was recalibrated and successfully validated for incorporated immature cover crop residues by Justes and Mary (2004).

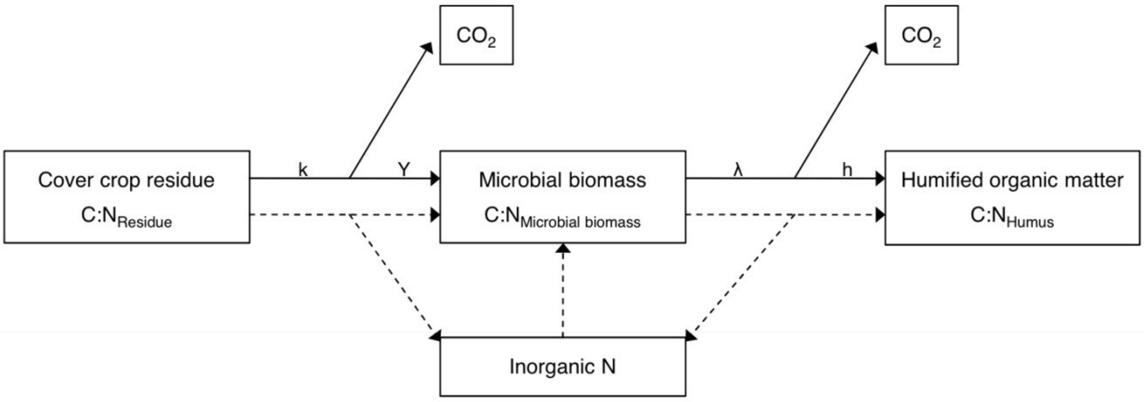

Fig. 2.1. Conceptual diagram of the residue decomposition model (Nicolardot et al. 2001), continuous lines indicating C fluxes, dashed lines indicating N fluxes.

For the C : N ratio model parameter the input bounds are 6 and 200. However preliminary simulations displayed N mineralisation inconsistencies at low C : N ratios. The simulations using hypothetical immature crop residues with a fixed dry matter (1 Mg ha^{-1}) and C content (40%) as well as variable C : N ratios (8 to 20 : 1) showed that under no-till conditions the simulated proportionate net N mineralisation (% of added N) was not graduated according to its residue C : N ratio (Fig. 2.2a). Default climate conditions from April to December were used (average temperature 14.2°C, cumulative precipitation 513 mm). Within the first 180 days, the N mineralisation on the soil surface was lower for residues with a C : N ratio of 10 to 12 than for residues with a C : N ratio of 13 to 20. With tillage (0.25 m depth), the simulated net N mineralisation was fine graded and fell with increasing C : N ratios from 8 to 20 (Fig. 2.2b), similar to the results published by Nicolardot et al. (2001) and Justes et al. (2009). Due to the discrepancy between the literature and the simulation results under no-till conditions, the simulation with tillage was applied instead. Within the soil, the net N mineralisation is usually lower (Coppens et al., 2006) due to N stabilisation by microbial biomass, but the simulation still delivers valuable indicators for the evaluation of cover crop species.

Inputs in the present implementation of the model were gained from own samplings and measurements (initial cover crop and soil parameters), measurements from weather stations (climate data) (DWD 2014 and LfULG 2014 personal communication), and from external sources and the literature (soil characterisations) (LfULG, 2014a; LfULG 2014 personal communication; Lux, 2015; Table 2.1 and 2.2). The model was run from 25 October, 30 October and 31 October (day of biomass harvest) at PI, GR and KÖ, respectively for 140 days up to the intended seeding of pea cash crops in March (Table 2.1). The initial condition for the simulation was the presumed termination of the cover crops with a roller-crimper at the day of the biomass harvest. The input for the model was a single intervention (stem or leaf biomass) or two interventions (stem and leaf biomass) of organic residue supply with the same quantity of stem, leaf or combined stem and leaf dry matter present at biomass harvest. The residue type input parameter was 'immature crop residues' with plant species and plant compartment specific C contents and C : N ratios. For the residue incorporation, a single pass of tillage (0.25 m depth) was assumed at the day of cover crop termination. No additional fertilisation or irrigation was supplied during the simulation period. Location specific climate conditions were used for each simulation.

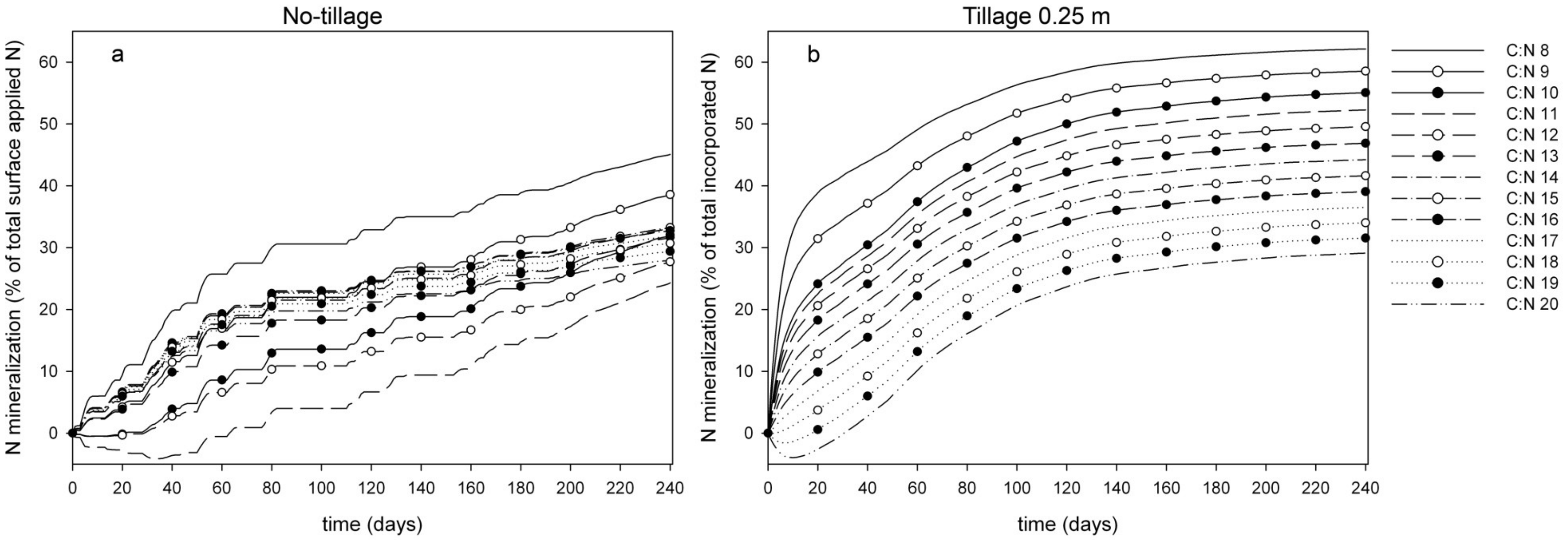

Fig. 2.2a-b. Comparison of proportionate net N mineralisation in no-till (a) and tilled conditions (b) from immature crop residues with fixed dry matter (1 Mg ha^{-1}) and C content (40%) as well as variable C : N ratios (8 to 20 : 1).

Table 2.2. Monthly mean, trial period and simulation period mean temperature, monthly precipitation and cumulative precipitation during the cover crop trial and simulation period.

	Temperature (°C)						Precipitation (mm)					
	Pillnitz (PI)[a]		Groß Radisch (GR)[b]		Köllitsch (KÖ)[b]		Pillnitz (PI)[a]		Groß Radisch (GR)[b]		Köllitsch (KÖ)[b]	
Month	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009	2008	2009
January	3.2	-2.5	3.8	-2.1	4.3	-3.2	65	16	50	16	57	8
February	5.1	1.4	5.0	0.5	4.8	0.8	13	61	18	30	14	27
March	5.6	5.8	4.9	5.3	4.9	5.3	45	62	42	57	53	48
April	8.8	13.0	8.5	12.9	8.3	12.2	93	7	61	5	110	9
May	15.1	14.7	14.4	14.6	14.9	14.4	26	68	17	91	11	54
June	18.5	15.8	18.3	15.7	18.1	15.6	48	85	48	123	63	45
July	19.2	19.3	19.1	19.1	19.2	19.0	59	70	87	77	39	91
August	18.9	19.6	18.6	19.3	19.0	19.7	95	98	83	69	42	75
September	13.5	15.9	13.6	15.8	13.2	15.3	41	28	30	30	55	29
October	9.8	8.9	10.0	8.4	9.9	10.7	81	98	90	65	55	56
November	6.1	8.1	5.7	8.2	5.7	8.0	28	42	24	39	10	99
December	2.9	0.9	2.6	0.3	1.8	0.2	49	79	34	53	30	148
Year	10.6	10.1	10.4	9.8	10.3	9.8	643	714	584	655	539	689
	Mean temperature (°C) trial and simulation period						Cumulative precipitation (mm) trial and simulation period					
	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2	P1	P2
	14.1	2.7	14.1	2.4	14.0	2.1	217	216	203	161	152	123

P1, mean temperature and cumulative precipitation during the cover cropping period from cover crop seeding to cover crop dry matter sampling (from August to October 2008).
P2, mean temperature and cumulative precipitation during the crop simulation period from termination to seeding of the cash crop (November 2008 to March 2009).
[a] Climate data (DWD 2014 personal communication).
[b] Climate data (LfULG 2014b).

2.3 Results

2.3.1 Climate

The climate differed between locations in terms of total precipitation and its monthly distribution. In both years, the total precipitation at PI, GR and KÖ ranged above the historical average (597, 554 and 453 mm, respectively) (LfULG 2014 and SBS 2015 personal communication; LfULG, 2014b; DWD 2014 and 2015 personal communication). The total precipitation in 2008 and 2009 was largest at PI with a difference of +59 mm in both years to GR, and +104 and +25 mm (2008 and 2009, respectively) to KÖ (Table 2.2). In the cover cropping period, the monthly precipitation in August 2008 at PI and GR was 126 and 98% higher, respectively than at KÖ, while in September slightly more precipitation occurred at KÖ than at the other locations. During the main months of the simulation period the cumulative precipitation at PI and GR was 76 and 31% higher, respectively than at KÖ.

Mean annual temperatures in 2008 at PI, GR and KÖ were 10.6, 10.4 and 10.3°C, respectively (Table 2.2). These temperatures were between 0.3 and 0.5°C above the long term average, whereas in 2009 they were similar or slightly below the average (10.1, 9.9, 10.0°C, at PI, GR and KÖ, respectively) (LfULG 2014 and SBS 2015 personal communication, LfULG, 2014b; DWD 2014 and 2015 personal communication). Monthly mean temperatures in the cover cropping period (August to October) varied only marginally between the three locations. However, monthly mean temperatures during the second and third month of the N mineralisation simulation were at PI 1.1 and 0.7°C (December and January, respectively) higher than at KÖ.

2.3.2 Cover crop emergence

Precipitation before and after cover crop seeding was sufficient for high field emergences, which differed slightly between species and locations (Table 2.3). At all three locations sunflower, oats and buckwheat consistently displayed the highest field emergences (between 82 and 97%, Table 2.4). At PI and GR the field emergences of mustard and hemp were below the other species. At KÖ the mustard and hemp emergence was higher and within the range of the other species.

Table 2.3. Sources of variation, field emergence, dry matter production of combined and separated cover crop materials and the proportion of stem dry matter (stem%), weed dry matter production, N accumulation in combined and separated cover crop materials and N accumulated in the cover crop stem (N% stem), N accumulation in weed biomass, C : N ratio in stem and leaf material, and the inorganic soil N in the 0 to 0.6 m soil horizon after harvest.

Source of	Field	Shoot dry matter production					Shoot N accumulation					C : N ratio		Soil N[c]
variation	emergence	Total	Stem	Leaf	Stem%[a]	Weeds	Total	Stem	Leaf	N% Stem[b]	Weeds	Stem	Leaf	0 to 0.6 m
Location (L)	n.s.	***	***	***	n.s.	***	***	***	***	n.s.	***	***	***	n.s.
Fertiliser (F)	n.s.	***	***	***	*	n.s.	***	***	***	***	**	**	***	***
Species (S)	***	***	***	***	***	***	***	***	***	***	***	***	***	***
L x F	n.s.	**	***	*	**	n.s.	*	n.s.	*	n.s.	n.s.	*	*	*
L x S	***	**	***	***	***	***	**	***	*	***	***	***	***	***
F x S	n.s.	n.s.	n.s.	*	***	**	n.s.	n.s.	n.s.	***	*	n.s.	n.s.	n.s.
L x F x S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	*	n.s.	n.s.	**

[a] proportion of cover crop stem dry matter on total cover crop dry matter production;
[b] proportion of N accumulation stored in the cover crop stem; [c] inorganic soil N.
Component of variation: *, **, *** significant at *P* levels of $P < 0.05$, 0.01, 0.001, respectively; n.s., not significant.

Table 2.4. Cover crop field emergences (averaged across fertiliser levels).

	Cover crop field emergence (% germinated plants of viable seeds)		
Species	Pillnitz (PI)	Groß Radisch (GR)	Köllitsch (KÖ)
Rye	80 b A	70 b A	75 b A
Oats	83 ab A	97 a A	91 a A
Sunflower	93 a A	94 a A	82 ab A
Mustard	51 c B	46 c B	75 b A
Buckwheat	87 ab A	86 a A	93 a A
Hemp	61 c B	58 c B	88 a A

Within a column, lower case letters display significant differences between cover crops based on Tukey-Kramer means separation (α = 0.05);
within a row, upper case letters display significant differences between locations based on Tukey-Kramer means separation (α = 0.05).

2.3.3 Dry matter production

At PI the seedbed preparation took place almost 7 weeks earlier, and the cover crop seeding was carried out 13 and 14 days ahead of the locations GR and KÖ, respectively. This might have contributed to a larger biomass for all species at PI compared to GR and KÖ. Cover crop plant stands in early September are shown in Fig. A 4 and A 5 to A 8a-c. Total dry matter production ranged from 4.32 to 7.73 Mg ha^{-1}, 0.95 to 3.73 Mg ha^{-1} and 2.16 to 3.94 Mg ha^{-1} at PI, GR and KÖ, respectively (Table 2.3, Fig. 2.3a-c). Even with this variation, the cover crop species with the largest biomass production were similar at all locations. At PI and KÖ the sunflower displayed the largest dry matter production (7.46 and 3.53 Mg ha^{-1}, respectively, data not shown), while at GR the sunflower, oats and rye produced equally large amounts of biomass (3.15, 2.59 and 2.43 Mg ha^{-1}, respectively). At PI and KÖ the total biomass production by rye (5.51 and 2.82 Mg ha^{-1}, respectively) was second to sunflower.

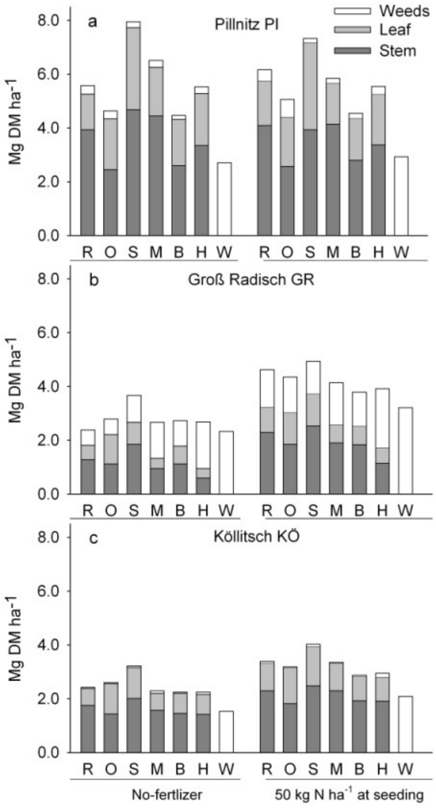

Fig. 2.3a-c. Total dry matter (DM) partitioned into cover crop stem and leaf material, as well as weed biomass in plots of rye (R), oats (O), sunflower (S), mustard (M), buckwheat (B), hemp (H) and no cover crop – weeds (W), respectively. The cover crop and weed dry matter was produced without fertiliser (left side columns) and with 50 kg N ha^{-1} fertiliser (right side columns), respectively.

The separation of the total biomass into stem and leaf material revealed divergent amounts of stem and leaf biomass produced by the different species. The largest stem dry matter production at PI, GR and KÖ was shown by sunflower and rye and, at PI, by mustard. At PI, sunflower had the largest leaf biomass, while at GR and KÖ oats and sunflower displayed an equally large leaf dry matter production. Sunflower produced large amounts of stem and leaf material, but the stem proportion of the total biomass was comparatively low. Rye and mustard were the species which displayed, at all locations, consistently the largest stem% (Table 2.5). At all locations oats displayed the lowest stem% among the species. It was noted that at PI the sunflower stem% was equally low, while it was larger than oats at GR and KÖ.

Averaged over locations, the incorporation of fertiliser before seeding only increased the stem% of oats and buckwheat. Fertiliser consistently increased the total cover crop and stem biomass at GR and KÖ, but had no effect at PI. Averaged over locations, the leaf dry matter was significantly larger in the fertilised plots of rye, sunflower, mustard and hemp while the remaining species showed no response to additional fertilisation.

The weed biomass in the cover crop plots was highest at GR and lowest at KÖ, ranging from 0.02 to 2.18 Mg ha^{-1}, without cover cropping the weed biomass was similar at PI and GR and larger than at KÖ (Table 2.3, Fig. 2.3a-c). At all locations cover cropping significantly reduced the weed biomass compared to weed plots without cover crops. At GR and KÖ, the weed biomass in hemp plots was larger than in the other cover crops. At PI the weed biomass in plots of hemp was without difference to the other crops. Fertilisation before seeding increased the weed biomass in rye and oats, but had no effect on the weed biomass in the plots with the other species.

2.3.4 Shoot N accumulation and inorganic soil N

The total N accumulation in the combined stem and leaf material ranged from 66.9 to 129.7 kg ha^{-1}, 13.5 to 50.2 kg ha^{-1}, and 29.5 to 62.9 kg ha^{-1} at PI, GR and KÖ respectively (Fig. 2.4a-c). The available inorganic soil N contents at harvest showed interactions between location, additional fertilisation and cover cropping (Table 2.3). The inorganic soil N resources in the bare soil fallow plots were, at the end of October in both the unfertilised and fertilised plots, higher at PI compared to GR and KÖ. Cover cropping significantly reduced the available inorganic N resources compared to the fallow plot without plant cover. Only buckwheat in the fertilised plots at KÖ and rye and hemp in the unfertilised plots at GR were not able to significantly reduce the inorganic soil N resources compared with the fallow plot.

Table 2.5. Proportion of the cover crop stem (stem%) on the total dry matter production.

	stem% on total dry matter production										
	Pillnitz (PI)			Groß Radisch (GR)			Köllitsch (KÖ)			Fertiliser x Species[b]	
Species	-N	+N	L x S[a]	-N	+N	L x S	-N	+N	L x S	-N	+N
Rye	75	71	73 a A	71	71	71 ab A	74	69	71 a A	73 a A	70 ab A
Oats	57	58	57 c A	51	61	56 d A	56	58	57 d A	54 c B	59 d A
Sunflower	61	55	58 c C	69	68	69 b A	64	63	63 c B	65 b A	62 d A
Mustard	71	73	72 a A	72	74	73 a A	71	69	70 a A	71 a A	72 a A
Buckwheat	60	65	62 b B	63	72	67 bc A	66	68	67 b A	63 b B	68 bc A
Hemp	63	64	64 b A	62	66	64 c A	66	68	67 b A	64 b A	66 c A

-N: without fertiliser; +N: with 50 kg N ha^{-1} incorporated before seeding;

[a] L x S, Location x Species interaction: Within a column lower case letters display significant differences between species based on Tukey-Kramer means separation ($\alpha = 0.05$), within a row, upper case letters display significant differences between locations based on Tukey-Kramer means separation ($\alpha = 0.05$);

[b] Fertiliser x Species interaction: Within a column lower case letters display significant differences between species based on Tukey-Kramer means separation ($\alpha = 0.05$), within a row, upper case letters display significant differences between fertiliser treatments based on Tukey-Kramer means separation ($\alpha = 0.05$).

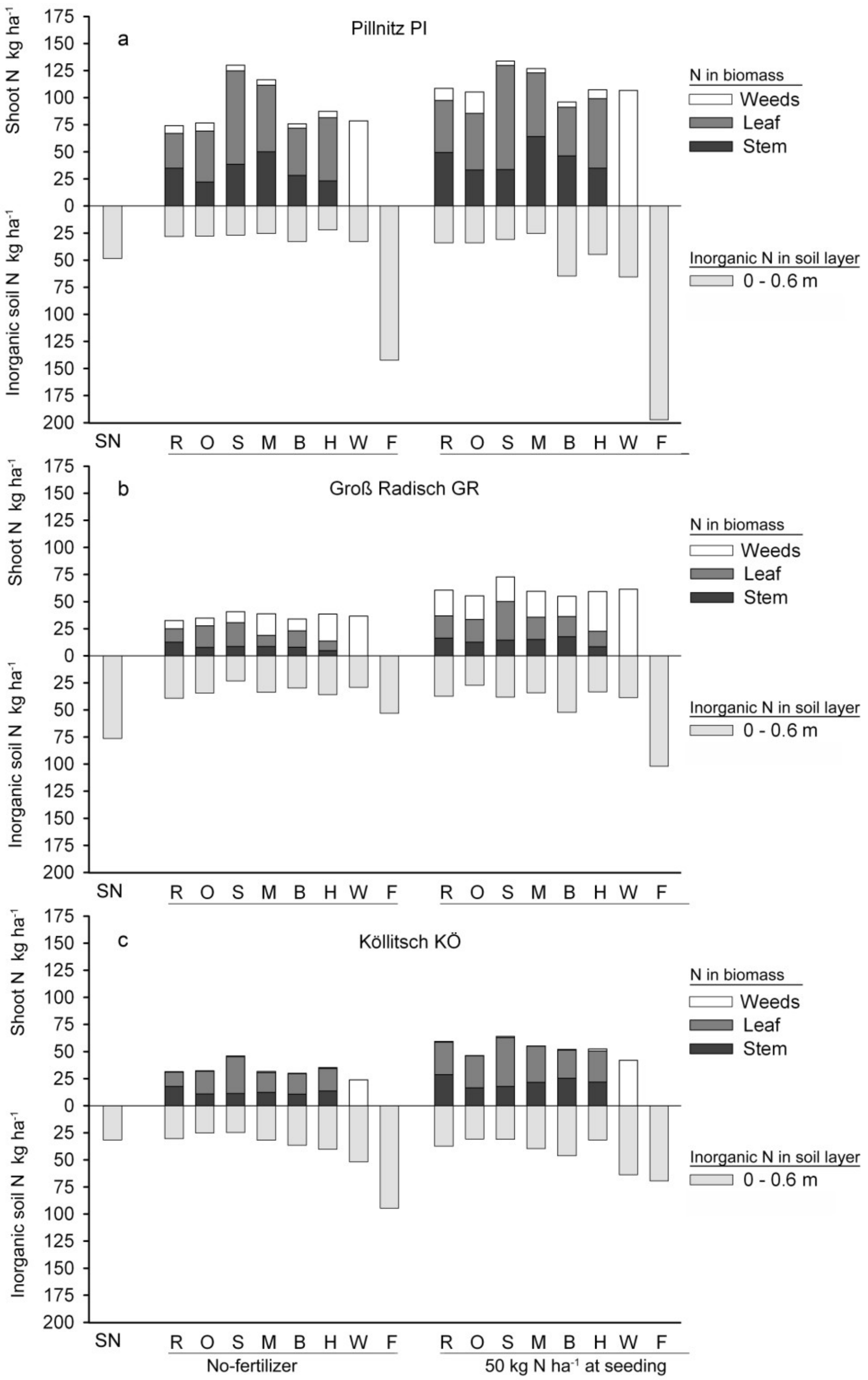

Fig. 2.4a-c. Inorganic soil N at seeding (SN) and after harvest in plots of rye (R), oats (O), sunflower (S), mustard (M), buckwheat (B), hemp (H), no cover crop – weed plot (W) and bare soil fallow (F), respectively. Shoot N accumulation of the respective cover crops partitioned into stem and leaf material as well as weed shoot N accumulation. Shoot N accumulation without fertiliser (left side columns) and with 50 kg N ha^{-1} fertiliser (right side columns), respectively.

Within the species there were only small variations in their ability to reduce inorganic soil N resources as shown by similar inorganic soil N contents in cover crop plots.

At PI and GR fertilisation before seeding significantly increased the inorganic soil N resources in the bare soil fallow plots; this was not the case in most of the cover crop plots. Exceptions were plots of buckwheat at PI and GR, hemp at PI and sunflower at GR which showed significant larger inorganic soil N contents in the fertilised compared to the unfertilised plots.

At PI, GR and KÖ the largest total N accumulation was displayed by sunflower with 127.8, 39.2 and 53.3 kg ha^{-1}, respectively (data not shown). Equally large was the accumulation by mustard at PI (117.3 kg ha^{-1}), and by rye, oats (both species 30.4 kg ha^{-1}) and buckwheat (29.2 kg ha^{-1}) at GR (data not shown). The total N accumulation of the remaining cover crops at PI and KÖ did not vary significantly from one to another.

At PI and KÖ the largest N accumulation in stem material was shown by mustard (56.7 kg ha^{-1}) at PI and rye (22.6 kg ha^{-1}) at KÖ (data not shown). At GR the rye (14.4 kg ha^{-1}) accumulated the most N in the stem, but without significant difference to buckwheat, mustard and sunflower. Instead of storing N in the stem, the sunflower allocated significantly more N than the other species in its leaf material. Only at GR the N in oats leaf material was similarly large as in sunflower.

A species specific increased allocation of N towards the immature cover crop stem was consistently shown at all locations by rye. The proportion of total N in the rye stem material ranged between 48 and 53% (Table 2.6). Similarly large allocations to the stem material were only shown by mustard at PI and GR. For sunflower the proportion of accumulated N in the stem material only ranged between 27 and 29%.

Table 2.6. Proportion of total N accumulated in the stem (N% stem) of individual cover crops (averaged over fertiliser levels).

	% of total N accumulation in cover crop stem		
Species	Pillnitz (PI)	Groß Radisch (GR)	Köllitsch (KÖ)
Rye	51 a	48 a	53 a
Oats	36 c	33 cd	35 c
Sunflower	29 d	28 d	27 d
Mustard	48 ab	44 ab	39 b
Buckwheat	45 b	42 b	43 b
Hemp	32 cd	37 c	42 b

Within a location column, lower case letters display significant differences cover crop species based on Tukey-Kramer means separation (α = 0.05).

The influence of fertilisation before seeding on the total cover crop N accumulation was consistent. At PI, GR and KÖ it increased the total N accumulation in cover crop biomass by

21, 56 and 61%, respectively (data not shown). Furthermore, fertiliser increased the share of N accumulated in stem material for buckwheat and hemp. In the fertilised rye the proportion of accumulated N in the stem was reduced and a higher percentage of N was stored in the leaf material. The accumulation of N in leaf material at GR and KÖ was increased through additional fertilisation by 49 and 57%, respectively, while it had no effect at PI.

In cover crop plots the accumulation of N in weed biomass was significantly lower than in the no cover crop – weed plot. The exception was the N accumulation in weed biomass in the unfertilised hemp plot at GR which was similar to the no cover crop – weed plot.

2.3.5 C : N ratio in stem and leaf material

During biomass harvest at the end of October most cover crops had an emerging inflorescence or were flowering. Due to the earlier seeding at PI, the majority of species displayed advanced growing stages compared to the other locations. Growing stages at GR and KÖ were similar at the time of harvest (data not shown). However, the C : N ratio of stem and leaf material displayed no consistent differences between locations. The stem C : N ratio ranged from 25 to 64, 42 to 88 and 32 to 74 at PI, GR and KÖ, respectively (Table 2.7). Independent from fertilisation the largest stem C : N at PI, GR and KÖ was consistently shown by sunflower (52, 82, 67, respectively). Only at PI, hemp (53) displayed an equally large stem C : N ratio. The growing stages of mustard at all locations and of buckwheat at the PI and KÖ locations were similar. Yet all cover crops, with the exception of rye and hemp, displayed a significantly lower C : N ratio at the PI location than at GR and KÖ. N fertilisation reduced the stem C : N only at PI and KÖ (-14 and -11, respectively) but had no effect at GR.

The leaf C : N ratio ranged from 11 to 18, 14 to 25 and 12 to 23 at PI, GR and KÖ, respectively (Table 2.7). Independent from fertilisation, oats displayed, at all locations, the largest leaf C : N ratio, although at PI the leaf C : N of rye and buckwheat were similarly high. The second largest leaf C : N at PI was shown by sunflower and at GR and KÖ by rye, as well as by buckwheat at GR. A low leaf C : N at all locations was shown by mustard and hemp, and at GR and KÖ, also by sunflower. Fertiliser reduced the leaf C : N at PI and KÖ slightly, but had no effect at GR.

2.3.6 Simulated N mineralisation from cover crop residues

2.3.6.1 Proportionate net N mineralisation and immobilisation from residue N input

The proportionate net N mineralisation (percentage mineralised of total incorporated N) from separate and combined leaf and stem material input displayed some variations between locations in conjunction with the variability of C : N ratios at the PI, GR and KÖ location (Table 2.7 and Fig. 2.5a-f). The proportionate net N mineralisation from leaf N input after 140 days ranged from 8.0 to 29% at PI, -12 to 27% at GR and -9 to 25% at KÖ. In March, the N input of leaf material for the majority of cover crops was, to some extent, mineralised at GR and KÖ. Exceptions were the N immobilisation at GR for both fertilised and unfertilised oats and fertilised rye leaf material and at KÖ for unfertilised leaf material of oats and rye (Fig. 2.5b-c). A larger proportional net N mineralisation cumulation after 140 days was shown by fertilised mustard leaf material (29, 24 and 24% of total incorporated leaf N at PI, GR and KÖ, respectively) as well as by unfertilised sunflower leaf material (20, 16 and 21% of total incorporated leaf N at PI, GR and KÖ, respectively) (Fig. 2.5a-c).

The proportionate net N immobilisation ranged, for the majority of cover crops stem materials, from -14 to -96% at PI, -72 to -139% at GR and -37 to -121% at KÖ for total incorporated stem N (Fig. 2.5d-f). Exceptions, with a larger net N immobilisation proportional to its N input, were shown at PI by unfertilised hemp stem material (-136% of total incorporated stem N) and at GR and KÖ by unfertilised and fertilised sunflower stem material (between -137 and -230% of total incorporated stem N). However, in the presence of sunflower leaf material the net N immobilisation would not be as high.

The combined proportional net N mineralisation of sunflower stem and leaf material after 140 days amounted at GR to -49 and -43% of total incorporated leaf and stem N (unfertilised and fertilised sunflower, respectively) and at KÖ to -28 and -19% of total incorporated leaf and stem N (unfertilised and fertilised sunflower, respectively) (Fig. 2.7a-c). At the different locations, the combined net N mineralisation (% of N input by leaf and stem residues) ranged from +6 to -48% at PI, -23 to -57% at GR and -8 to -46% at KÖ. Cover crops from fertilised plots at PI and KÖ displayed a tendency to proportionally immobilise less N based on their N input, while at GR this was reversed and many cover crops demonstrated a larger proportionate net N immobilisation when they were fertilised.

Table 2.7. C : N ratio in cover crop stem and leaf material.

	C : N ratio in cover crop stem and leaf material								
	Pillnitz (PI)			Groß Radisch (GR)			Köllitsch (KÖ)		
Cover crop stem	-N	+N	L x S[a]	-N	+N	L x S	-N	+N	L x S
Rye	50	36	43 b AB	44	61	53 bc A	42	34	38 c B
Oats	48	32	40 bc B	61	61	61 b A	55	46	51 b A
Sunflower	54	49	52 a C	88	75	82 a A	74	60	67 a B
Mustard	39	27	33 c B	43	54	49 c A	55	46	50 b A
Buckwheat	40	25	32 c B	58	42	50 bc A	56	32	44 bc A
Hemp	64	42	53 a A	52	58	55 bc A	44	37	41 c B
Cover crop leaf									
Rye	18	15	17 a B	19	21	20 b A	21	15	18 b B
Oats	18	16	17 a C	24	25	24 a A	23	20	21 a B
Sunflower	14	14	14 b A	15	14	15 d A	14	13	14 d A
Mustard	12	11	11 c B	15	14	15 d A	14	13	13 d A
Buckwheat	17	15	16 a B	19	17	18 bc A	17	15	16 c B
Hemp	13	12	12 c B	16	16	16 cd A	14	12	13 d B

-N: without fertiliser; +N: with 50 kg N ha^{-1} incorporated before seeding;

[a] L x S, Location x Species interaction: Within a column lower case letters display significant differences between species based on Tukey-Kramer means separation (α = 0.05), within a row, upper case letters display significant differences between locations based on Tukey-Kramer means separation (α = 0.05).

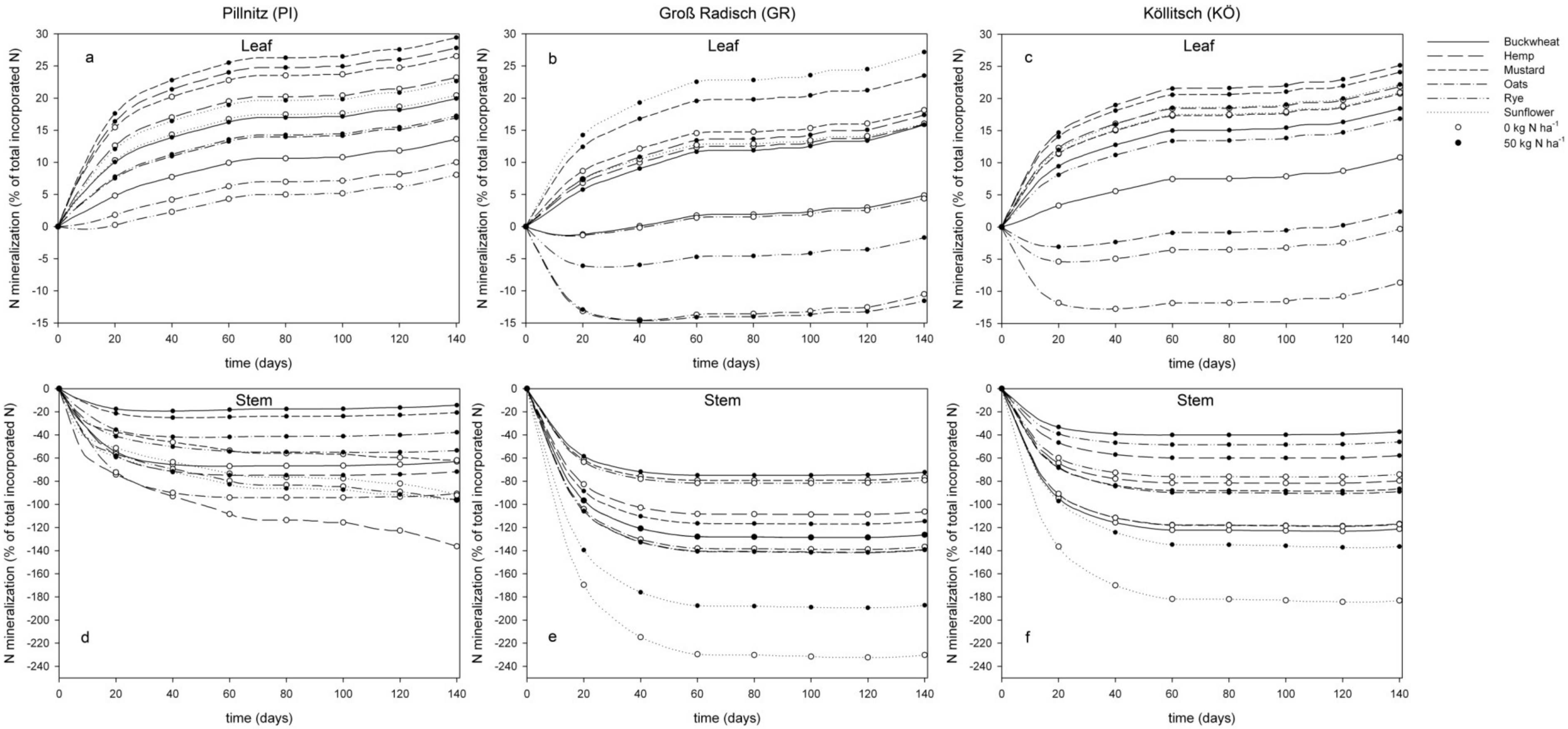

Fig. 2.5a-f. Proportionate net N mineralisation of separate cover crop leaf material (a-c) and stem material (d-f) at the Pillnitz (PI), Groß Radisch (GR) and Köllitsch (KÖ) location.

Without fertiliser, oats and rye were the only species which displayed a large net N immobilisation (between -40 and -50% of N input by leaf and stem residue) at two locations, while for sunflower this was only the case at one location (Fig. 2.7a-c). Oats grown in low inorganic soil N conditions at GR and KÖ showed net N immobilisation of -45 and -46% of N input by leaf and stem residue, respectively (PI -21%). The net N immobilisation for unfertilised rye was -48, -34 and -42% of N input by leaf and stem residue at PI, GR and KÖ, respectively. For unfertilised sunflower -20, -49 and -28% of N input by leaf and stem residue was immobilised at PI, GR and KÖ, correspondingly. Fertilisation decreased the potential N immobilisation at PI and KÖ for all three species and increased the N immobilisation at GR for rye and oats by 23 and 7 percentage points, respectively.

2.3.6.2 Net N mineralisation from separated and combined leaf and stem material

The estimated net N mineralisation patterns of leaf and stem material, as well as combined stem and leaf material, were influenced by the residue material and varied between the cover crop species. Differences in N mineralisation of residues between locations appeared in the form of increased N mineralisation from leaf material and reduced N immobilisation from stem material at PI compared with GR and KÖ (Fig. 2.6a-f). After 140 days the potential N mineralisation from leaf material ranged from 2.6 to 22.1, -3.1 to 7.3 and -1.8 to 10.0 kg N ha^{-1} at PI, GR and KÖ, respectively (Fig. 2.6a-c). At all locations the majority of N mineralisation from leaf material occurred during winter, within the first 60 days of the simulation. At the end of the simulation in March the cumulative net N mineralisation from unfertilised oats leaf material was 4.8, -2.2 and -1.8 kg N ha^{-1} at PI, GR and KÖ, respectively and lower than the N mineralisation by unfertilised sunflower (17.9, 3.8 and 7.2 kg N ha^{-1} at PI, GR and KÖ, respectively).

The net N mineralisation from stem material was negative (N immobilisation). With a few exceptions at PI, the majority of N immobilisation occurred also in the first 60 days (Fig. 2.6d-f). After 140 days, the potential N immobilisation ranged from -7.0 to -33.8, -5.6 to -25.8 and -9.4 to -23.5 kg N ha^{-1} at PI, GR and KÖ, respectively. In conjunction with the large amount of sunflower stem material produced without fertiliser at PI, the potential net N immobilisation (-33.8 kg N ha^{-1}), was larger than at GR and KÖ (-19.9 and -20.7 kg N ha^{-1}, respectively).

For sunflower and the majority of the other cover crops, the N immobilisation through stem material could be large enough to offset the net N mineralisation from leaf material. The combined net N mineralisation from stem and leaf material ranged after 140 days from 7.4 to -32.2, -4.2 to -22.5 and -4.1 to -14.7 kg N ha^{-1} at PI, GR and KÖ, respectively (Fig. 2.7 d-f). Only at PI two crops (fertilised mustard and buckwheat: 7.4 and 3.1 kg N ha^{-1}, respectively) displayed a net N mineralisation.

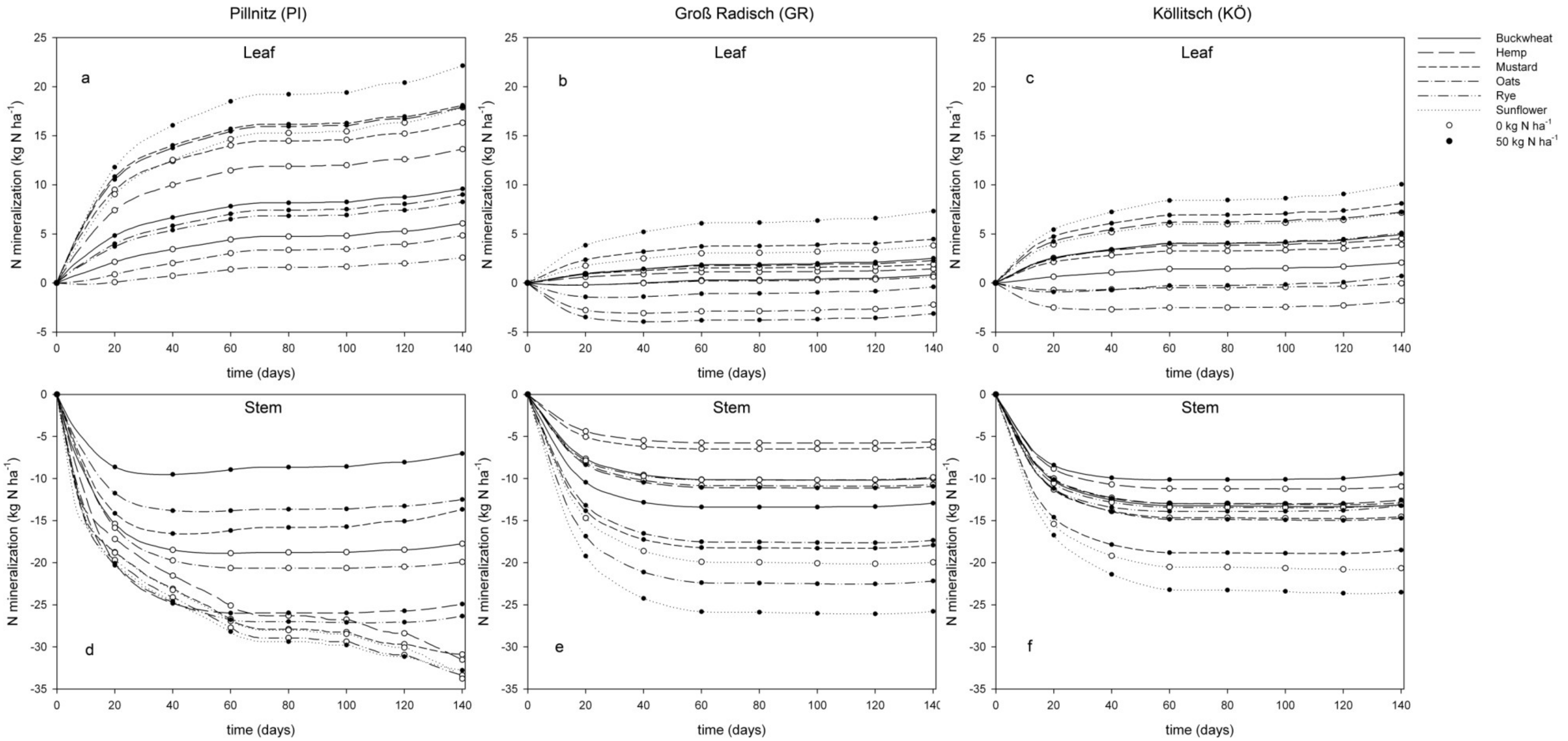

Fig. 2.6a-f. Net N mineralisation of separate cover crop leaf material (a-c) and stem material (d-f) at the Pillnitz (PI), Groß Radisch (GR) and Köllitsch (KÖ) location.

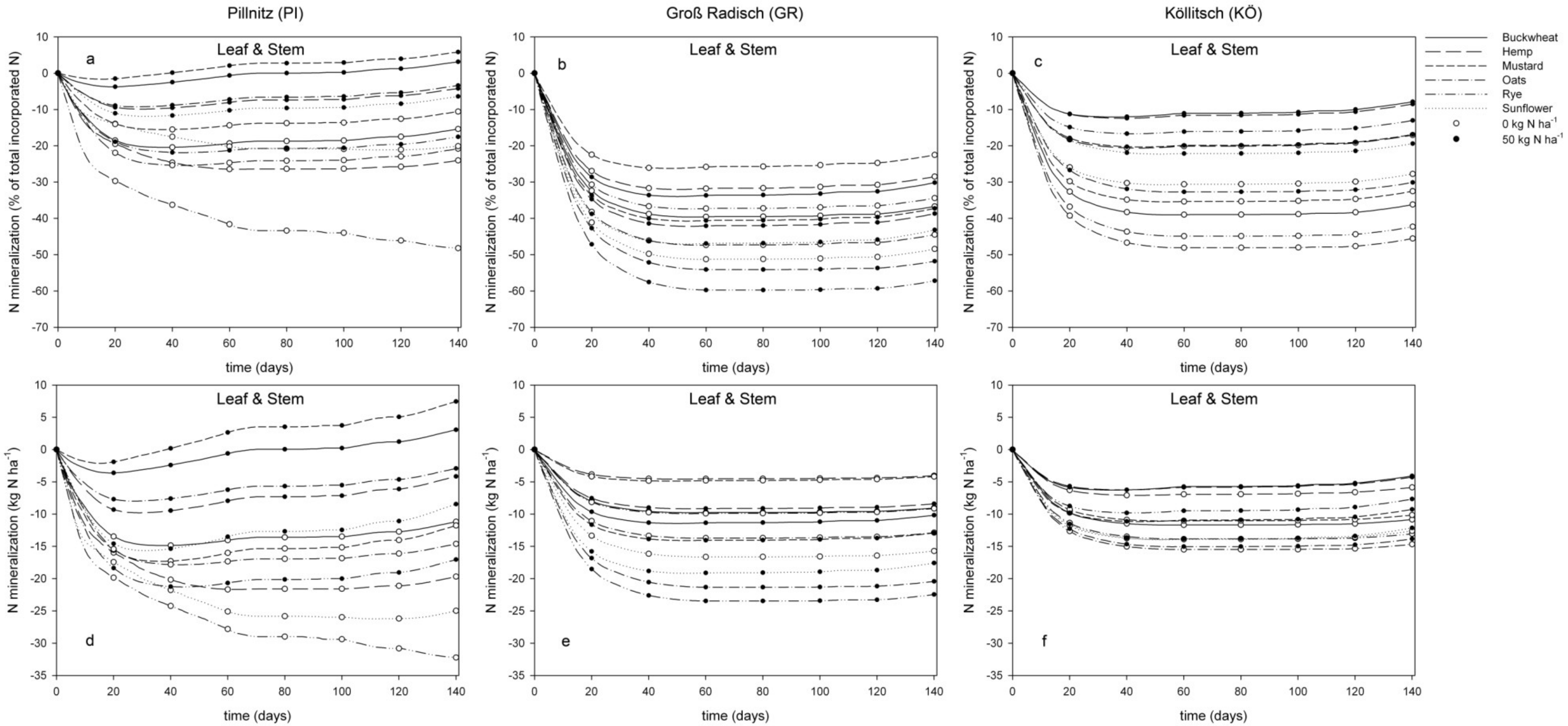

Fig. 2.7a-f. Proportionate net N mineralisation (a-c) and net N mineralisation (d-f) of combined cover crop leaf and stem material at the Pillnitz (PI), Groß Radisch (GR) and Köllitsch (KÖ) location.

2.4 Discussion

2.4.1 Dry matter production

The total biomass production at PI was nearly double than at GR and KÖ. This could be attributed to the earlier seeding at PI, but was likely also the result of large inorganic soil N resources at PI. These resources were accumulated by the cover crops but remained in the bare soil fallow at the end of October (Fig. 2.4a). At PI, the preceding spring barley crop was terminated by flail mowing and the chopped residue was incorporated nearly one month before cover crop seeding, probably increasing the available inorganic soil N resources through N mineralisation during the cover cropping phase so that inorganic soil N was not a limiting factor for cover crop growth. This hypothesis is supported by the large available inorganic soil N resources in the unfertilised bare soil fallow plot at harvest (Fig. 2.4a) and the absent response of the cover crop biomass production to additional fertilisation with 50 kg N ha^{-1} before seeding at PI. At the GR and KÖ locations, fertilisation increased the total dry matter production, which indicates a limitation by low available N resources.

Particularly at GR, N resources were limited because cover crops competed with large amounts of weeds, resulting in reduced N accumulation by cover crops compared to KÖ and PI. Differences in N availability and accumulation between locations also manifested in the C : N ratio of stem and leaf material. Averaged over species, at PI and KÖ, fertilisation before seeding reduced the C : N ratio of both the stem and leaf material while it had no effect at GR (data not shown), indicating a stronger N shortage at GR than at KÖ. Campbell et al. (1977) showed in a study with cereal grain that plant N content increased with N input rates through fertiliser application. At PI and KÖ elevated N accumulation through fertilisation increased the proportion of N in plant biomass (data not shown), reducing the C : N ratio as a consequence. For the individual species differences between locations were less consistent, but four of the six species grown at PI and KÖ displayed significantly lower C : N ratios in the leaf material than at GR.

The impact of advanced plant development at PI compared to GR and KÖ on the cover crop C : N ratio was not consistent. Differences between PI and the other locations did not consistently occur even with the advanced growing stage at PI. Furthermore differences occurred between stem and leaf C : N ratios at the GR and KÖ location with similar growing stages. This indicates that the impact of advanced plant development at PI was less influential for the C : N ratio of the plant compartments. The C : N ratios were probably influenced to a larger extent through the N supply during growth.

The N mineralisation from cover crop material is influenced by the amount of carbon input and the C : N ratio of the incorporated dry matter. In the present study the simulated N mineralisation tended to be larger at PI than at GR and KÖ. For example at PI unfertilised oats leaf material displayed a positive proportional net N mineralisation, while it demonstrated N immobilisation at GR and KÖ (Fig. 2.5a-c). This probably was due to larger N accumulation in the unfertilised oats leaf material at PI (47 kg N ha^{-1}) compared to GR and KÖ (19.9 and 20.9 kg N ha^{-1}, respectively) and the low C : N ratio at PI (18) compared to GR and KÖ, (24 and 23, respectively; Table 2.7). During decomposition mineralised inorganic N which is not incorporated into microbial biomass would at PI be easily available for additional microbial biomass production leading to increased N mineralisation. At GR and KÖ the N immobilisation was concurrent with reduced N accumulation and increased C : N ratio of oats leaf material. This could be attributed to the reduced N availability from cover crop biomass, requiring increased supply of N from the already diminished inorganic soil N resources to allow for decomposition of the supplied cover crop material.

The seeding rate of cover crops influences the relation of stem and leaf material for the cover crops used in this study. Steer et al. (1986) found larger stem percentages on the shoot dry matter in dense plant stands of sunflower. Conclusions drawn from the present results are only applicable for similar seeding rates. The results of the present study can be used as a point of reference for future examinations that are needed to determine the relations of stem and leaf material with different seeding rates under conditions of organic cover cropping.

Sunflower produced consistently large amounts of biomass (Fig. 2.3a-c), which at PI were similar to the sunflower biomass stated by Forentìn et al. (2011) for high fertility conditions, and at GR and KÖ in the unfertilised plots in accordance with cover crop biomass in another organic system (Neuhoff and Range, 2012). It was higher than in a reduced tillage organic trial (Rühlemann and Schmidtke, 2015), which could be attributed to the sunflower seedbed preparation in the present study by plough tillage which alleviated soil compaction and controlled weeds effectively. At the same time, sunflower was one of the cover crops with the largest N accumulation, even in low N availability, which could be attributed to water and nutrient assimilation through the deep rooting taproot (up to 2.9 m soil depth) while the majority of the sunflower roots are present between 0 and 0.1 m soil depth (Dardanelli et al., 1997; Miyazawa et al., 2010). Hocking and Steer (1982) showed that sunflowers are able to sufficiently increase N uptake efficiency in low N conditions, explaining the large N accumulation in the present study. However, the preferred use of shallow inorganic soil N resources leaves deeper resources exposed for leaching or use by deep rooting weeds.

Sunflower dry matter accumulation was mostly in the stem, while the majority of N was accumulated in the leaf material in accordance with results found for sunflower by Hocking and Steer (1983). The resulting low leaf C : N ratio could lead to a fast N mineralisation after cover crop termination through a killing frost in no-tillage conditions or through plough tillage (Fig. 2.6a-c). The N mineralisation simulation from stem material with a large C : N ratio indicated that the strong N immobilisation by sunflower stem material could compensate for the N mineralisation of sunflower leaf material when both materials mineralised simultaneously next to each other (Fig. 2.7e-f).

Nevertheless, sunflower leaves would decompose quickly on the soil surface and only sunflower stems would be left to cover the ground and reduce the light interception. Due to the low number of stems, sunflower would likely not be sufficient to suppress weeds. Sunflower can, therefore, only be recommended for systems in which winter legumes are sown into autumn-rolled sunflower plant stands.

Contrasting to sunflower, rye and oats displayed consistently large leaf C : N ratios (Table 2.7). Rye additionally exhibited large stem% on the total biomass and a biomass production similar (GR) or second (PI and KÖ) to sunflower. At PI, the rye biomass without and with fertiliser was larger than in an autumn cover crop trial with winter rye by Kruidhof et al. (2008) who used fertiliser and a higher seeding rate, presumably due to their late seeding in early September compared to end of July in the present trial. In another experiment by Kruidhof et al. (2008), the winter rye was sown into a fertilised seedbed on July 25 2003 resulting in an autumn biomass production that was intermediate between the unfertilised and fertilised rye at the GR and KÖ location (Fig. 2.3b-c). This can be attributed to the winter rye establishment of only 37% and shows that a high N level and an early seeding date does not guarantee a biomass production as large as at PI.

Oats had diverging characteristics to rye in terms of the stem fraction on the total biomass, which was lower (GR and KÖ) than or similar (PI) to sunflower (Table 2.5). However, oats also showed consistently large leaf C : N ratios and its combined leaf and stem material N mineralisation (% of total incorporated N) was similar to rye. The oats dry matter production at PI was similar to the late season biomass in the second trial year by Stivers-Young (1998) and at GR and KÖ similar to the first trial year by Stivers-Young (1998) and Brennan and Smith (2005).

At PI, under conditions of high N availability, mustard produced more biomass than rye and oats while at the GR and KÖ location, with its lower N status, the unfertilised oats displayed a tendency for a larger biomass production than mustard (Fig. 2.3a-c). These results were similar to a trial by Stivers-Young (1998) and indicate that choice of species between oats and mustard should depend on the N status of the soil. For the no-till system it is also important that the mustard decomposes faster than oats over the winter (Stivers-Young, 1998, Grimmer and Masiunas, 2004). Stivers-Young (1998) also found that mustard loses more N over winter than oats, which is in accordance with the N mineralisation simulation in the present study. Thorup-Kristensen (1994) observed that the recovery of incubated nitrogen from fresh biomass was larger for mustard than for oats biomass. This and the stronger N mineralisation especially at PI could lead to increased weed growth in mustard plots due to larger N availability (Blackshaw et al., 2003). Nevertheless, mustard has shown to suppress weeds well into spring (Stivers-Young, 1998; Brust et al., 2014a). Therefore, it could be suited for the transition to no-till organic farming, but a non legume cash crop should be grown after a well developed mustard plant stand with large N accumulation to benefit from increased N mineralisation.

On soils with increased inorganic soil N resources, rye can accumulate large amounts of inorganic soil N and release it over longer time periods making it more suitable as a cover crop before grain legume cash crops. In low soil N conditions, rye and oats both seemed to be well-suited for the transition period due to their large amount of stems and slow N mineralisation. Furthermore, both rye and oats contain allelopathic compounds which could further reduce the emergence of weeds (Putnam and DeFrank, 1983; Grimmer and Masiunas, 2005).

The buckwheat biomass production at PI was lower than for sunflower and mustard, but larger than in a buckwheat summer cover crop in a vegetable system in a study by Creamer and Baldwin (2000), most likely because the cover cropping period in the present study was about three weeks longer. At GR and KÖ the buckwheat dry matter production was similar to another organic system (Neuhoff and Range, 2012). Buckwheat germinates and develops quickly making it effective at suppressing weeds (Creamer and Baldwin, 2000), but it is also susceptible to light frost which limits its biomass production potential in temperate climate conditions. Buckwheat ceases its biomass production after the first light frost, while other species like rye and oats can continue their growth. The extended growing period increases the biomass production potential of rye and oats since the timeframe between the first frost and the end of the growing season can be one month or more (Rühlemann and Schmidtke, 2015). The buckwheat stem percentage of the total biomass was consistently large and could be increased through fertilisation. However, the low stem C : N ratio was further reduced when fertiliser was incorporated before seeding. The N mineralisation percentage of incorporated leaf material was average, but the N immobilisation from stem material was low, particularly when buckwheat was fertilised (Fig. 2.5a-f). As a result, the combined N mineralisation percentage of incorporated leaf and stem material was similar to fertilised mustard at PI and at GR and KÖ within the crops with low N immobilisation. Even without fertilisation at PI and GR, the combined N immobilisation was reduced. Due to the low frost tolerance of buckwheat and its marginal N immobilisation effect, weed growth could resume in late autumn and over winter thus buckwheat is not recommended to be used as a cover crop before the no-till seeding of spring grain legumes.

The hemp dry matter production at PI was above and, at GR and KÖ, below the results from another study by Brust et al. (2014b). The elevated biomass production at PI was lower than in a full summer season biomass trial (May till September) with the same variety, where hemp produced more than 10 Mg ha^{-1} (Poiša et al., 2010). Poiša et al. (2010) also showed that fertilisation can increase hemp dry matter production, which explains the increased biomass production at PI and in the fertilised plots at GR and KÖ. At PI and GR the hemp field emergence was lower than at KÖ (Table 2.4). However, only at GR the weed biomass in hemp was larger than in the other species, while at PI the weed biomass in plots of hemp was similar to the other crops (Fig. 2.3b-c). This shows that increased available soil N resources can improve the competitive ability of hemp through increased dry matter production even if the emergence is reduced. A cover crop study by Brust et al. (2014b) confirmed that during growth, hemp has low weed suppression and showed that weeds can regrow in spring. This might be explained by the low leaf C : N ratio and the resulting loss of ground coverage through fast decomposition. Fertilisation also increases the leaf biomass, which showed a high N mineralisation percentage of the incorporated N (Fig. 2.5a-c). For fertilised hemp the N immobilisation from combined leaf and stem material was low at PI and average at GR and KÖ. Due to its lower weed suppression during growth weeds can establish and accumulate mineralised N making hemp not a viable option for the transition period to organic no-till farming when growing spring sown grain legumes as a succeeding crop.

The weed biomass in all cover crops was largest at GR and lowest at PI while in plots without cover cropping the weed biomass at KÖ was lower than at PI and GR (Fig. 2.3a-c). Due to the larger dry matter production at PI the cover crops were able to suppress weeds more successfully than at GR. The lower weed dry matter production at KÖ could be attributed to low inorganic soil N resources at seeding. The weed species and the weed seed bank were not determined in this study but could have influenced the weed biomass production significantly resulting in differences between the locations.

2.4.2 Evaluation of cover crops for N immobilisation in no-till systems based on N mineralisation after conventional tillage

N mineralisation was simulated using model calculations that estimated the mineralisation under the assumption of residue incorporation. Coppens et al. (2006) compared N mineralisation from mature Brassicaceae (*Brassica napus* L.) between incorporation and surface application under controlled conditions with simulated rainfall at a temperature of 20°C. The cumulative N mineralisation after about 63 days was 75% larger for the surface applied residue than for the control, while the incorporated residues were 45% lower than the control. In a field study during the winter period with surface applied frozen Brassicaceae leaves, about 30% of the leaf N mineralised within 56 days (Dejoux et al., 2000). In the present study Brassicaceae (*Sinapis alba* L.) leaf material displayed similar N mineralisation rates at PI after 140 days and remained lower at GR and KÖ (Fig. 2.5a-c). This shows that the N mineralisation was probably underestimated and the majority of N from cover crop leaf material would be mineralised on the soil surface during winter. The inorganic N in the soil surface layer could then be subject to gaseous loss, leaching or uptake by weeds. This demonstrates that the simulation under tillage conditions has only limited predictive value for N mineralisation under no-till conditions. The residue incorporation by tillage increases the contact area between plant material and soil, resulting in increased N immobilisation compared to residue decomposing on top of the surface. However, it can be assumed that different plant materials will show a similar differentiation by N mineralisation when they decompose below or on top of the surface, so that the cover crop species evaluation obtained with the present simulation offers some indications for no-till systems. The model should be further improved and evaluated for N mineralisation simulations under no-till conditions to better predict the amount and time N is released from residues under no-till conditions.

Nicolardot et al. (2007) described in a study with surface applied wheat straw and rye leaves the presence of a very active microbial zone in the soil adjacent to the residues. In this zone, the surface application of wheat straw with a large C : N ratio resulted in net N immobilisation, while net N mineralisation occurred for rye leaves with a low C : N ratio. Under no-till conditions the fungal partition of the microbial biomass can translocate inorganic soil N into the residues to support the fungal population. This transfer is low towards residues with high N content (leaves) and high for residues with low N content (stem and leaf mixture) (Frey et al., 2000). This indicates that the proximity of leaf and stem material and the soil surface could result in a larger N immobilisation through microbial biomass. It can therefore be advantageous to increase the proximity of the plant material and the soil surface after the killing frost through the creation of a soil cover with the help of a roller-crimper. Besides its potential to protect accumulated N from leaching or gaseous losses, the rolling of cover crops could also decrease the weed biomass in the following cash crop (Davis, 2010).

2.5 Conclusion

The present study showed that cover crop dry matter production can be increased through early seeding and improved N availability as fertiliser increased biomass production in locations with low inorganic soil N supply. However, additional fertilisation also reduced in many cases the C : N ratio of the plant materials leading to potentially increased N mineralisation from combined leaf and stem material.

Sunflower produced large amounts of biomass, but the majority of its N was accumulated in easily decomposable leaf material. The stem amount is low and continuous soil cover and weed suppression over winter cannot be ensured due to fast decomposing leaves. In low N conditions, rye and oats produced similar amounts of biomass with increased amounts of stems. The N mineralisation from combined rye and oats material was low. Both species could be suited as cover crops in which spring grain legume cash crops are directly sown. Buckwheat biomass production was larger than that of hemp, but its stem C : N ratio was low. The hemp biomass production was reduced especially in low input conditions. Both species produce residues that are not suited for cover cropping before spring sown grain legume cash crops. Our study offered some indications on the suitability of sunflower and rye for early cover cropping in high N availability conditions (PI) ahead of autumn (sunflower and rye) and spring (rye) sown no-till cash crops; while rye and oats could be suited for locations with lower N resources (GR and KÖ) ahead of spring sown cash crops.

3. Chapter: Short-term Effects of Differentiated Tillage on Dry Matter Production and Grain Yield of Autumn and Spring Sown Grain Legumes Grown Monocropped and Intercropped with Cereal Grains in Organic Farming

3.1 Introduction

The use of mulch from cover crop residue for weed suppression and N immobilisation can be advantageous for subsequent legume cash crops. Establishment of the legume cash crop in autumn by no-till seeding into cover crop stands could increase the legume overwintering and enable early development and weed competition in spring. Intercropping of legume cash crops and cereal grains could further improve the weed suppression.

For both the faba bean and the field pea winter and spring cultivars are available. Another high potential legume for the transition period to conservation tillage in organic farming is the spring sown narrow-leafed lupin. Due to their ability to symbiotically fix N_2 they can compensate for the soil N deficiencies which gives them a competitive advantage over non-legume weeds during the period of conversion to no-tillage organic agriculture. Faba beans, field peas and lupins have been widely tested in organic low input systems and have shown their ability to reach good yields after plough tillage (Šarūnaitė et al., 2010; Šarūnaitė, 2013 personal communication; Urbatzka et al., 2011) yet only a few studies have been conducted under reduced or no-tillage conditions (Köpke and Schulte, 2008).

Therefore the objective of our trials with legume cash crops was to test the following hypotheses: (i) Legumes are well suited for the transition period to the organic no-tillage system and can reach grain yields similar to those in the reduced tillage and the plough tillage system. (ii) The legume-weed competition in the organic no-tillage system can be increased by the legume seeding in autumn. (iii) Legumes intercropped with cereal grains show a better weed suppression and can reach higher yields than the MC legume plant stands.

3.2 Material and methods

3.2.1 Experimental study site

Field trials were conducted from August 2009 until August 2010 on long-term organically farmed ground (equivalent to Council Regulation (EC) No 834/2007, European Union, 2007) at the Teaching and Research Farm Köllitsch (KÖ, 51° 30'N, 13° 06'E, 84 m a.s.l.) and two long-term certified organic farms (based on Council Regulation (EC) No 834/2007, European Union, 2007) located at Bockelwitz (BO, 51° 12'N, 12° 55'E, 209 m a.s.l.) and at Reinhardtsgrimma (RG, 50° 53' N, 13° 45' E, 350 m a.s.l.) in the South-East of Germany. The trials were set up as multi-location trials with three environments (three site-years) which were characterised by the three locations that differed in the climate and the soil. The trail site KÖ was chosen to represent a warm and dry climate at a planar location. The temperature and the precipitation averages for the 14 year period up to 2008 for the KÖ location were 9.9°C and 489 mm. The average temperature in 2009 (9.8°C) was similar to the long-term average while it was below the average in 2010 (8.1°C). The total annual precipitation was 689 mm in 2009 and 959 mm in 2010 which was much higher than the long term value. The site BO is located in a hill-land area of the foothill zone which has a climate with an average temperature slightly lower than at KÖ and a total precipitation intermediate between KÖ and RG. In the BO area the 14 year average temperature was 9.7°C while the total precipitation was 633 mm. The mean annual temperature and the total precipitation for the BO area was 9.7°C and 669 mm in 2009 and deviated from the long-term averages in 2010 with 8.1°C and 810 mm (LfULG, 2013). To represent a submontane location with lower temperatures and higher precipitation, the location RG was chosen. The 14 year mean annual temperature and total precipitation was 8.5°C and 781 mm, respectively. The mean annual temperature and total precipitation were 8.3°C and 808 mm, respectively in 2009 and 6.8°C and 1017 mm, respectively in 2010 (DWD, 2012, 2013 personal communication). Average monthly temperatures and total monthly precipitation during the experimental phase of the field trials are given in Fig. 3.1a-b. The late autumn temperatures in October ranged at BO and RG below the 14 year average and at all locations in November above the long term average (Fig. 3.1a). The winter period was long and the daily mean temperatures in January and February ranged almost constantly below 0°C (Fig. 3.2).

The soils at the three locations are different due to their varying origin. The soil at the KÖ location is a Fluvisol with a pH (0.01 M $CaCl_2$) of 5.4 and a plant available content of 25 mg kg^{-1} soil P, 47 mg kg^{-1} soil K, and 121 mg kg^{-1} soil Mg. At the BO location the soil is a

Luvisol with a pH (0.01 M $CaCl_2$) of 6.1 and a plant available content of 52 mg kg^{-1} soil P, 120 mg kg^{-1} soil K, and 131 mg kg^{-1} soil Mg. The soil at the RG location is a Cambisol with a pH (0.01 M $CaCl_2$) of 6.3 and a plant available content of 54 mg kg^{-1} soil P, 140 mg kg^{-1} soil K, and 88 mg kg^{-1} soil Mg. The plant available Mg was extracted in 0.01 M $CaCl_2$ while plant available P and K were extracted using the Calcium Acetate lactate (CAL) method after (Schüller, 1969). The soil C_{org} content was lowest at KÖ (1.45%) and largest at RG (3.31%) while it amounted to 1.57% at BO.

3.2.2 Field trial setup

The fields at all three locations had been under conventional plough tillage until the seeding of cereal grain as the preceding crop for the cover crop in 2009. At KÖ the preceding crops were winter wheat, alfalfa and alfalfa at BO winter barley, faba bean and winter wheat and at RG winter rye, potato and winter wheat in 2009, 2008 and 2007, respectively.

Before the cover crop seeding, stubble tillage with shallow soil inversion was conducted at a depth of 0.08 to 0.12 m using a stubble plough (Type Zobel, Germany), followed by the cover crop seedbed preparation (0.08 m depth) with a rotary harrow (Type Erpice Rotante, Maschio, Italy). The seeding of the cover crop spring rye (variety *Sorom*, seeding rate 400 viable seeds per m^2) was conducted at a depth of 0.02 m using a common seed drill (Type D9, Amazone, Germany) in August 2009 (Table 3.1). After two months of cover cropping the trial area was split into four blocks ahead of the winter crop seeding. The cover crop areas for the spring crops were left undisturbed until the field preparation and the seeding in spring 2010.

The field trial design was a completely randomised split plot with four replications for the main plot factor no-tillage, reduced tillage and plough tillage. Each main plot was divided into twelve sub plots (22.5 m^2 - 1.5 m wide and 15 m long) five with MC legumes (two winter and three spring legumes), five with IC legumes (two winter legumes intercropped with winter wheat, three spring legumes intercropped with oats) and one separate plot with MC winter wheat and MC oats. The winter field pea used in this study was a normal leafed variety with long vines while the spring field pea was a semi-leafless, short variety (Table 3.2). The legume seeding rates in the IC plots were identical to the MC legume with the cereal grain seeds added at 20% of the MC cereal grain seeding rate.

The seeding of the cash crops was conducted by preparing the reduced tillage and plough tillage plots and by seeding all three tillage systems at the same day. In October 2009,

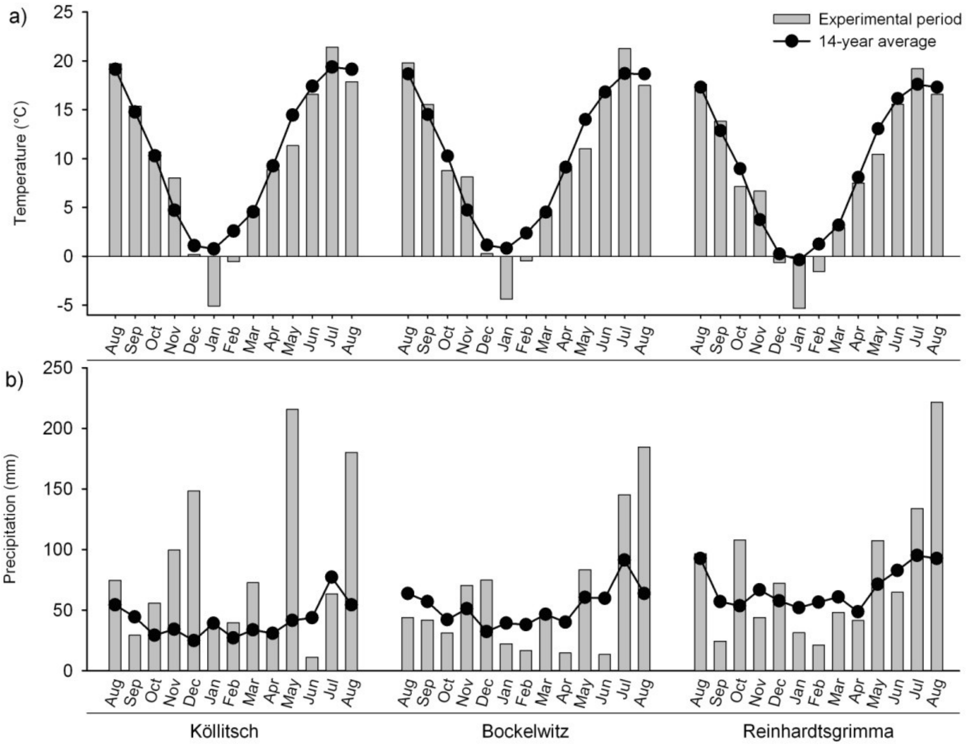

Fig. 3.1a-b. Monthly mean temperatures and precipitation from August 2009 to August 2010 in Köllitsch (KÖ), Bockelwitz (BO) and Reinhardtsgrimma (RG).

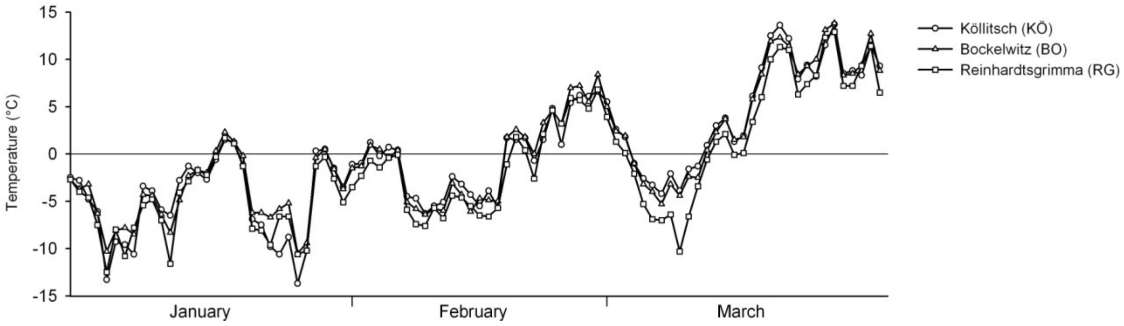

Fig. 3.2. Daily mean temperatures from 1 January to 31 March 2010 at Köllitsch (KÖ), Bockelwitz (BO) and Reinhardtsgrimma (RG).

at the BO location in the no-tillage system three main plots were seeded nine days after the reduced tillage and the plough tillage system due to a technical defect of the no-tillage plot seeder. In the no-tillage system at BO the first sown main plot was excluded and the three later sown main plots were included in the trail. In 2010 at the KÖ location the spring seeding in the reduced and plough tillage system was delayed by four days after the seeding in the no-tillage system due to heavy rainfall.

At the day of seeding the reduced and plough tillage plots received two passes of tillage. The first pass in the ploughed plots was a soil inversion (0.25 m depth) conducted with a three-furrow plough (Type OS523A02, Vogel & Noot, Germany) while the soil was tilled without inversion (0.15 m depth) in the reduced tillage plots using a cultivator with wing shares (Type EG3/11, Rabe, Germany). In both tillage systems the first tillage pass was followed by the seedbed preparation (0.08 m depth) with a rotary harrow (Type Erpice Rotante, Maschio, Italy). In the reduced tillage and the plough tillage system the crops were sown with a plot seeder (Type HEGE 80, Wintersteiger, Austria, 0.17 m row spacing) with shoe openers (Wintersteiger, Austria - trial preparation winter crops in 2009) and single disk coulters (RoTeC Control coulter, Amazone, Germany - trial preparation spring crops in 2010). The seeding in the no-tillage system was conducted using a no-tillage plot drill with inverted T-cross slot openers (Baker No-Tillage Limited, New Zealand, 0.17 m row spacing). The narrow-leafed lupin seeds were inoculated before seeding with *Bradyrhizobium spp. lupinus*, (HiStick, Becker Underwood Ltd., Canada). None of the other legume species required inoculation due to a natural level of *Rhizobium leguminosarum* as a result of various legumes in the organic crop rotation.

3.2.3 **Sampling and measurement**

The plant population for the winter legumes was determined before and after the winter in a 1.5 m long plot area (Table 3.1), which was also used for the dry matter and the grain yield harvest. In autumn six repetitions per plot were counted (six parallel rows 1.5 m long). The winter legume emergence can continue throughout the winter so that the plant stand numbers should also be determined in the spring (Urbatzka et al., 2012). In spring the plant population of the winter legumes and the emergences of the spring legumes as well as the oats were determined on all nine parallel rows of each sub plot.

Table 3.1. Field trial preparation, data measurement and sample collection dates.

Location	Köllitsch (KÖ)		Bockelwitz (BO)		Reinhardtsgrimma (RG)	
Activity/ Date	Winter crop	Spring crop	Winter crop	Spring crop	Winter crop	Spring crop
Cover crop sowing	13 August 2009		13 August 2009		14 August 2009	
Cash crop sowing	10 Oct. 2009	26 & 30 Mar. 2010[1)]	11 & 20 Oct. 2009	03 Apr. 2010	11 Oct. 2009	06 Apr. 2010
Field emergence A[2)]	21 Nov.2009	-	12 Dec. 2009	-	14 Dec. 2009	-
Field emergence S[3)]	21 Mar. 2010	27 May 2010	03 Mar. 2010	08 & 10 Jun. 2010	23 Mar. 2010	18 & 25 May 2010
Soil temperature measurement	31 Oct. 2009	-	31 Oct. 2009	-	24 Oct. 2009	-
	9 Nov. 2009	-	12 Dec. 2009	-	11 Nov. 2009	-
	7 May 2010	-	30 Apr. 2010	-	28 Apr. 2010	-
Harvest	20 Jul. 2010		21 Jul. 2010		17 Aug. 2010	

[1)] No-tillage sowing 26 March, Reduced and plough tillage sowing 30 March 2010; [2)] Autumn counting (1.5 m - 6 rows per plot);
[3)] Spring counting (1.5 m - 9 rows per plot)

Table 3.2. Crop species, cultivar, 1000 seed weight, monocropped (MC) and intercropped (IC) seeding rate (target plant population) used in the field trials.

Crop species		Cultivar	1000 seed weight (g per 1000 seeds^{-1})	Seeding rate (viable seeds m^{-2}) MC	IC
Faba bean[w)] (WF)	*Vicia faba* L.	*'Hiverna'*	655	48	48
Faba bean[s)] (SF)	*Vicia faba* L.	*'Fuego'*	607	59	59
Field pea[w)] (WP)	*Pisum sativum* L.	*'Arkta'*	130	60	60
Field pea[s)] (SP)	*Pisum sativum* L.	*'Santana'*	221	100	100
Narrow-leafed lupin[s)] (NL)	*Lupinus angustifolius L*	*'Boruta'*	178	150	150
Oat[s)] (O)	*Avena sativa* L.	*'Dominik'*	37	300	60
Winter wheat[w)] (W)	*Triticum aestivum* L.	*'Achat'*	49	280	56

[w)] Winter crop; [s)] Spring crop

The plant population of the winter wheat was not determined before the winter because of the delayed emergence in the no-tillage system, while the tillering in spring prevented the subsequent counting.

The winter legume overwintering capabilities were tested for 100 randomly selected legumes in each MC and IC legume plot by marking the emerged plants with wooden sticks. Both the overwintered and the frozen plants were counted after winter (April 2010).

The soil temperatures were recorded in the morning at two different dates in autumn and one day in spring (Table 3.1). The measurements were conducted with a digital quick-response thermometer (Type GTH 1160, Greisinger electronic GmbH, Germany). The thermocouple probe of the thermometer was perpendicularly inserted into the soil up to the seeding depth (0.05 m) and the instantaneous value was recorded. These measurements were repeated ten times within each of the three tillage system main plots.

At the dry matter and grain harvest of the fully ripe crops an area of 2.25 m^2 of each plot was cut above the soil surface and the plant cover was separated into legumes, cereal grains and weeds. The legume pods and the grain ears were removed from the plant and the above ground gross fresh weight was determined separately for straw, pods and ears. Straw samples of 200 to 400 g and all pods and ears were dried to constant weight in the drying cabinet at 60°C. The threshing of the legume and the cereal grains was conducted with a stationary threshing machine (Baumann Saatzuchtbedarf, Germany) and followed by the determination of the grain dry matter weight.

Dried plant samples of MC oats and weeds were fine ground (< 0.2 mm) with an ultra centrifugal mill (ZM 1000, Retsch, Germany). Analysis for %N and %C was performed with an Elemental Analyser (TruSpec Macro, LECO, USA) in compliance with the VDLUFA method 4.1.2 (Bassler, 1976) and DIN ISO 10694 : 1996-08 (DIN Deutsches Institut für Normung e.V., 1996), respectively. The plant available soil N resources during the trial period in the different tillage systems at the KÖ, BO and RG location were assumed to correspond with the total N accumulation of MC oats and weeds. The total N accumulation of MC oats and weeds until harvest amounted at KÖ in the no-tillage, reduced tillage and plough tillage system to 79, 70 and 81 kg ha^{-1}, respectively which shows the comparatively high soil N status at the KÖ location. At BO the N accumulation of MC oats and weeds was very low in the no-tillage system (23 kg ha^{-1}) and increased in the reduced tillage and plough tillage system up to 57 and 72 kg ha^{-1}, respectively. At the RG location the soil N status and the N accumulation of MC oats and weeds was very low in all tillage systems; it amounted in the no-tillage system to 27 kg ha^{-1} and to 23 and 22 kg ha^{-1} in the reduced tillage and plough tillage system.

3.2.4 Statistical Analyses

The data for the winter and spring plant population, overwintering, soil temperature, crop and weed shoot dry matter, grain yield and harvest index were subjected to analysis of variance (ANOVA) using the MIXED procedure (SAS v. 9.3 SAS Institute, Cary, NC). The statistical analyses for all data sets except the soil temperatures were performed over the three environments at the KÖ, BO, RG locations using a linear mixed model with location, tillage system and species as fixed and replicates as random effects. The fit of the model was tested using residual plots of the pooled data and when necessary data transformations after Piepho (2009) were used to achieve the required assumptions for the linear regression analyses (Ireland, 2010). The logarithmic transformation was applied to all data sets with the exception of the overwintering percentage which was transformed using the arcsine transformation.

The homogeneity of variance was tested and in case of heterogeneous variances the model was fitted for partitioned variances (Littell, 2011). The degrees of freedom were determined based on the Kenward-Roger method. Least squares means were calculated and mean comparisons were conducted with the Tukey-Kramer test ($\alpha = 0.05$) within the SAS procedure MIXED.

The soil temperatures were analysed separately for each sample date and location with the tillage systems as fixed and the replications as random effects

There was a significant three way interaction between location x tillage system x species for the crop plant population in spring and the legume overwintering percentage (Table 3.3). This required a separate analysis for each location, tillage system and species (Table 3.4, 3.5). At the KÖ, BO, and RG location within the no-tillage, reduced tillage and plough tillage system lower case letters indicate significant differences between the different crops within the specific tillage system. Values which do not share the same lower case letter are significantly different ($\alpha = 0.05$) based on Tukey Kramer means separation.

For each individual crop at the KÖ, BO, RG location the values were compared between the no-tillage, reduced tillage and plough tillage system, values which do not share the same upper case letter indicate significant differences ($\alpha = 0.05$) between the tillage systems based on Tukey Kramer mean separation.

3.3 Results

3.3.1 Crop establishment

The establishment of the winter legumes was influenced by their field emergence in autumn which was reduced in the no-tillage compared to the plough tillage system (averaged across species: -17, -7 and -32% at KÖ, BO, RG, respectively, autumn data not shown) and by the legume overwintering (Table 3.3, 3.4). Although the seed emergence factors were not quantitatively determined in the present study, it became apparent during soil temperature measurements that a compacted layer was present above the seed.

The overwintering varied with the tillage system in particular for winter faba bean (Table 3.4). At both the KÖ and BO location the overwintering of MC winter faba bean was lower in the plough tillage compared with the no-tillage system (58 versus 21% and 89 versus 43%, at KÖ and BO, respectively). The overwintering percentages of MC winter faba bean at RG on the other hand were higher in the plough tillage compared with the no-tillage system (85 versus 70%). At KÖ and BO, in spring the MC and IC winter faba bean plant stand density in the reduced tillage and plough tillage system was very low due to the overwintering damage so that the MC and IC winter faba bean was at all locations excluded from further examinations. At all locations the winter field pea displayed in all tillage systems high overwintering percentages without differences between the no-tillage and plough tillage system.

The final spring plant population of the MC and IC winter field pea was lower in the no-tillage system than in the plough tillage system with the exception of MC winter field pea at KÖ and BO which did not show differences between the no-tillage and plough tillage system (Table 3.5).

The plant population of most spring sown crops was only slightly influenced by the omission of tillage before seeding. With the exception of MC and IC narrow-leafed lupin at KÖ and BO which were strongly reduced in the no-tillage system compared with the tilled systems.

Table 3.3. Sources of variation of percentage of target crop plant population, legume overwintering, crop and weed dry matter production, grain yield and harvest index.

	Crop plant population		Over-	Dry matter production			Grain - yield		Harvest - Index	
Source of	autumn[a]	spring[b]	wintering[c]	M[d]	ICG[e]	Weed	M[d]	ICG[e]	M[d]	ICG[e]
Location (L)	0.0008 **	<0.0001 ***	0.001 **	0.0229 *	<0.0001 ***	0.5557 ns	0.0073 **	<0.0001***	0.0078 ***	<0.0001 ***
Tillage system (T)	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001***	0.0005 ***	0.0003 ***
Species (S)	0.3269 ns	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001***	<0.0001 ***	<0.0001 ***
L x T	0.0014 **	0.1431 ns	<0.0001 ***	<0.0001 ***	<0.0001 ***	0.079 ns	<0.0001 ***	0.0003***	<0.0001 ***	<0.0001 ***
L x S	0.3932 ns	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001***	<0.0001 ***	<0.0001 ***
T x S	0.0018 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	<0.0001 ***	0.0027 **	<0.0001 ***	<0.0001***	<0.0001 ***	0.0662 ns
L x T x S	0.1044 ns	<0.0001 ***	0.0001 ***	<0.0001 ***	<0.0001 ***	0.0851 ns	0.0019 **	<0.0001***	<0.0001 ***	0.0113 *

[a] Crop plant population legumes only; [b] Crop plant population legumes and MC oats; [c] Legumes only; [d] Main crop (legumes and MC cereal grain); [e] Intercropped grain

Component of variation: *, **, *** significant at *P* levels of *P* < 0.05, 0.01, 0.001, respectively; ns, not significant

Table 3.4. Monocropped (MC) and intercropped (IC) winter legume overwintering in the no-tillage (NT), reduced tillage (RT) and plough tillage system (PT).

	Legume overwintering (% overwintered plants of 100 marked plants per sub plot before winter)								
	Köllitsch (KÖ)			Bockelwitz (BO)			Reinhardtsgrimma (RG)		
Species	NT	RT	PT	NT	RT	PT	NT	RT	PT
MC faba bean (WF)	58 b A	26 b B	21 b B	89 a A	17 b C	43 b B	70 b B	73 bc AB	85 a A
IC faba bean (WF)	50 b A	42 b AB	26 b B	86 a A	22 b B	33 b B	73 b A	69 c A	80 a A
MC field pea (WP)	72 ab A	85 a A	81 a A	91 a A	78 a B	92 a A	87 a A	88 a A	89 a A
IC field pea (WP)	82 a A	76 a A	77 a A	91 a A	79 a B	84 a AB	83 ab A	85 ab A	90 a A

Within a tillage column, lower case letters display significant differences between crop species within tillage systems based on Tukey-Kramer mean separation (α = 0.05); Within locations, upper case letters display significant differences between tillage systems within crop species based on Tukey-Kramer mean separation (α = 0.05)

3.3.2 Soil temperature

The omission and variation of tillage before the autumn seeding led to variable autumn and spring soil temperatures in the three tillage systems. In early November 2009 the soil temperatures in the no-tillage system reached at the KÖ and RG location 5.5 and 5.0°C, respectively while they were significantly lower in the plough tillage system (5.3 and 4.8°C, respectively; Table 3.6). The spring measurement at the KÖ location in early May 2010 and at both the BO and RG location in late April 2010 displayed only at the KÖ location higher soil temperatures in the no-tillage compared with the plough tillage system (10.7 versus 10.4°C) and no differences between the no-tillage and the plough tillage system at the remaining two locations.

3.3.3 Shoot dry matter production

The shoot dry matter production of legumes, cereal grains and weeds varied with the location, tillage system and species (Fig. 3.3a-c, Table 3.3). At the KÖ location the conditions in the no-tillage system reduced the crop dry matter production slightly but equally for most legumes and cereal grains (Fig. 3.3a). At BO the omission of tillage reduced the crop biomass less for legumes than for cereal grains (Fig. 3.3b). For both the MC spring faba bean and field pea the dry matter production in the no-tillage compared with the plough tillage system was reduced by -35 and -64%, respectively while for MC oats the biomass was reduced by -94%. The described differentiated biomass production by legumes and cereal grains in the no-tillage system was also present at RG (Fig. 3.3c). The reduced tillage on the other hand only led at the BO location for the MC narrow-leafed lupin and the MC winter wheat and at the RG location for the IC narrow-leafed lupin to a lower dry matter production compared with the plough tillage system (Fig. 3.3b-c).

The dry matter production by the winter field pea at all three locations was largely unaffected by the different tillage systems, as illustrated for the RG location in Fig. A 9a-c. Exceptions with a lower biomass production in the no-tillage compared with the reduced tillage system were the MC winter field pea (-38%) at the BO location and the IC winter field pea (-37%) at the RG location (Fig. 3.3b-c). The no-tillage dry matter production of the MC winter field pea at the BO location was also different to the plough tillage system while the dry matter production in the no-tillage system by the IC winter field pea at the RG location was not different to the plough tillage system.

Table 3.5. Percentage of target crop plant population in spring of monocropped and intercropped legumes and oats in the no-tillage (NT), reduced tillage (RT) and plough tillage system (PT).

	Crop plant population in spring (% overwintered and germinated plants of viable seeds)								
	Köllitsch (KÖ)			Bockelwitz (BO)			Reinhardtsgrimma (RG)		
Species¶	NT	RT	PT	NT	RT	PT	NT	RT	PT
MC faba bean w) (WF)	54 cd A	35 f B	47 c AB	52 b A	10 e C	32 ef B	49 ce B	59 ce AB	64 cd A
IC faba bean w) (WF)	62 bc A	41 ef B	53 bc AB	52 b A	17 e B	25 f B	54bcd AB	53 de B	68 bd A
MC field pea w) (WP)	52 ce A	59 ac A	66 ab A	34 c B	49 bd A	44 cd AB	56bcd B	46 e B	75 abc A
IC field pea w) (WP)	35 fg B	57 acd A	57 ac A	40 bc B	45 cd AB	54 bc A	47 ce B	73 ac A	73 abc A
MC faba bean s) (SF)	78 ab A	72 a A	70 a A	67 a A	72 a A	78 a A	76 a A	81 ab A	87 a A
IC faba bean s) (SF)	84 a A	66 ab B	61 ac B	76 a A	72 a A	78 a A	76 a A	86 a A	83 ab A
MC field pea s) (SP)	52 ce A	52 bce A	63 ab A	49 b B	60 ab AB	64 b A	67 ab B	83 ab AB	86 a A
IC field pea s) (SP)	46 def A	48 cf A	52 bc A	44 bc A	55 bc A	50 cd A	62 ac B	76 ab AB	87 a A
MC narrow-leafed lupin s) (NL)	19 h B	46 cf A	58 ac A	14 d B	52 bd A	54 bc A	46 de B	71 ac A	72 abc A
IC narrow-leafed lupin s) (NL)	23 gh B	42 def A	47 c A	10 d B	44 cd A	47 cd A	74 a A	65 bcd AB	54 d B
MC oat s) (O)	39 ef A	44 def A	51 bc A	34 c A	41 d A	40 de A	36 e B	67 bcd A	62 cd A

¶ Monocropped (MC) and intercropped (IC) crop species; w) winter crop; s) spring crop; NT: no tillage; RT: reduced tillage; PT: plough tillage; Within a tillage column, lower case letters display significant differences between crop species within tillage systems based on Tukey-Kramer mean separation (α = 0.05)

Within locations, upper case letters display significant differences between tillage systems within crop species based on Tukey-Kramer mean separation (α = 0.05)

Table 3.6. Soil temperatures in autumn and spring in no-tillage (NT), reduced tillage (RT) and plough tillage (PT) winter-legume plots.

	Soil temperature °C – winter legume plots – autumn and spring measurements											
	Köllitsch				Bockelwitz				Reinhardtsgrimma			
Year	Date	NT	RT	PT	Date	NT	RT	PT	Date	NT	RT	PT
2009	31 Oct.	7.2	7.4	7.6 ns	31 Oct.	5.9A	4.4B	3.8B	24 Oct.	9.9	10.1	10.2 ns
2009	9 Nov.	5.5A	5.3B	5.3B	12 Dec.	2.6A	1.8B	1.7B	11 Nov.	5.0A	4.8B	4.8B
2010	7 May	10.7A	10.5AB	10.4B	30 Apr.	15.8	15.6	16.1 ns	28 Apr.	9.8A	9.1B	9.4AB

Within locations, upper case letters display significant differences between tillage systems within sample dates based on Tukey-Kramer mean separation (α = 0.05); ns, not significant

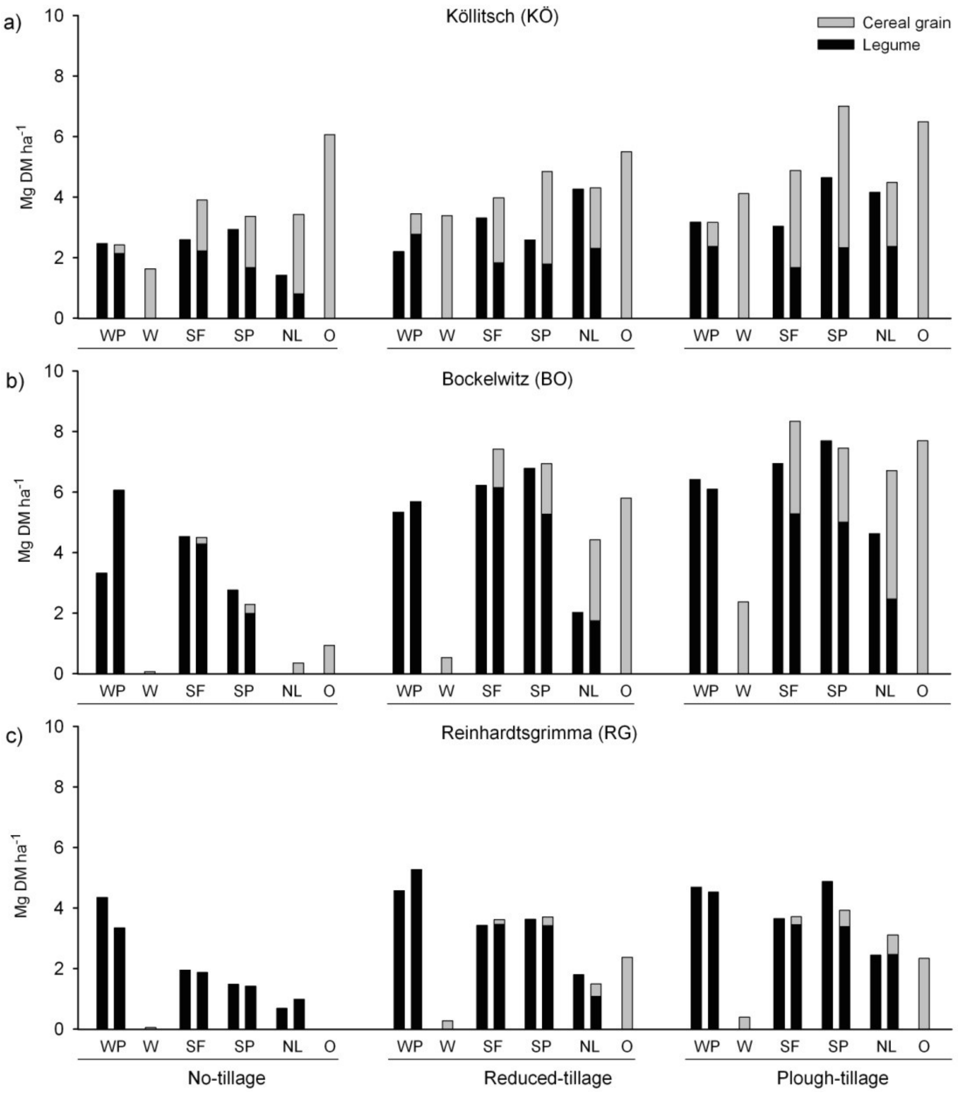

Fig. 3.3a-c. Shoot dry matter (DM) production of legume and cereal grain. Each column pair represents monocropped (left) and intercropped (right) plant stands of winter field pea (WP), spring faba bean (SF), spring field pea (SP), and narrow-leafed lupin (NL), respectively. The single columns represent monocropped plant stands of winter wheat (W) and oats (O).

The no-tillage compared with the plough tillage resulted in a reduced dry matter production of the MC winter wheat at both the KÖ and BO location while at the RG location the winter wheat dry matter production was very low in all tillage systems (Fig. 3.3a-c).

At the KÖ location the dry matter production of the spring cash crops was only influenced by the differentiated tillage in the case of the MC and IC narrow-leafed lupin. No-tillage instead of plough tillage decreased the dry matter production for both the MC and IC narrow-leafed lupin by -66% at the KÖ location (Fig. 3.3a). In the no-tillage system at the BO location the MC and IC narrow-leafed lupin failed to produce any dry matter, while at RG this was the case for IC and MC oats (Fig. 3.3b-c).

The production of biomass by the winter and spring cultivars of the field pea was similar. However, in some cases the winter cultivar exceeded the biomass production of the spring cultivar. This was the case at the BO location in the no-tillage system for the IC winter field pea and at the RG location for the MC and IC winter field pea in the no-tillage system as well as for the IC winter field pea in the reduced tillage system (Fig. 3.3b-c).

The intercropping of legumes with cereal grains at both the KÖ and BO location resulted in most cases in an increased dry matter production compared with the MC plant stands (Fig. 3.3a-b). Due to the additional cereal grain dry matter production the total biomass was significantly increased at the KÖ location in the no-tillage system for the IC narrow-leafed lupin (+141%), in the reduced tillage and plough tillage system for the IC spring field pea (+88 and +61%, respectively) and at the BO location in the reduced tillage system for the IC narrow-leafed lupin (+119%). At the RG location the dry matter production of cereal grains was low and the total biomass in the IC plant stands was only marginally higher than in the MC legume plant stands (Fig. 3.3c).

The reduction of tillage was accompanied by an increased weed pressure and weed biomass production (Fig. A 10a-c). The weed biomass in the no-tillage system in the winter crop plots at the KÖ location contained substantial amounts of volunteer spring rye. The volunteer spring rye was also present in both the RG and BO location but only in very small amounts. Other weeds at the KÖ location included *Lamium amplexicaule* L., *Polygonum aviculare* L., *Stellaria media* (L.) Vill. and *Matricaria inodora* L. with *Matricaria inodora* L. being the main weed in most of the winter crop plots in the reduced tillage and the plough tillage system. The weed species diversity at the BO location was limited and *Matricaria inodora* L. was the main weed, which grew into a soil cover especially in the no-tillage plots of both the MC and IC narrow-leafed lupin and the MC oats. At the RG location, on the other hand, the weed species were highly diverse with *Stellaria media* (L.) Vill., *Cirsium arvense*

(L.) Scop. and *Galinsoga ciliata* (Raf.) Blake present in all tillage systems, *Apera spica-venti* L. and *Vicia cracca* L. in the no-tillage and to some extent in the reduced tillage system.

The weed dry matter production was influenced by both the tillage system and the crop species and two-way interactions occurred between location x species and tillage system x species (Fig. 3.4a-c, Table 3.3).

The best weed suppression was achieved by legumes and cereal grains after the plough tillage and reduced tillage. The lowest weed biomass was found at KÖ and BO in the plough tillage system, in the MC oats plots (0.04 and 0.15 Mg ha^{-1}, respectively) and at the RG location in the plough tillage system in the IC spring field pea plots (0.31 Mg ha^{-1}) as well as in the reduced tillage system in the IC winter field pea plots (0.36 Mg ha^{-1}) (Fig. 3.4 a-c).

Averaged over locations the weed suppression of the MC and IC winter field pea was generally high and did not vary between the no-tillage and the plough tillage system. MC winter field pea also displayed in all tillage systems a tendency to a stronger weed suppression compared with the MC spring field pea. For the spring legumes and the oats the weed biomass increased in general with the omission of tillage.

The intercropping of legumes with cereal grains resulted only for spring legumes in a reduced weed biomass production. This was the case in all tillage systems at KÖ and in the tilled systems at BO and RG (Fig. 3.4a-c). The largest weed biomass reduction due to intercropping was found in the reduced tillage system, at KÖ in plots of IC spring field pea (-54%) and at BO and RG in plots of IC narrow-leafed lupin (-50 and -48%, respectively).

3.3.4 Grain yield

The grain yields of legumes and cereal grains were influenced differently by the omission of tillage (Fig. 3.5a-c, Table 3.3). At the KÖ location the variation of tillage influenced the different crops only slightly with the exception of the MC and IC narrow-leafed lupin as well as the MC winter wheat which displayed a lower grain yield in the no-tillage instead of the plough tillage system (Fig. 3.5a).

At the BO location the no-tillage instead of the plough tillage reduced the grain yield of the MC spring field pea by -54% while the reduction was more distinct for the MC oats (-86%) (Fig. 3.5b). The no-tillage instead of the plough tillage also reduced the yield of the other spring crops at both the BO and RG location, except for the MC and IC spring faba bean at the BO location which only displayed a tendency to lower yields in the no-tillage system.

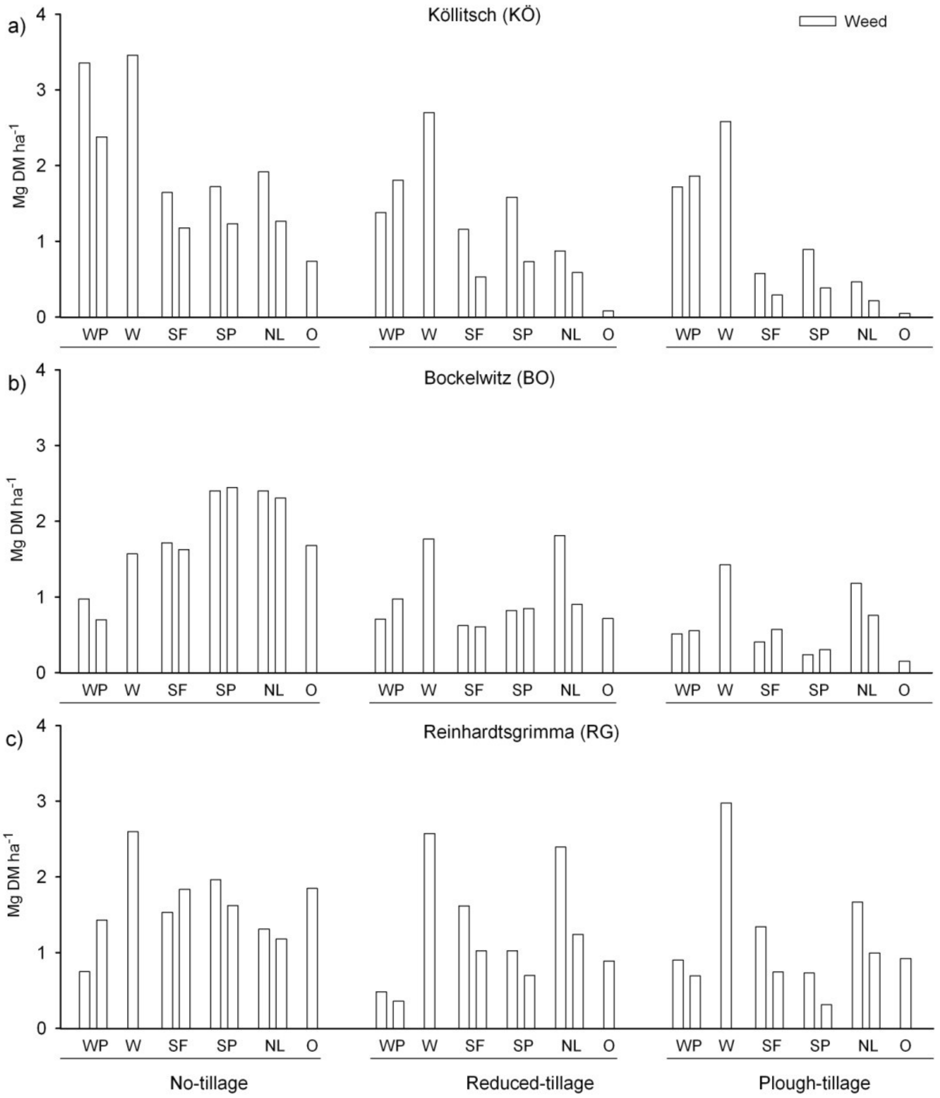

Fig. 3.4a-c. Shoot dry matter (DM) production of weeds. Each column pair represents the weed dry matter production in plots of monocropped (left) and intercropped (right) plant stands of winter field pea (WP), spring faba bean (SF), spring field pea (SP), and narrow-leafed lupin (NL), respectively. The single columns represent the weed dry matter production in monocropped plant stands of winter wheat (W) and oats (O).

For the crops in the reduced tillage system, on the other hand, the grain yields were not different to the plough tillage system with the exception of the MC narrow-leafed lupin at the BO location, which displayed a lower yield in the reduced tillage compared with the plough tillage system. The grain yields of the MC and IC winter field pea were only influenced in one case by the tillage system: the MC winter field pea at the BO location displayed a yield reduction of -44% in the no-tillage compared with the plough tillage system.

The grain yields of the spring and winter field pea were largely without difference. However, some plant stands especially in the no-tillage system displayed significantly lower spring field pea grain yields compared with winter field pea yields. This was the case in the no-tillage system at the BO location for the IC spring field pea (-63%) and at the RG location for the MC and IC spring field pea (-73 and -65%, respectively) and for the IC spring field pea (-36%) in the reduced tillage system (Fig. 3.5b-c).

The intercropping of legumes and cereal grains increased in many cases at KÖ and BO the total grain yield compared with the MC legume plant stands. At the KÖ location this increase was shown in all tillage systems while at the BO location it was limited to the reduced tillage and the plough tillage system (Fig. 3.5a-b). Significantly increased total grain yields were for example shown at the KÖ location in the no-tillage system by the IC narrow-leafed lupin (+157%), in the reduced tillage system by the IC spring field pea (+125%) and in the plough tillage system by the IC spring field pea (+66%) as well as at the BO location in the reduced tillage system by the IC narrow-leafed lupin (+124%) in comparison with their respective MC crop yields.

3.3.5 Harvest index

The legume harvest index was not influenced by the omission of tillage compared with plough tillage before seeding (Fig. 3.6a-c). The harvest index of winter and spring field pea was also without difference with the exception of the MC spring field pea at the KÖ location which displayed in the reduced tillage system a larger harvest index than the MC winter field pea (Fig. 3.6a). At BO in the no-tillage system the harvest index of IC spring field pea and the IC oats was similar so that only the IC oats harvest index is visible in Fig. 3.6b.

Between the different legume crops the harvest indices varied only slightly while for the IC cereal grains the harvest indices for the IC oats were often larger than for the IC winter wheat resulting in significant interactions (Table 3.3).

For winter wheat and oats at KÖ the harvest indices in the three tillage systems differed only slightly (Fig. 3.6a). However, at the BO location the MC winter wheat displayed a lower harvest index in the no-tillage than in the plough tillage system (Fig. 3.6b). At the RG location the harvest indices of IC oats in the reduced tillage system were much lower than in the plough tillage system (Fig. 3.6c).

Due to the nearly complete crop suppression by the IC legumes and weeds some harvest indices could not be calculated. This was the case at BO in the no-tillage and plough tillage system for IC winter wheat in the winter field pea plots and in the no-tillage system for MC and IC narrow-leafed lupin (Fig. 3.6b). At RG in the no-tillage system the MC and IC oats failed to produce dry matter and the harvest index could not be calculated (Fig. 3.2c, 3.6c).

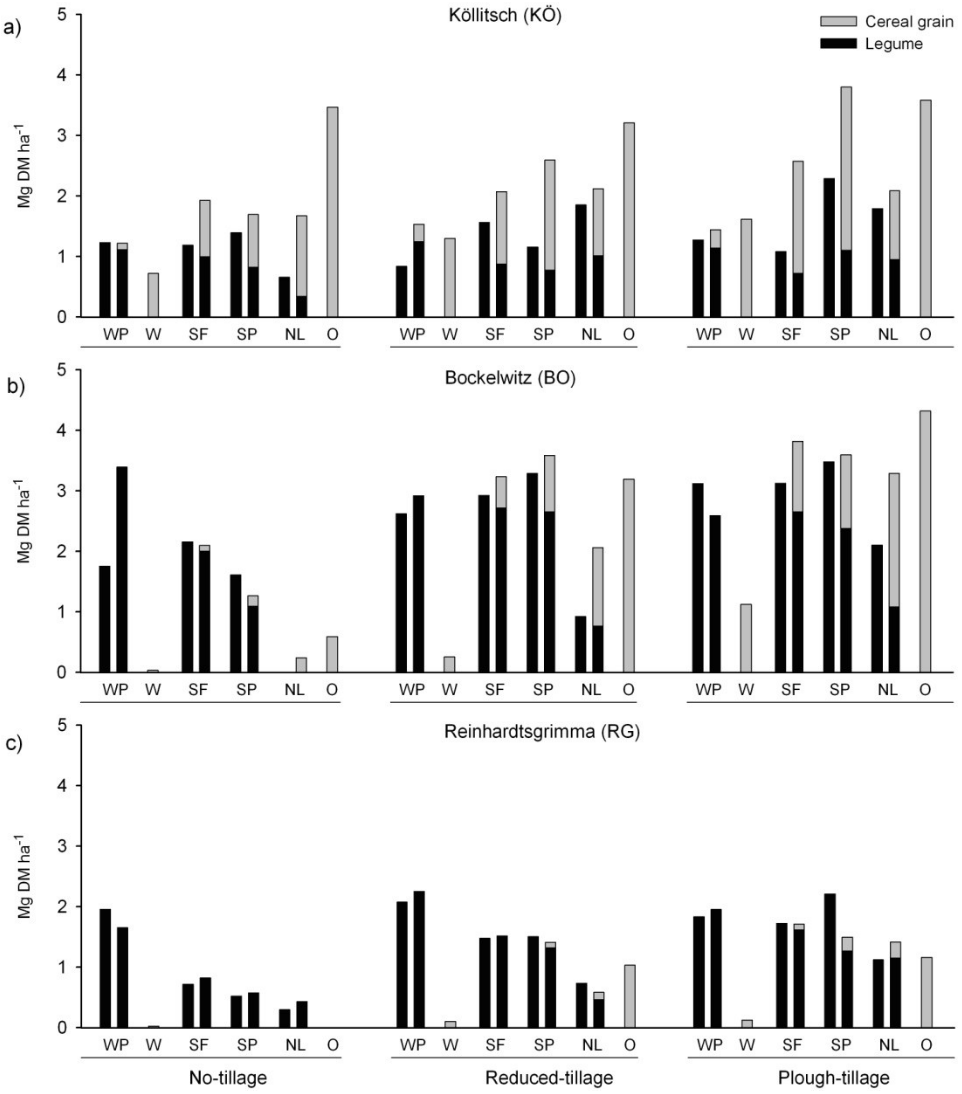

Fig. 3.5a-c. Grain yield of legumes and cereal grains. Each column pair represents monocropped (left) and intercropped (right) plant stands of winter field pea (WP), spring faba bean (SF), spring field pea (SP), and narrow-leafed lupin (NL), respectively. The single columns represent monocropped plant stands of winter wheat (W) and oats (O).

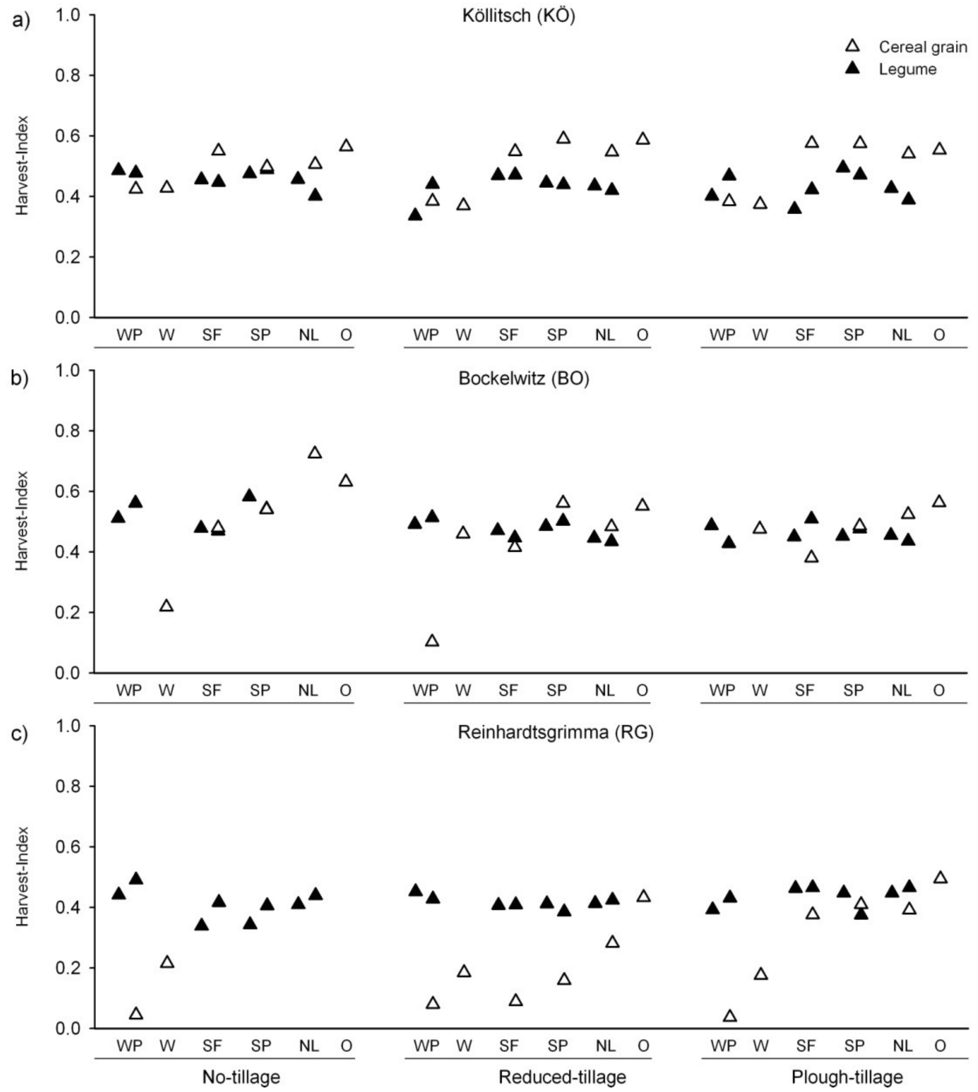

Fig. 3.6a-c. Harvest index of legumes and cereal grains. Each column pair represents monocropped (left) and intercropped (right) plant stands of winter field pea (WP), spring faba bean (SF), spring field pea (SP), and narrow-leafed lupin (NL), respectively. The single columns represent monocropped plant stands of winter wheat (W) and oats (O).

3.4 Discussion

3.4.1 Crop establishment and overwintering

In autumn the reduced winter legume field emergences in the no-tillage system were probably due to soil compaction introduced by seeding into an easily compactable soil that had been tilled recently for the seeding of the cover crop (Table 3.1). The single disk type opener used in the present study utilizes two angled press-gauge wheels to maintain the seeding depth and to close the soil slot (Baker, 2007; Baker and Saxton, 2007). Soil compaction can be introduced by gauge wheel downforce pressure and the reduced speed of emergence has been reported for double disk openers with one gauge wheel (Chen et al., 2004) or when increased downward pressure is applied to a pair of angled gauge wheels (Hanna et al., 2010).

Over winter the topsoil consolidated and soil strength increased so that in spring only the narrow-leafed lupin showed substantially lower emergences in the no-tillage system (Table 3.5). This can be explained by the sensitivity of the narrow-leafed lupin seedlings to obstructions above the seeds and by their epigeal seedling development. White and Robson (1989) showed that the narrow-leafed lupin emergence was reduced in the presence of a soil crust while field pea was not affected. Lupin seedlings only expand their cotyledons if they are brought above the soil surface (Walker and Edwards, 2011), the seedlings in the present experiment could probably not tolerate the soil consolidation in combination with the press-gauge wheel compaction resulting in low emergences. The field pea and faba bean on the other hand show a hypogeal germination and were less influenced because their hypocotyl remains below the soil surface and only the epicotyl grows towards the soil surface.

The winter legume overwintering and the resulting spring plant population is a decisive factor for their yield formation. At KÖ and BO the overwintering of the winter faba bean was reduced in the plough tillage compared to the no-tillage system (Table 3.4). This can be attributed to the climate conditions in the different tillage system before and during the winter period. In a study by Ussiri and Lal (2009) and in the present experiment it has been shown that the soil temperatures in autumn can be higher in the no-tillage system compared to tilled soil (Table 3.6). In the no-tillage system this likely reduced the frost events without snow cover in late autumn and early winter.

With snow cover the soil temperatures in the no-tillage system with stubble will remain higher than in bare ground or tilled soil (Aase and Siddoway, 1980; Malhi et al., 1992), which can be advantageous for the overwintering legumes. In the present study the snow cover and frost period was interrupted in February by a ten day long warm period (Fig. 3.2), with maximum air temperatures up to 11°C. Without snow, the soil surface temperatures during sunshine can be higher than the air temperatures (Aase and Siddoway, 1980). This period likely reduced the winter faba bean freezing resistance because the dehardening process starts at >7°C (Herzog, 1989). The warm period was followed by a frost period. During clear frost nights the temperatures on the surface of bare ground can fall several degrees below those of stubble ground (Aase and Siddoway, 1980). This explains why the winter faba beans in the tilled systems were damaged to a larger extent than in the no-tillage system (Table 3.4).

At the BO location, the overwintering difference between the no-tillage and the reduced tillage system were exceptionally large which can be attributed to the delayed seeding in the no-tillage system (nine days later) that likely resulted in better plant pre-hardening at earlier growing stages (Herzog, 1989).

The elevated and precipitation-rich location RG did not show higher frost damages in the tilled systems because the snow cover was probably higher and remained intact in the warm period. In contrast to the KÖ and BO location, at RG the overwintering had a tendency to be higher in the plough tillage system compared with the no-tillage system (Table 3.4), which was likely the result of increased fungal disease pressure in the humid conditions of the residue covered no-tillage plots.

For the winter field pea the seeding date in October led to well developed and hardened plants which displayed large overwintering percentages with almost no differences between the tillage systems. The observed winter hardiness can be attributed to the seeding date in early October which resulted in an ideal growth stage at the onset of winter and a favourable light intensity and photo period during the cold acclimation (Lejeune-Hénaut et al., 1999; Bourion et al., 2003). Furthermore, the allocation of soluble sugars and the related frost tolerance seems to remain for some time after the frost influence even if the temperatures rise to 15°C (Bourion et al., 2003), which explains the low influence of the brief warm period on the winter pea overwintering.

3.4.2 Crop biomass production and weed suppression

At KÖ there were no large differences between the MC and IC legume and cereal dry matter production in the different tillage systems. At BO and RG the omission of tillage affected the dry matter production of the legumes less than for the cereal grains (Fig. 3.3b-c). The reduced cereal grain biomass can be explained with the low soil N status in the no-tillage system at BO and RG, which was without effect for the legumes due to their ability for symbiotic N_2 fixation (Urbatzka et al., 2011).

The legume biomass production at all locations was without difference between the reduced and plough tillage system. This can be attributed to the similar weed biomass in both tillage systems. Nakamoto et al. (2006) showed in field trials in central Japan that the disruption of the continued use of plough tillage through the use of the reduced tillage reduces the biomass of certain weeds, which explains the low weed biomass in the reduced tillage system even without plough tillage. Furthermore, tillage prevented the weed emergence before the legume emergence, while weeds in the no-tillage system were able to emerge before the legumes which increased the early weed pressure especially for spring sown legumes (Nelson and Nylund, 1962).

At all locations, the variation in tillage systems influenced the winter field pea biomass production only slightly and the largest dry matter production in the no-tillage system (IC winter field pea at BO) was not different to the plough tillage system (Fig. 3.3a-c). Nevertheless the largest biomass production in the no-tillage system at both the BO and RG location were only at the low to average level of the winter field pea potential compared with a conventional no-tillage system at two Pacific Northwest sites in North America (Chen et al., 2006).

The MC spring faba bean dry matter production in the no-tillage system which was largest at BO was lower than in other organic no-tillage trials (Köpke and Schulte, 2008). In the plough tillage system without the strong weed competition the much larger biomass production displayed the potential of faba bean at this site (Fig. 3.3b).

Similarly, the MC spring field pea biomass production in the no-tillage system at BO was only about half of the biomass production reported for a less productive sandy loam in an organic plough tillage system (Fig 3.3b; Hauggaard-Nielsen et al., 2001; Hauggaard-Nielsen, 2014 personal communication). The dry matter production in the plough tillage system of the present study, on the other hand, was similar to a low yielding non-organic system (Reiter et al., 2002).

In the no-tillage system at both the BO and the RG location the biomass production of the winter field pea was higher than for spring field pea (Fig 3.3b-c), due to the crop establishment before winter and the strong weed suppression capacity by the winter pea (Urbatzka et al., 2011). At KÖ this effect was not present, because the weed biomass production and competition was very high in the winter field pea plots. This can in part be attributed to the composition of the weeds which included large amounts of voluntary rye in the no-tillage system and also to the high soil N status at KÖ. In the reduced and plough tillage system the increased weed biomass did not contain voluntary rye. However, similar to the no-tillage system the high soil N status reduced the competitive advantage for the legume and increased the growth of the weeds (Blackshaw et al., 2003). This shows that autumn sown field pea can have a better legume-weed competition but identifies low available soil N resources as a main factor for the success of this strategy.

The intercropping of spring legumes and oats reduced the weed biomass compared with the MC legumes in all tillage systems at the KÖ location and in the tilled systems at the BO location (3.4a-b). This could be attributed to the increased soil N status in all tillage systems at KÖ and the tilled systems at BO which can increase both the growth and the competitive ability of the IC cereal grain (Neumann et al., 2007). A better competitive ability against weeds by IC legumes instead of MC legumes was also reported by Hauggaard-Nielsen et al. (2001) for a replacement intercrop which differed from the additive intercrop in the present study.

3.4.3 Grain yield and harvest index

At the KÖ location the winter and spring legume grain yield was consistently low in all tillage systems. This can be explained by the weed pressure which was particularly high in the winter legume plots (Fig. 3.4a). The largest winter and spring legume yields were reached at BO (Fig. 3.5b), due to the overall lower weed pressure (except in the spring sown no-tillage crops). At RG even with a large weed competition the legume yield level was not as low as at KÖ, because at RG there was a tendency to a larger legume plant population (Fig. 3.4c, Table 3.5).

The winter field pea displayed almost no difference between the tillage systems and the yields of IC winter field pea in the no-tillage system at the BO location, can be classified as high compared with another study in an organic plough tillage system (Urbatzka et al., 2011). The other winter field pea yields in the no-tillage system were average and similar to a conventional no-tillage system in the Pacific Northwest of North America (Chen et al., 2006).

Grain yield differences between the no-tillage and the tilled systems were present in the spring sown legumes at BO and RG. In the no-tillage system the MC spring field pea yields were considerably lower than their potential as shown by higher yields in the plough tillage system in the present and other studies in eastern and central Europe (Fig. 3.5a-c; Šarūnaitė et al., 2010; Šarūnaitė, 2013 personal communication; Urbatzka et al., 2011). The MC spring faba bean yields in the no-tillage system were at a very low to medium level compared with other studies of organic no-tillage or plough tillage systems (Köpke and Schulte, 2008; Šarūnaitė et al., 2010; Šarūnaitė, 2013 personal communication). These low yields can be attributed to the high weed competition in the no-tillage system (Fig. 3.4b-c). The weed competition in all tillage systems and the low field emergence in the no-tillage system led to the lower narrow-leafed lupin yield compared with spring field pea and faba bean (Fig. 3.4a-c, 3.5a-c). This is in agreement with results by Šarūnaitė et al. (2010) and can be attributed to the low competitive ability of lupins (Strydhorst et al., 2008).

There was no difference between the different legume harvest indices in the different tillage systems, similar to reports for field pea by Reiter et al. (2002) in a trial with minimal and conventional tillage. This indicates that the nutrient supply was not limited which can in part be attributed to the legumes ability for adapted symbiotic N_2 fixation (Matus et al., 1997).

The winter field pea yields in the no-tillage system were in many cases higher than spring field pea yields even with a lower winter field pea plant population, which shows that autumn seeding was advantageous (Table 3.5). An additional advantage was that the winter field pea was a normal leafed cultivar with a large biomass production while the spring field pea was a semi-leafless cultivar which is less competitive against weeds (Semere and Froud-Williams, 2001; Spies et al., 2011).

Intercropping increased the total grain yields of spring sown crops at KÖ in all tillage systems and in the reduced tillage and plough tillage system at BO (Fig. 3.5a-b). In these particular tillage systems, at the KÖ and BO location MC oat also displayed high yields which in the no-tillage system at KÖ were similar to organic oats grain yields in plough tillage systems (Kadžiulienė et al., 2011; Šarūnaitė, 2013 personal communication). The increased performance of the IC and MC oats was likely a result of the high soil N status in all tillage systems at KÖ and in the tilled systems at BO. However particularly at KÖ it was apparent that the legume share of the total grain yield was decreased and the oats share was increased, probably due to the high soil N status which increased the competitive ability of the IC cereal grain similar to the results reported by Hauggaard-Nielsen and Jensen (2001) for an intercrop of barley and pea in a replacement design. Additionally, cereal grains show a faster early development than legumes (Giunta et al., 2009), which can be a disadvantage for the legumes in well fertilised IC plant stands. The IC and MC winter wheat displayed low yields due to the strong competition by the winter field pea in IC plant stands and the strong weed pressure in the MC plant stands (Fig. 3.4a-c).

3.5 Conclusion

The integration of conservation tillage practices is an important part to advance the sustainability of organic farming systems. However, particularly the omission of tillage in the transition period has drawbacks. These might be overcome by the integration of legumes intercropped with cereal grains as cash crops early in the transition period. The present study indicates that only certain legumes are suited for the transition period to an organic no-tillage system. The normal leafed winter field pea was well suited for the no-tillage system and achieved consistently grain yields similar to the reduced tillage and plough tillage system. This was not the case for the semi-leafless spring field pea and spring faba bean which were better suited for the reduced tillage system. Narrow-leafed lupin appeared not to be suited for conservation tillage systems in organic farming. There was increased weed competition in the no-tillage system by autumn sown field pea which in part can be attributed to the seeding in autumn and the advanced growth stage in spring. However, the winter field pea cultivar also had a higher competitive ability than the spring field pea cultivar. The advantage of autumn seeding could not be evaluated for faba bean because in spring they had to be excluded from the experiment. Further research is required to determine the benefits of autumn seeding for legumes in the organic no-tillage system. Intercropping of legumes and cereal grain only increased the weed suppression if sufficient soil N resources were available for the cereal grain and if the competition by the IC legume was not too high. Furthermore, the total grain yield of the IC plant stands was only increased if the soil N status supported the cereal grain growth which was, with the exception of the KÖ location, not the case in the no-tillage system. The available soil N resources during the growing period appeared to be an important factor for the IC cereal grain – weed competition. For organic no-tillage systems with a high soil N status and low weed competition the intercropping of legumes and cereal grains needs to be further investigated. The present study showed that for organic systems with low available soil N resources it is advisable to use normal leafed winter field pea as the first crop in the transition period to an organic no-tillage system. With this strategy the implementation of no-tillage phases in the crop rotation appears to be possible and could make organic farming more sustainable.

4. Chapter: Evaluation of monocropped and intercropped grain legumes for cover cropping in no-tillage and reduced tillage organic agriculture

4.1 Introduction

Between two non-legume cash crops it can be useful to grow legume cover crops to suppress weeds and heighten the available N resources for the following cash crop through symbiotic N_2 fixation. Non-legume cover crops intercropped with legumes can function as a sink for nutrients and provide the nutrients to the succeeding spring cash crops. Cover crops are usually sown during or after reduced tillage a fuel and time intensive procedure which disturbs the topsoil structure. The present trials were conducted to determine whether the transition into organic no-till is possible after the grain cash crop harvest by growing legume cover crops in a no-till compared with a reduced tillage system.

The legumes faba bean (*Vicia faba* L.), field pea (*Pisum sativum* L.), narrow-leafed lupin (*Lupinus angustifolius* L.), grass pea (*Lathyrus sativus* L.) and common vetch (*Vicia sativa* L.) are capable of N_2 fixation and have been tested as summer green manure (Biederbeck et al., 1993; Townley-Smith et al., 1993; Miller et al., 2011;) and as winter annual cover crops (Hargrove, 1986; Holderbaum et al., 1990; Keeling et al., 1996). Only a few studies (Martens et al., 2001; Franczuk et al., 2010) have evaluated the use of large seeded legumes as late season cover crops that are terminated by frost. Compared to cover crop termination in spring, the legume cover crop termination in winter offers the potential of early N mineralisation which can improve the growth of non-legume cash crops. In central European conditions, frost termination is ensured for the species used in this study and they might be better suited than other legumes for late season cover cropping due to their adaptation to dry late summer conditions (grass pea) or to biomass production and N_2 fixation under wet and cold late autumn conditions (faba bean, field pea) (Biederbeck et al., 1993; Power and Zachariassen, 1993).

The objective of our trials with legume cover crops was to evaluate five large seeded legumes, both monocropped (MC) and intercropped (IC) with sunflowers as late season cover crops, all sown without tillage (no-till seeding) and after shallow soil inversion (reduced tillage), with a view to finding suitable species for organic no-till cover cropping.

4.2 Material and methods

4.2.1 Experimental sites and setup

Field trials were conducted from August to October 2009 and 2010 at a long-term certified organic farm in Reinhardtsgrimma (50° 53' N, 13° 45' E, 350 m a.s.l.) and at the Teaching and Research Farm Köllitsch (51° 30' N, 13° 06' E, 84 m a.s.l.), Germany. Soil parameters are presented in Table 4.1. The sites Reinhardtsgrimma (RG), situated at the northern slope of the Eastern Ore Mountains and Köllitsch (KÖ), situated in the low land area of northwest Saxony, were chosen to represent the late season climate conditions at a submontane and planar location in central Europe, respectively.

The fields at both locations had been under conventional plough tillage up until the cash crop preceding the cover crops in 2009 and 2010. The cash crops were winter rye (2009) and oats (2010) at the RG location and winter wheat (2009 and 2010) at the KÖ location. Winter cash crops were sown during the autumn of the previous year and the oats was sown during the spring of the harvest year. The cash crops were harvested during early August and the straw was transported off the fields, with one exception at the KÖ site where the straw was chopped in 2010. No fertiliser was applied after cash crop harvest and during the cover cropping period.

As cover crops, the legumes faba bean (cv. Scirocco), field pea (cv. Livioletta - normal leaf type), narrow-leafed lupin (cv. Azuro), grass pea (cv. Merkur) and common vetch (cv. Mery), (1000 seed weight: 437, 169, 145, 224, 46 g, respectively), were sown in MC and IC plant stands. The tested varieties are commonly used as cover crops in Central Europe. The seeding rate (viable seeds) in the MC plant stands was 55 seeds m^{-2} for faba bean, 110 seeds m^{-2} for field pea, narrow-leafed lupin and grass pea, 165 seeds m^{-2} for common vetch, and 139 seeds m^{-2} for sunflower. In the IC plant stands an additive mixture was used which consisted of legumes at 100% of their full MC seeding rate plus sunflower (cv. Iregi; 1000 seed weight: 65 g) at 20% (28 seeds m^{-2}) of the full MC sunflower seeding rate. These seeding rates were in the upper range of the regional, experienced based seeding rates to ensure rapid ground cover and high weed suppression. The seed lots, which originated from certified organic seed, differed between 2009 and 2010. Seed rates were adjusted to accommodate variations in the germination ability of the individual seed lots and equal quantities of viable seeds were sown each year.

Table 4.1. Soil, experimental details and date of first daily mean below 0°C (End of growing season by temperature definition).

Site	Reinhardtsgrimma (RG)		Köllitsch (KÖ)	
	2009	2010	2009	2010
Soil type (FAO classification)[a]	Dystric Cambisol (shallow)	Dystric Cambisol (shallow)	Arenic Fluvisol (deep)	Arenic Fluvisol (deep)
Soil texture	Loamy Sand	Loamy Sand	Loamy Sand	Loamy Sand
Field capacity (Vol. %)[b]	34	34	32	32
Soil pH (0.01 M $CaCl_2$)	6.1	5.6	5.6	5.6
Soil P (CAL; mg kg^{-1})[c]	71	29	31	35
Soil K (CAL; mg kg^{-1})[c]	156	135	41	40
Soil Mg (0.01 M $CaCl^2$; mg kg^{-1})	88	84	159	131
Cover crop sowing dates	19 August 2009	24 August 2010	17 August 2009	15 August 2010
Biomass harvest I	18 September 2009	24 September 2010	18 September 2009	20 September 2010
Biomass harvest II	22 October 2009	25 October 2010	25 October 2009	27 October 2010
End of growing season[d]	31 October 2009	24 November 2010	13 December 2009	24 November 2010

[a] Soil type according to IUSS Working Group WRB, (2006).

[b] Estimated according to DIN 4220 (DIN Deutsches Institut für Normung e.V., 2008).

[c] Calcium Acetate Lactate (CAL) extraction method after Schüller (1969).

[d] First daily mean temperature <0°C, temperature indicator according to the Saxon climate impact monitor.

The design of the field trial was a completely randomised split plot with four replications. The main plot factors were no-till and reduced tillage. Each main plot was divided into twelve sub plots (22.5 m^2, 1.5 m wide and 15 m long), five plots had MC legumes, five plots had IC legumes with sunflowers, one plot had MC sunflowers as the reference crop for the calculation of the N_2 fixation, and one fallow plot was without any cover crop.

On the day of seeding, the reduced tillage plots received two passes of tillage. The first pass was a shallow soil inversion (0.10 to 0.12 m depth) conducted with a stubble plough (Type Zobel, Germany) followed by the seedbed preparation (0.08 m depth) with a rotary harrow (Type Erpice Rotante, Maschio, Italy). At both locations the reduced tillage cover crops were sown at 0.17 m row spacing with a plot seeder (Type HEGE 80, Wintersteiger, Austria) with shoe openers (Wintersteiger, Austria - trial preparation in 2009) and single disk coulters (RoTeC Control coulter, Amazone, Germany - trial preparation in 2010). The direct seeding was conducted using a no-till plot drill with inverted T-cross slot openers (Baker No-Tillage Limited, New Zealand) at 0.17 m row spacing.

Narrow-leafed lupin seed inoculation took place just before seeding with *Rhizobium lupinii* (Radicin Nr. 6, JOST GmbH, Germany). Other legume species were not inoculated because it was assumed that legumes in the crop rotation maintained a natural level of *Rhizobium leguminosarum*. Field emergence was determined three to four weeks after seeding at a row length of 1.5 m with six repetitions per plot. The weed flora was determined visually by means of plot pictures taken in the course of the study. In the no-till system, weeds were differentiated as weeds present at seeding or newly germinated weeds based on their growth stage. In the reduced tillage system, tillage removed weeds before seeding, and all weeds present in the study germinated or regrew after the cover crop seeding.

4.2.2 Sample collection and analysis

The cover crop and weed biomass were harvested twice; each harvest sample contained the biomass produced between seeding and the individual harvest date (Table 4.1). The first harvest (harvest I) was performed four to five weeks after seeding to determine the cover crop and weed biomass production during the early cover cropping phase. The second harvest (harvest II) was conducted in the period between the first frost day (first daily minimum temperature <0°C) and the end of the growing season by temperature definition (first day with a daily mean temperature <0°C; DWD, 2013 personal communication). This determined the total cover crop and weed biomass during autumn. At harvest I and harvest II, an area of 2.25

m^2 of each plot was cut by hand and the plant cover was separated into legumes, sunflowers and weeds.

The above ground gross fresh weight was determined directly after harvest in the laboratory using a laboratory scale (SI 6002, Denver-Instrument). Samples of 200 to 400 g were dried to constant weight for the dry matter weight calculations in the drying cabinet at 105°C (harvest I) and 60°C (harvest II). Dried plant samples of harvest II were fine ground (< 0.2 mm) with an ultra centrifugal mill (ZM 1000, Retsch, Germany). Analysis for %N and %C was performed with an Elemental Analyser (TruSpec Macro, LECO, USA) in compliance with the VDLUFA method 4.1.2 (Bassler, 1976) and DIN ISO 10694 : 1996-08 (DIN Deutsches Institut für Normung e.V., 1996), respectively.

With the extended difference method the N_2 fixation of legume cover crops was estimated based on a formula by Stülpnagel (1982) with a modification to include the above ground N accumulation in weeds and IC sunflowers as follows:

N_2 fixation monocropping = $(N_{Leg}+N_{WeedLeg}) - (N_{Ref}+N_{WeedRef}) + (\text{soil } N_{Leg} - \text{soil } N_{Ref})$

N_2 fixation intercropping = $(N_{Leg}+N_{ICsunflower}+N_{WeedLeg}) - (N_{Ref}+N_{WeedRef}) +$
$(\text{soil } N_{Leg} - \text{soil } N_{Ref})$

where N_{Leg}= shoot N accumulation in the legume; N_{Ref}= shoot N accumulation in the reference crop MC sunflower; $N_{ICsunflower}$= shoot N accumulation in intercropped sunflower; $N_{WeedLeg}$ and $N_{WeedRef}$= weed shoot N accumulation in the legume and reference crop plot, respectively; soil N_{Leg} and soil N_{Ref}= inorganic soil N content in the legume and reference crop plot, respectively.

Herbicides had been used in the trial by Stülpnagel (1982), in the current study the inclusion of the shoot N accumulation in weeds and IC sunflowers was necessary to estimate the actual soil N depletion in the organic system. The root N accumulation was not accounted for neither in the present study nor in the method description by Stülpnagel (1982). During the vegetative growing phase nodulated legume roots can account for up to 35% of the total plant N, whereas the root fraction of the total sunflower plant N can account for up to 33% at floret initiation (Armstrong et al., 1994; Hocking and Steer, 1995). It is therefore assumed, that the proportion of total plant N excluded from the calculation was similar for the legume and reference crop.

Soil samples (0 to 0.3 m depth) were collected after seeding (ten sample points for each main plot) and after harvest II (four sample points for each sub plot). In 2009, soil sampling at KÖ was delayed three days after seeding, and during 2010 there was a delay of one day at RG as well as five days at KÖ. The core samples were homogenised and stored in cold storage coolers in the field, followed by deep freezing to -18°C the day of sample collection until the final analyses. Within one hour of defrosting, soil extracts with 0.01 M $CaCl_2$ were prepared, and NO_3^-N and NH_4^+N concentrations were examined using a Continuous Flow Analyser (SAN++, Skalar Analytical B.V., Breda, Netherlands) based on the VDLUFA method A 6.1.4.1 (Thun and Hoffmann, 1991) and DIN ISO 14255 : 1998-11 (DIN Deutsches Institut für Normung e.V., 1998), respectively.

4.2.3 Statistical analyses

Basic data was examined for outliers with boxplots. Less than 5% of the data points were identified as outliers above and below the 1.5 interquartile range, and removed before conducting statistical analyses. The unbalanced data set was accounted for in the statistical analysis. The cover crop shoot dry matter biomass of IC legumes and IC sunflowers were then combined to total IC plant stand dry matter production, so that subsequent analyses always compared the MC and IC cover crop plant stands as total values. This was also the case for total cover crop shoot N accumulation. Values of IC legumes and IC sunflowers were combined as a result of the low IC sunflower biomass production. Data for field emergence, total shoot dry matter at harvest I and II, inorganic soil N after harvest II, total shoot N accumulation and N_2 fixation were subjected to analysis of variance (ANOVA) using the MIXED procedure (SAS v. 9.3 SAS Institute, Cary, NC). Statistical analyses were performed for two locations (RG and KÖ) and two years (2009 and 2010) using a linear mixed model with location, year, tillage system and species as fixed effects and replicates as random effects. The fit of the model was tested using residual plots of the pooled data, and data transformations (Piepho, 2009), when necessary, were used to achieve the required assumptions for linear regression analyses (Ireland, 2010). The arcsine transformation was applied to cover crop field emergence; the logarithmic transformation was applied to cover crop and weed biomass at harvest I as well as inorganic soil N after harvest II; the Box-Cox transformation (fixed λ 0.4) was applied to cover crop and weed biomass at harvest II; data for N_2 fixation did not require any transformation.

Homogeneity of variance was tested and in the case of heterogeneous variances the model was fitted for partitioned variances (Littell, 2011). The degrees of freedom were determined based on the Kenward-Roger method. Least squares means were calculated and mean comparisons were conducted using the Tukey-Kramer test ($\alpha = 0.05$) within the SAS procedure MIXED. A letter display for the mean comparisons was created with the %MULT macro by Piepho (2012). In the presence of significant four way interactions between the main factors year, location, tillage system and species, the slice option within the %MULT macro was used to test for significant simple main effects by comparing one specific factor at variable levels of another factor (Schabenberger et al., 2000). Data that had been transformed was transformed back to the original scale for presentation.

4.3 Results

4.3.1 Weather conditions

In 2009, the mean annual temperatures at RG and KÖ were 8.3 and 9.8°C, respectively (Table 4.2). This was similar to the ten year average, whereas in 2010 temperatures were 2°C below the average (8.8 and 10.1 °C, at RG and KÖ, respectively) (LfULG, 2012; DWD, 2012 and 2013 personal communication). The total precipitation in 2009 was similar at RG and higher at KÖ than the historical average (773 and 473 mm, respectively). In 2010 the total precipitation was substantially higher at RG (+244 mm) and KÖ (+487 mm) than the historical average (LfULG, 2012; DWD, 2012 and 2013 personal communication). The first part of the cover cropping period from August to September in 2009 was dry in both locations while in 2010, there was considerably more precipitation. In the second part from September to October a particularly low mean temperature of 7.1 °C was reached at RG in 2010.

4.3.2 Cover crop emergence

The cover crop field emergence was influenced by interactions between year x location x tillage system and year x location x species (Table 4.3). The emergence at the RG location in both years was lower in the no-till system than in the reduced tillage system (2009: 55 versus 64%; 2010: 58 versus 66%, respectively; data not shown). At KÖ the emergence was significantly reduced only in 2010 (57 versus 74%; 2009: 64 versus 62%, respectively). Species specific emergence differences were significant at the two locations for both years (Table 4.4). For MC and IC faba bean at RG in 2010 emergence was considerably higher than it was for the other species. There was less variation demonstrated between the species at RG in 2009 and at KÖ in 2010.

Table 4.2. Monthly mean and trial period mean temperature, monthly precipitation and cumulative precipitation during the cover crop trial period.

	Temperature (°C)				Precipitation (mm)			
	Reinhardtsgrimma (RG)[a]		Köllitsch (KÖ)[b]		Reinhardtsgrimma (RG)[a]		Köllitsch (KÖ)[b]	
Month	2009	2010	2009	2010	2009	2010	2009	2010
January	-4.2	-5.3	-3.2	-5.1	22	31	8	36
February	-0.4	-1.6	0.8	-0.5	69	21	27	39
March	3.9	2.9	5.3	4.9	76	48	48	73
April	11.2	7.5	12.2	8.9	18	41	9	31
May	12.8	10.5	14.4	11.3	91	107	54	216
June	13.9	15.5	15.6	16.6	80	65	45	11
July	17.6	19.2	19.0	21.4	108	134	91	63
August	17.6	16.6	19.7	17.9	96	222	75	180
September	13.8	11.0	15.3	12.9	24	138	29	144
October	7.1	6.7	10.7	8.1	108	7	56	14
November	6.7	4.2	8.0	5.3	44	107	99	117
December	-0.7	-5.7	0.2	-4.3	72	96	148	36
Mean temperature (°C) during cover crop trial period					Cumulative (mm)			
P1	15.6	12.3	17.4	15.1	43	90	38	146
P2	9.4	7.1	13.7[c]	9.0	115	118	60	130
P3	12.3	9.8	-	12.0	158	208	98	276

P1, mean temperature and cumulative precipitation during the first period from seeding to harvest I (from August to September).
P2, mean temperature and cumulative precipitation during the second cover crop growth period between harvest I and II (from September to October).
P3, mean temperature and cumulative precipitation in whole cover crop growing period (from August to October).

[a] Climate data (DWD 2012 personal communication).

[b] Climate data (LfULG 2012), Temperature data not available from 10 to 27 October 2009.

[c] Only timeframe 19 Sept. - 9 Oct. available.

4.3.3 Cover crop shoot and weed dry matter production

The cover crops in the two tillage systems displayed a variable response to the conditions in 2009 and 2010 at RG and KÖ resulting in significant year x location x tillage system x species interactions for the cover crop dry matter production at harvest I and II (Table 4.3). Weed pressure varied between the two trial years concurrent with the weather conditions, strongly influencing the cover crop dry matter production. In 2009, the weed biomass production in the early crop development phase up to harvest I reached 1.16 Mg ha^{-1} and 0.11 Mg ha^{-1} in the no-tillage and reduced tillage system, respectively (Table 4.5). In 2010, the weed biomass at harvest I reached 0.28 and 0.07 Mg ha^{-1} in the no-tillage and reduced tillage system, respectively.

The total cover crop dry matter production in the no-till system in 2009 at harvest I was largest for MC field pea (0.37 and 0.31 Mg ha^{-1}) at RG and KÖ, respectively (Fig. 4.1). That same year, the IC field pea and MC sunflower produced up to harvest I the most biomass at both locations in the reduced tillage system. Between the first and second harvest the cover crop species differed in their biomass production particularly in the no-till system at RG. At harvest I, the common vetch displayed a low initial biomass production in the no-till system, while it showed strong growth in the second trial period. Conversely, MC and IC narrow-leafed lupin showed weak growth in the second trial period. Between harvest I and II in the no-till system at RG, the MC and IC field pea showed a strong biomass increase, resulting at harvest II in a large difference between MC and IC narrow-leafed lupin and the field pea. At harvest II within the no-till system at RG the MC and IC field pea produced the most biomass by a large margin (Fig. 4.2). At KÖ at harvest II there were only small differences between the cover crops with the largest biomass production (MC and IC field pea and IC narrow-leafed lupin) and the biomass of other species. MC faba bean and grass pea were within the group of species with the least biomass production in the no-till system.

In the reduced tillage system in 2009 at RG the same species as in the no-till system (MC and IC field pea) displayed the largest biomass production at harvest II with significant differences in relation to the other species. The second largest dry matter production was shown by MC and IC grass pea and MC sunflower. At KÖ, the MC sunflower produced the most biomass in the reduced tillage system although not significantly different to IC field pea and grass pea. The conditions in 2009 favoured the sunflower growth at both locations in the reduced tillage system but the intercropping of legumes and sunflowers was only successful in

Table 4.3. Sources of variation, degrees of freedom and statistical significance of the sources of variation for of field emergence (legumes and monocropped sunflower), total cover crop and weed dry matter production at harvest I and II, inorganic soil N 0 to 0.3 m soil core, shoot N accumulation (shoot N) and N_2 fixation.

			Harvest I		Harvest II		Harvest II		
		Field	Dry matter production		Dry matter production		Inorganic	Shoot	N_2
Source of variation	df[a]	emergence	Cover crop[b]	Weed	Cover crop[b]	Weed	soil N	N[b]	fixation
Year (Y)	1	n.s.	***	***	***	***	***	***	*
Location (L)	1	n.s.	***	n.s.	***	n.s.	***	***	n.s.
Tillage system (T)	1	***	***	***	***	***	*	***	n.s.
Species (S)	10, (11, 9)	***	***	n.s.	***	***	n.s.	***	***
Y x L	1	n.s.	***	n.s.	***	*	***	***	***
Y x T	1	**	*	***	***	***	n.s.	***	n.s.
L x T	1	n.s.	n.s.	***	**	**	*	***	*
Y x S	10, (11, 9)	***	***	n.s.	***	***	*	***	***
L x S	10, (11, 9)	n.s.	***	n.s.	***	*	n.s.	***	***
T x S	10, (11, 9)	n.s.	***	n.s.	***	n.s.	*	***	n.s.
Y x L x T	1	**	*	n.s.	n.s.	n.s.	n.s.	*	**
Y x L x S	10, (11, 9)	*	***	n.s.	***	n.s.	n.s.	***	n.s.
Y x T x S	10, (11, 9)	n.s.	***	n.s.	*	n.s.	n.s.	**	n.s.
L x T x S	10, (11, 9)	n.s.	**	n.s.	**	n.s.	n.s.	*	n.s.
Y x L x T x S	10, (11, 9)	n.s.	**	n.s.	***	n.s.	n.s.	***	*
Total	351, (383, 319)								

Component of variation: *, **, *** significant at *P* levels of $P < 0.05$, 0.01, 0.001, respectively; n.s., not significant.

[a] Degrees of freedom (df), values in brackets correspond to weed dry matter production, and N_2 fixation, respectively.

[b] Intercropped cover crop data includes combined dry matter production of intercropped legumes and intercropped sunflowers.

Table 4.4. Field emergence of legumes and monocropped sunflowers (averaged across tillage systems).

	Cover crop field emergence (% germinated plants of viable seeds)			
	Reinhardtsgrimma		Köllitsch	
Cover crop species[a]	2009	2010	2009	2010
MC faba bean	68 d	79 e	67 cde	75 c
IC faba bean	63 cd	82 e	63 bcd	73 bc
MC field pea	65 cd	68 d	70 de	72 bc
IC field pea	58 bc	65 d	67 cde	69 abc
MC narrow-leafed lupin	68 d	46 a	59 abc	63 ab
IC narrow-leafed lupin	64 cd	63 cd	62 bcd	67 abc
MC grass pea	63 cd	48 ab	74 e	61 a
IC grass pea	56 abc	55 abc	67 cde	59 a
MC common vetch	51 ab	49 ab	52 ab	57 a
IC common vetch	48 a	58 bcd	49 a	61 a
MC sunflower	52 ab	62 cd	62 bcd	65 abc

[a] Monocropped (MC) and intercropped (IC) cover crop.
Within a column, lower case letters display significant differences between cover crops within years based on Tukey-Kramer means separation (α = 0.05).

Table 4.5. Shoot dry matter (DM) production of weeds in no-till (NT) and reduced tillage (RT) cover crop plots and the control plot at harvest I and II, as well as weed dry matter production at harvest II averaged over tillage systems and locations, lower case letters within a column indicate significant weed dry matter differences in the plots of the cover crops and the fallow plot, based on Tukey-Kramer means separation (α = 0.05).

	Weed dry matter production (Mg ha^{-1})																	
	Reinhardtsgrimma (RG)								Köllitsch (KÖ)									
	2009				2010				2009				2010				Year x Species***	
	Harvest I		Harvest II		Harvest I		Harvest II		Harvest I		Harvest II		Harvest I		Harvest II		Harvest II	
Cover crop plots[a]	NT	RT	NT	RT	NT	RT	NT	RT	NT	RT	NT	RT	NT	RT	NT	RT	2009	2010
MC faba bean	0.61	0.08	0.67	0.43	0.12	0.05	0.15	0.08	0.71	0.06	0.58	0.24	0.16	0.06	0.16	0.15	1.92 d	0.54 ab
IC faba bean	0.66	0.06	0.73	0.39	0.12	0.03	0.14	0.07	0.92	0.05	0.63	0.24	0.22	0.05	0.21	0.09	1.99 de	0.51 ab
MC field pea	0.59	0.06	0.42	0.17	0.14	0.05	0.12	0.10	0.91	0.05	0.47	0.17	0.20	0.06	0.19	0.13	1.23 a	0.54 ab
IC field pea	0.35	0.06	0.44	0.20	0.15	0.04	0.11	0.11	0.81	0.04	0.57	0.11	0.20	0.05	0.17	0.08	1.32 a	0.47 ab
MC narrow-leafed lupin	0.63	0.07	0.69	0.32	0.10	0.06	0.14	0.12	0.99	0.07	0.60	0.25	0.17	0.06	0.18	0.11	1.86 d	0.55 ab
IC narrow-leafed lupin	0.62	0.09	0.61	0.28	0.17	0.05	0.14	0.13	0.89	0.03	0.46	0.11	0.23	0.05	0.23	0.13	1.46 ac	0.63 b
MC grass pea	0.74	0.06	0.64	0.24	0.14	0.05	0.13	0.11	0.56	0.04	0.58	0.22	0.16	0.05	0.20	0.09	1.68 bcd	0.53 ab
IC grass pea	0.38	0.07	0.63	0.25	0.14	0.04	0.15	0.09	0.86	0.05	0.49	0.08	0.17	0.06	0.11	0.07	1.45 ab	0.42 a
MC common vetch	0.67	0.11	0.61	0.48	0.11	0.04	0.11	0.13	0.78	0.06	0.40	0.21	0.17	0.04	0.14	0.05	1.70 cd	0.43 a
IC common vetch	0.59	0.08	0.45	0.28	0.13	0.05	0.12	0.10	1.16	0.03	0.54	0.13	0.23	0.03	0.17	0.05	1.40 ab	0.44 a
MC sunflower	0.70	0.05	0.68	0.17	0.12	0.05	0.15	0.13	0.89	0.05	0.58	0.09	0.27	0.04	0.21	0.08	1.52 ab	0.57 ab
Fallow	0.65	0.08	0.71	0.47	0.14	0.05	0.15	0.09	1.08	0.07	0.78	0.36	0.24	0.05	0.24	0.13	2.32 e	0.61 ab

[a] Weed dry matter in plots of monocropped (MC) and intercropped (IC) cover crops and fallow without any crop.

*** Year x Species interaction significant at $P < 0.001$, Within a column, lower case letters display significant differences between trial plots based on Tukey-Kramer means separation (α = 0.05).

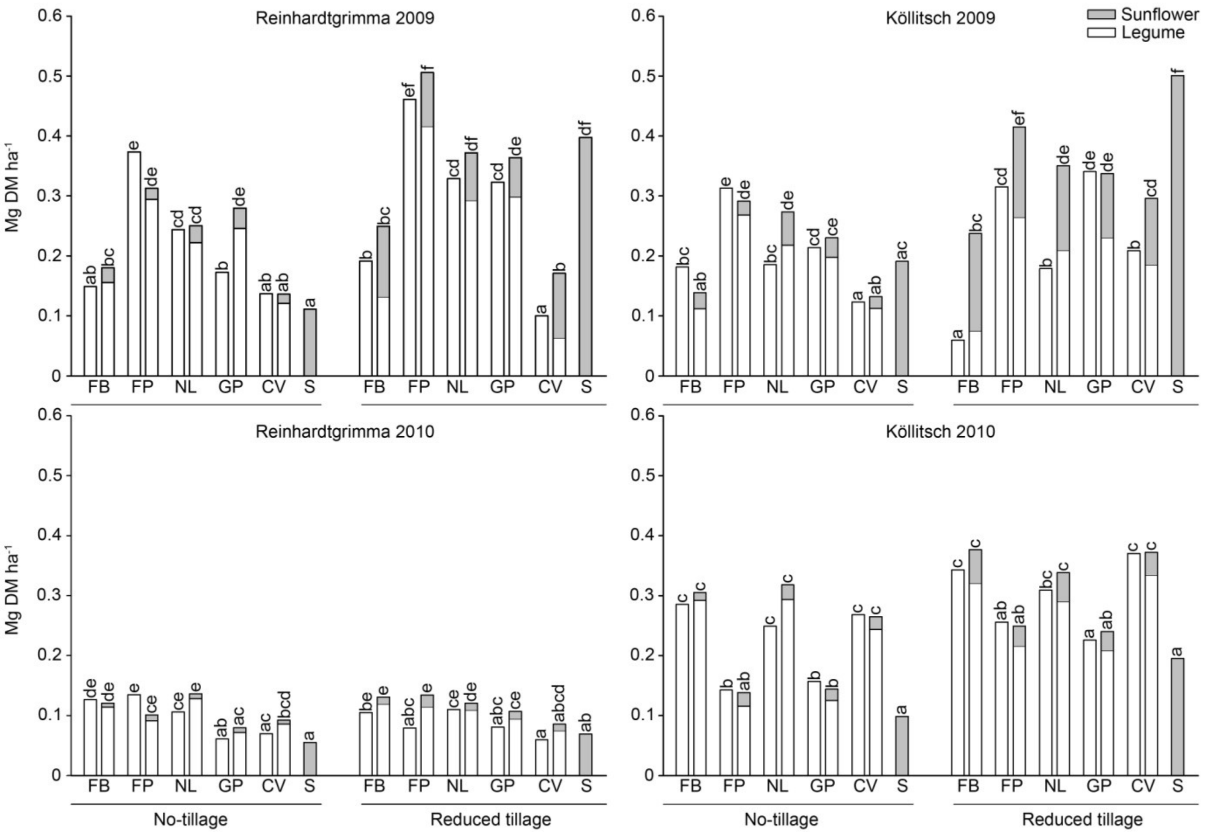

Fig. 4.1. Shoot dry matter (DM) of legumes and sunflowers at harvest I. Each column pair represents monocropped (left) and intercropped (right) plant stands of faba bean (FB), field pea (FP), narrow-leafed lupin (NL), grass pea (GP), and common vetch (CV), respectively. The single column represents monocropped plant stands of sunflower (S). Lower case letters indicate cover crop specific significant differences within tillage systems, based on Tukey-Kramer means separation (α = 0.05).

the reduced tillage system at KÖ. In the no-till system the IC sunflower biomass production was low and contributed not significantly to an increased total dry matter production in IC compared to MC plant stands.

In 2010 at RG the largest dry matter production at harvest I was in both tillage systems shown by MC and IC faba bean, narrow-leafed lupin and IC field pea. Up to harvest II the narrow-leafed lupin biomass production fell behind the one by MC and IC faba bean and IC field pea. Both species displayed the largest dry matter production in the no-tillage and reduced tillage system at harvest II although it was consistently below 0.52 Mg ha^{-1}. At KÖ in 2010, the MC and IC faba bean, narrow-leafed lupin and MC common vetch showed within the no-tillage and reduced tillage system the largest dry matter production at both harvest dates; reaching at harvest II a biomass of up to 1.49 and 1.65 Mg ha^{-1}, in the no-tillage and reduced tillage system, respectively. The sunflower was, at both locations, negatively influenced by the conditions in 2010; the intercropping with sunflowers was not successful and even the biomass production of MC sunflowers at RG and KÖ remained below 0.13 and 0.55 Mg ha^{-1}, respectively.

The weed population in both years and locations in the no-till system mainly consisted of weeds that were already present at seeding and continued to grow after the cash crop harvest. In 2009, many of those weeds were able to finish their life cycle in the period up to harvest II so that the weed dry matter declined between harvests I and II. After shallow tillage, the weeds in the reduced tillage system consisted of both newly germinated weeds and weed regrowth (Table 4.6). In 2009 at KÖ the dominant weed species were *Poa annua* L. in the no-tillage system and *Chenopodium album* L. in the reduced tillage system. In 2010 at KÖ the largest weed abundance was shown by *Matricaria inodora* L. in both tillage systems. In 2009 and 2010 at RG, *Stellaria media* (L). Vill., was the dominant weed species in both tillage systems.

The weed biomass production was increased in the no-till system, and up to harvest I and II influenced by multiple two way interactions (Fig. A 11-14a-c; Table 4.3). At harvest I in both years the average weed biomass was larger in the no-till than in the reduced tillage system (2009: 0.73 versus 0.06 Mg ha^{-1}; 2010: 0.16 versus 0.05 Mg ha^{-1}, respectively, derived from Table 4.5). This was also the case at harvest II although the differences between the no-tillage and reduced tillage system were smaller (2009: 0.57 versus 0.23 Mg ha^{-1}; 2010: 0.16 versus 0.10 Mg ha^{-1}, respectively).

Independent from the tillage system, the weed biomass varied considerably between the plots of the different cover crops and the fallow plot in 2009 (Table 4.5). The lowest weed dry

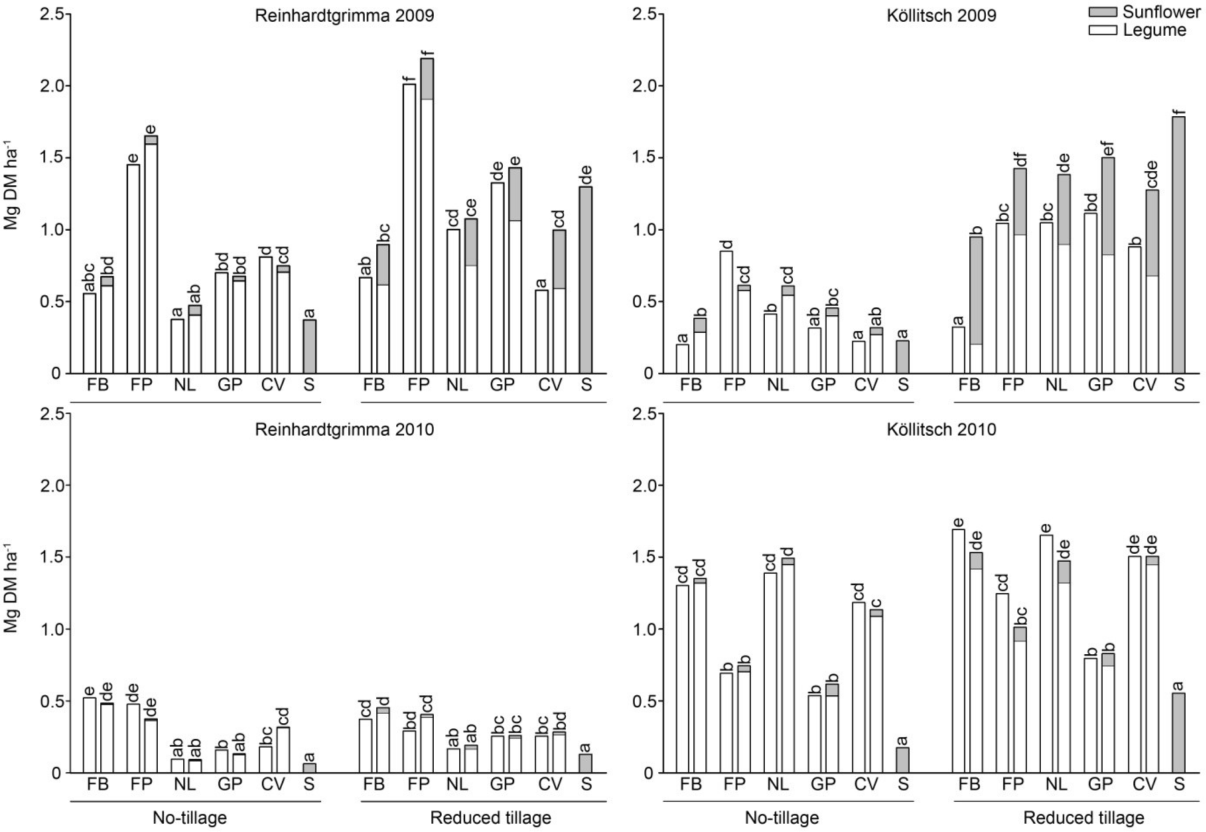

Fig. 4.2. Shoot dry matter (DM) of legumes and sunflowers at harvest II. Each column pair represents monocropped (left) and intercropped (right) plant stands of faba bean (FB), field pea (FP), narrow-leafed lupin (NL), grass pea (GP), and common vetch (CV), respectively. The single column represents monocropped plant stands of sunflower (S). Lower case letters indicate cover crop specific significant differences within tillage systems, based on Tukey-Kramer means separation (α = 0.05).

matter production was found in plots of MC and IC field pea, MC sunflower, IC common vetch, grass pea and narrow-leafed lupin. In 2009 all cover crops, except IC faba bean, displayed a lower weed biomass than in the fallow plot, while in 2010 there was no difference between the cover crop plots and the fallow plot. IC compared to MC plant stands influenced the weed biomass production only marginally.

4.3.4 Cover crop shoot N accumulation

The accumulation of N in cover crop biomass was affected by interactions between year x location x tillage system x species (Table 4.3). Within the no-till system in 2009 at RG the MC and IC field pea (60.7 and 61.1 kg ha^{-1}, respectively) showed the highest N accumulation by a large margin, while at KÖ the differences between species were smaller and the N accumulation remained below 28.7 kg ha^{-1} (Fig. 4.3). In the reduced tillage system at RG the MC and IC faba bean and grass pea accumulated the most N while at KÖ this was the case for MC and IC grass pea, IC narrow-leafed lupin and field pea as well as MC sunflower.

In 2010 at RG the N accumulation was low, the MC and IC faba bean and field pea displayed, in both tillage systems, the largest N accumulation (between 15.0 and 19.1 kg ha^{-1}) while both the MC and IC narrow-leafed lupin and the MC sunflower accumulated less than 4.2 kg ha^{-1}. Conversely at KÖ, the MC and IC narrow-leafed lupin accumulated in both tillage systems more than 46 kg ha^{-1} and displayed together with MC and IC common vetch and IC faba bean the largest N accumulation.

A larger shoot N accumulation in the IC compared with the MC plant stands was shown only in 2009 at RG by the IC common vetch in the reduced tillage system and at KÖ by the IC faba bean in both tillage systems and by the IC field pea in the reduced tillage system. The weeds in the no-till system displayed large shoot N accumulation, particularly in 2009 (data not shown).

At seeding, the inorganic soil N resources at RG in both years and at KÖ in 2010 were below 14 kg ha^{-1} in both tillage systems, while at KÖ in 2009 they reached 35 kg ha^{-1} in the no-till and 61 kg ha^{-1} in the reduced tillage system (Fig. 4.3). After harvest II, the inorganic soil N contents displayed a highly significant interaction between year and location (Table 4.3). In 2009 the inorganic soil N content after harvest II was significantly lower at RG compared to KÖ while in 2010 there was no difference between locations. At KÖ, the inorganic soil N contents after harvest II were also significantly larger in 2009 than in 2010. The different MC and IC cover crops influenced the inorganic soil N contents after harvest II only marginally.

Table 4.6. Weed biomass compositions at Reinhardtsgrimma and Köllitsch in 2009 and 2010 in the no-till (NT) and reduced tillage (RT) system.

	Present and newly emerged weeds at							
	Reinhardtsgrimma (RG)				Köllitsch (KÖ)			
	2009		2010		2009		2010	
Weed species	NT	RT	NT	RT	NT	RT	NT	RT
Capsella bursa-pastoris (L.) Medik.	-	-	-	-	-	-	¶	-
Chenopodium album L.	-	¥ **+**	-	-	¥	¥ **+**	-	¥
Cirsium arvense (L.) Scop.	¶ **+**	¥	¶ ¥ **+**	¥	¶	¥ **+**	¶ ¥	¥
Polygonum convolvulus L.	¶	-	-	-	-	-	-	-
Lamium amplexicaule L.	-	¥	¥	¥ **+**	-	¥ **+**	-	¥
Matricaria inodora L.	-	-	-	-	-	-	¥ **+**	¥ **+**
Matricaria recutita L.	-	-	¶	¥	-	-	-	-
Medicago sativa L.	-	-	-	-	¶	-	-	-
Plantago major L.	-	-	-	-	¶	-	-	¥
Poa annua L.	-	-	-	-	¶ **+**	-	¶ **+**	-
Polygonum aviculare L.	-	-	¶	-	¶ **+**	-	¶	-
Rumex obtusifolius L.	¶	¥	¶	¥	¶	¥	¶ ¥	-
Stellaria media (L.) Vill.	¶ ¥ **+**	¥ **+**	¶ ¥ **+**	¥ **+**	¶ ¥ **+**	¥	¶ ¥	¥ **+**
Taraxacum spp.	¶	-	¶	-	¶	¥	-	-
Veronica persica Poir.	-	-	¶	-	-	-	-	-
Viola arvensis Murr.	-	-	¶	-	-	-	¶	-
Volunteer cereal grain	¥ **+**	¥ **+**	¥ **+**	¥ **+**	¥	¥	¥	¥ **+**

- Weed not present.
¶ Weed present at seeding.
¥ Weed emerged after seeding.
¶ ¥ Existing and newly emerged weed.
+ Dominant weed species

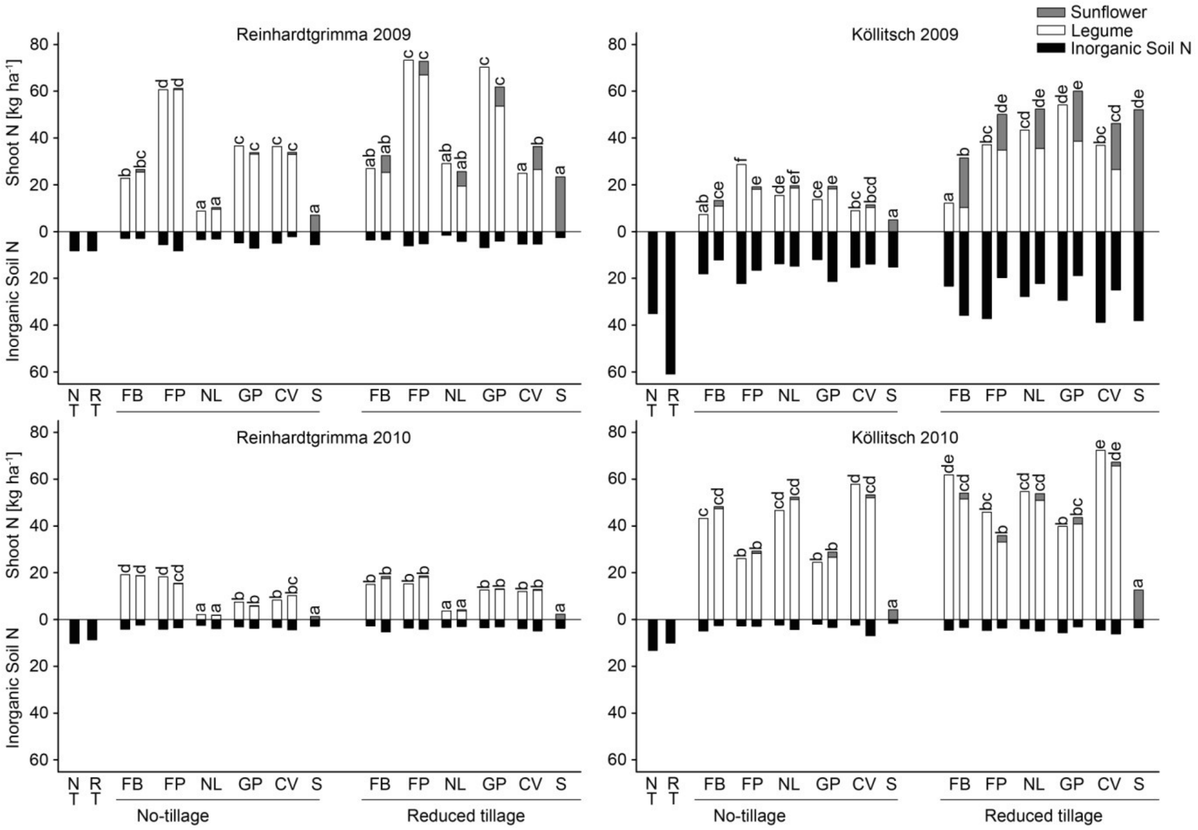

Fig. 4.3. Inorganic soil N at seeding, after harvest II, and shoot N accumulation of legumes and sunflower at harvest II. The first column pair represents the inorganic soil N content at seeding in the main plot for no-till (NT) and reduced tillage (RT), respectively; remaining column pairs represent monocropped (left) and intercropped (right) contents after harvest II of faba bean (FB), field pea (FP), narrow-leafed lupin (NL), grass pea (GP), and common vetch (CV), respectively. The single column represents monocropped plant stands of sunflower (S). Lower case letters indicate cover crop specific significant differences within tillage systems, based on Tukey-Kramer means separation (α = 0.05).

4.3.5 N_2 fixation

The N_2 fixation by the legume cover crops was influenced by interactions between year x location x tillage system x species (Table 4.3). Within the no-till system at RG in 2009, the MC and IC field pea fixed the most N_2 (46.5 and 44.3 kg ha^{-1}, respectively). In the reduced tillage system this was the case for MC and IC field pea and grass pea (Table 4.7). At KÖ, the N_2 fixation in the no-till system reached 33.8 kg ha^{-1} (MC field pea), while in the reduced tillage system the maximum N_2 fixation was only 5.5 kg ha^{-1} (MC common vetch). In contrast to the species in the no-till system the N_2 fixation of the legumes in the reduced tillage system showed no significant variations.

In 2010 at RG in the no-till system the MC and IC faba bean, field pea and IC common vetch displayed an equally large N_2 fixation of up to 19.3 kg ha^{-1}. In the reduced tillage system the largest N_2 fixation was shown by IC field pea (17.3 kg ha^{-1}), which was only significant to the lowest values shown by MC and IC narrow-leafed lupin. At KÖ in 2010 the N_2 fixation in the no-till system reached 53.7 kg ha^{-1} (IC common vetch), which was not significantly different compared to MC common vetch, IC faba bean and narrow-leafed lupin. In the reduced tillage system the maximum N_2 fixation was 60.5 kg ha^{-1} (MC common vetch) which was without difference to the N_2 fixation by IC common vetch and MC faba bean.

Table 4.7. N_2 fixation of legume cover crops in the no-till (NT) and reduced tillage (RT) system. Within a column, lower case letters indicate cover crop specific significant differences within tillage systems, based on Tukey-Kramer means separation (α = 0.05).

	N_2 fixation (kg ha^{-1})							
	Reinhardtsgrimma (RG)				Köllitsch (KÖ)			
	2009		2010		2009		2010	
Cover crop species[a]	NT	RT	NT	RT	NT	RT	NT	RT
MC faba bean	14.4 bc	15.2 abc	19.3 d	10.9 ab	7.3 ab	0.0 a	41.7 b	52.3 de
IC faba bean	14.4 bc	21.7 c	16.9 bcd	17.2 b	7.5 ab	0.0 a	44.5 bc	41.7 bcd
MC field pea	46.5 d	53.2 d	18.7 cd	12.8 ab	33.8 c	0.1 a	22.4 a	36.0 abc
IC field pea	44.3 d	53.2 d	15.0 bcd	17.3 b	17.8 b	0.0 a	23.7 a	24.5 a
MC narrow-leafed lupin	2.2 a	9.7 ab	1.9 a	1.0 a	9.6 ab	3.6 a	40.9 b	43.1 cd
IC narrow-leafed lupin	3.6 ab	6.8 a	2.1 a	1.9 a	16.3 ab	3.3 a	50.5 bc	44.8 cd
MC grass pea	23.3 c	53.9 d	5.8 ab	12.7 ab	10.4 ab	2.1 a	19.2 a	29.9 a
IC grass pea	24.7 c	46.5 d	5.4 ab	9.4 ab	18.1 b	1.8 a	23.0 a	29.5 ab
MC common vetch	26.5 c	18.8 bc	7.5 abc	10.5 ab	6.6 ab	5.5 a	53.6 bc	60.5 e
IC common vetch	17.3 c	20.7 bc	11.7 abcd	12.7 ab	5.5 a	0.0 a	53.7 c	57.5 e

[a] Monocropped (MC) and intercropped (IC) legume cover crop.

Within a column, lower case letters display significant differences between legume cover crops based on Tukey-Kramer means separation (α = 0.05).

4.4 Discussion

4.4.1 Crop establishment

The omission of conventional tillage has been commonly associated with increased soil density and impaired root growth (Carter, 1990; Pietola, 2005). This leads to the assumption that mechanical impedance of the seed-slot walls in the consolidated soil negatively influenced field emergence in the no-till system. However, the reduced field emergence in the no-till system was likely only slightly influential as weed competition is more important with relation to crop performance. Kapusta (1979) showed that even with similar legume plant populations in no-till and tilled systems, yields in the no-till system can be consistently reduced due to strong weed competition after tillage is omitted.

4.4.2 Evaluation of cover crop species

The field pea performed better than the faba bean when there was a strong weed pressure and poor access to water, as demonstrated in the first year of the cover crop trials. The explanation for this could be that the field pea is highly competitive (Spies et al., 2001) and has a high water efficiency use (Power, 1991), whereas the faba bean is less competitive and susceptible to dry conditions (Townley-Smith et al., 1993; Strydhorst et al., 2008). These characteristics recommend the normal leafed field pea for use in no-till systems with moderate weed abundance in years with low precipitation prior to any other tested legumes. It has to be noted that the suitability of the field pea in a weedy field can be considerably reduced if a semi-leafless pea variety is used (Semere and Froud-Williams, 2001; Spies et al., 2011).

The faba bean has potential as a cover crop in the no-till system if the weed pressure is low and precipitation is high, as was the case in 2010. The faba bean is better suited under these conditions than the field pea due to the susceptibility of field peas to transient water logging and fungal infections as shown in an Australian study where high precipitation led to increased faba bean and reduced field pea grain yields (Siddique et al., 1993).

In 2009, the narrow-leafed lupin displayed low biomass production, particularly at RG in the second half of the trial. This was likely the result of the strong weed competition, as lupin is a weak competitor against weeds (Strydhorst et al., 2008). In addition, the narrow-leafed lupin was the only legume species that required additional inoculation and the very low N_2 fixation at RG in both years and tillage systems suggests a failed inoculation of the seed. This likely resulted in a N deficiency and further reduced the competitive ability. By contrast, the large dry matter production in the no-till system at KÖ in 2010 shows that with a sufficient N_2 fixation and without high weed pressure, the narrow-leafed lupin can be well suited for an organic no-till system.

In 2009, the common vetch displayed particularly at RG, consistently low dry matter production in the dry conditions of the first growing period in both tillage systems. This can be explained by its sensitivity to dry conditions and its response of high biomass production with increased precipitation (Papastylianou, 1995), as was the case at KÖ in 2010. However, the biomass production in the no-till and reduced tillage system was still lower than in a study by Franczuk et al. (2010) who used plough tillage and a higher seeding rate (Franczuk, 2014 personal communication). Even at the lower biomass production rate in the present study, the N_2 fixation was high which makes the common vetch a very valuable cover crop for an organic no-till system.

The grass pea biomass production in the no-till and reduced tillage system of the present study were similar to low and high dry matter yields, respectively, in a conventional no-till system in Canada (Martens et al., 2001). The reduced biomass production in the no-till system of the present study can be attributed to the high weed pressure and the grass peas' poor competitive ability against weeds (Wall et al., 1988).

The IC sunflowers could not be successfully established in the no-till system and there was no consistent increase of the total above ground dry matter production and N accumulation in the IC compared with MC plant stands. This could be explained by the sunflowers' sensitivity to seeding into wet and compacted soils (Carvalho and Basch, 1994; Bayhan et al., 2002) and to early competition (Johnson, 1971; Kandel et al., 1997). In the reduced tillage system under the warm conditions in 2009, especially the MC sunflowers displayed their ability for a large dry matter production. By producing large amounts of biomass, MC sunflowers were able to strongly suppress weeds and accumulate large amounts of N, emphasizing the potential of this species for cover cropping in organic reduced tillage systems. The potential of sunflower was also shown through high sunflower yields in other organic reduced tillage trials (Berner et al., 2008). Nevertheless, the dry matter production of sunflower in the reduced tillage system can be strongly impaired by low temperatures and low inorganic soil N resources, as was the case at both locations in 2010.

Due to their importance for N_2 fixation, the legumes evaluated in this study may prove useful in conventional systems as well. For instance, they can be used as annual green manure crops or short term (frost killed) double crops with winter cereals (Townley-Smith et al., 1993; Martens et al., 2001). The largest N_2 fixation values shown by the legume cover crops were within the range of other trials, but might have been higher had root material been sampled. The N_2 fixation by faba bean at KÖ in 2010 and by the field pea in both tillage systems as well as by the grass pea in the reduced tillage system at RG in 2009 were similar to the N_2 fixation averages between 40 and 49 kg ha^{-1}, which were estimated by other methods in green manure trials in Canada (Townley-Smith et al., 1993; Biederbeck, et al., 1996;). The narrow-leafed lupin at KÖ in 2010 displayed a larger N_2 fixation than an undersown legume catch crop with a similar dry matter production in Danish organic farming trials (Askegaard and Eriksen, 2007). This might be because in the Danish trial the seedbed of the main crop (spring barley) was fertilised, increasing the availability and accumulation of N from inorganic soil N resources for the later undersown narrow-leafed lupin. The N_2 fixation by common vetch at RG in 2009 and at KÖ in 2010 was within the range (25 to 90 kg ha^{-1}) of another Danish organic system trial. Since the root material was not sampled in the present study, the total N_2 fixation was probably 10 to 25% higher (Mueller and Thorup-Kristensen, 2001). The calculation of the N_2 fixation only included inorganic soil N contents up to a depth of 0.3 m because the shallow soil at RG limited the soil sampling. Potential N leaching at RG and KÖ during the cover cropping period was not accounted for in the estimation of the N_2 fixation with the extended difference method.

4.4.3 Influence of available inorganic soil N level and weather conditions

Low available inorganic soil N resources at RG in both years and at KÖ in 2010 impaired the growth of the non-legume cover crop IC sunflower. Transfer of N from the legume to the IC sunflower was presumably negligible. The growing period was short, none of the legumes exceeded the early flowering period and, up to late flowering, the N transfer from the legume to non-legume can be very low (Jamont et al., 2013). In the no-till system at KÖ in 2009, the potential available inorganic soil N resources were higher, but the sunflowers were not able to acquire a larger amount of N due to the already established weeds. The weeds accumulated the majority of the available inorganic soil N resources, which further increased their growth (Blackshaw et al., 2003). In the reduced tillage system at KÖ in 2009 without the early weed competition and with alleviated soil compaction and even higher inorganic soil N resources, the intercropping was successful.

However, the large inorganic soil N resources at KÖ in 2009 also had a negative effect on the N_2 fixation by the legumes, which was reduced in the no-till system and almost nonexistent in the reduced tillage system. The large available inorganic soil N resources likely led to a depressed nodulation (Dean and Clark, 1980) and a delayed onset of the N_2 fixation (Voisin et al., 2002). Intercropping did not increase the N_2 fixation in the present study, presumably due to the short growing season in which the N immobilisation by the IC sunflower was not large enough to sufficiently reduce the available inorganic soil N resources.

The preceding cash crops of the cover crops were cereal grains, winter rye and oat at RG and winter wheat in both years at KÖ. The difference in grain species was caused by late harvest of organic wheat at the RG location, and could have influenced the weed spectrum and growing stage at cover crop seeding. The unfavourable climate conditions at RG in 2010 resulted in late harvest of winter cereal grains and the cover crops were sown after a spring sown oats crop. The low weed biomass at RG in 2010 in the no-till system could be attributed to the seedbed preparation and oats seeding in spring but the equally low cover crop biomass production suggest a much stronger influence of the low late season temperatures at this submontane location which displayed the limitations of late season cover cropping.

4.5 Conclusion

The present study under central European conditions indicated that no-till practices for legume cover cropping in organic farming are only applicable if the weed density at seeding is low; otherwise, the weeds will suppress the cover crop growth. In conditions with a high weed density, reduced tillage should be considered as an alternative because it strongly reduces the early weed pressure. Significant year x location x tillage system x species interactions emphasized that the choice of species for late season cover cropping is difficult and the potential weed pressure, the inorganic soil N resources, as well as the expected weather conditions during the cover cropping period must be considered. The variable legume performances indicated that under comparatively dry conditions with moderate weed pressure, the normal leafed field pea could be suited for cover cropping in the no-till system while under wet conditions and with a low weed pressure, the faba bean, the narrow-leafed lupin and the common vetch would be a better choice. The practical use of these legumes in the no-till system should be further investigated under different climate conditions, soils and within different weed communities. In the organic no-till system, the sunflower growth appeared to be impaired and the intercropping of legumes and sunflowers had no strong reduction effect on the weed biomass production as a result of the absence of an increased total cover crop biomass production. In the reduced tillage system legume intercropping with sunflowers or monocropping of sunflowers could be successful if adequate inorganic soil N resources are available and the weather conditions are favourable.

5. Chapter: General discussion

5.1 Introduction

The widespread use of no-till systems in conventional agriculture in North and South America as well as central Asia, has invoked great interest among organic producers in possibilities of conservation tillage implementation. Additional to the various economic advantages organic farmers are furthermore highly interested in environmental benefits offered by seeding without tillage as the organic production system is particularly reliant on healthy and fertile soil. However, the current organic farming practices use deep soil inversion by means of mouldboard plough for weed control (Gruber and Claupein, 2009), potentially leading to soil erosion and reduced soil fertility.

A few studies have used reduced tillage in organic systems (Berner et al., 2008; Krauss et al., 2010). But the complete omission of soil disturbance has proven to be difficult to realise in organic production systems without adverse consequences on crop yields. Particularly problematic is the weed pressure since synthetic herbicides that are commonly used in conventional no-till systems are not permitted in organic farming. In organic systems weed control usually is based on soil disturbance. There are certain bioherbicides consisting of cinnamon and clove oil (WeedZap), acetic and citric acid (AllDown) as well as caprylic and capric acid (SUPPRESS) that are permitted for organic farming within the USA (OMRI, 2015) and in Japan diluted acetic acid (vinegar) can be used if cultural physical and biological methods for weed control are not effective (MAFF, 2015). In central Europe the only direct weed control methods without soil disturbance are mowing (e.g. flail mowing) and thermal weed control but flail mowing of weeds possesses the risk of regrowth and thermal weed control has shown not to be very effective for large weeds, many grass species and perennial weeds (Wszelaki et al., 2007). Therefore, an approach for the transition to organic no-till has to suppress weed growth at an early stage through very competitive cover crops which produce large amounts of residue for extended soil coverage.

Weed growth is enhanced by larger amounts of soil nitrogen (Blackshaw et al., 2003), therefore it could be advantageous to use cover crop species to specifically accumulate and immobilise large amounts of N for an extended time period.

5.2 Non-legume species for cover crop biomass production and long-term N immobilisation

Under central European conditions the cover cropping of small grains (rye and oats) as well as mustard is common while sunflowers are seldom used for that purpose. Buckwheat and hemp can be considered as novel but have shown their potential as cover crops (Creamer and Baldwin, 2000; Brust et al. 2014b).

In the present study the biomass production of buckwheat and hemp was inconsistent. In other studies buckwheat has shown the ability to suppress weeds effectively (Creamer and Baldwin, 2000), but it is also susceptible to light frost which limits its potential to produce biomass as late season cover crop in temperate climates. The N mineralisation simulation revealed only a marginal N immobilisation effect. Therefore buckwheat cannot be recommended for cover cropping in the transition period. Hemp is also not suited for this period since the anticipated high biomass production could not be achieved by hemp resulting in low weed suppression and increased weed biomass production. Mustard has potential as a cover crop before no-till sown legume cash crops but it requires large amounts of N for high biomass production. Stivers-Young (1998) found that over winter N accumulated in plant biomass is lost to a larger extent from mustard than from oats. This is in accordance with the mineralisation simulation in the present study and indicated that mustard should only be used as cover crop before autumn sown non-legume cash crop that can utilise mineralised N from mustard residue.

In the present study sunflower produced consistently large amounts of biomass and was one of the cover crops with the largest N accumulation even in low N availability conditions which can be attributed to its ability to increase the N uptake efficiency in low N conditions (Hocking and Steer 1982). Solely based on its ability to produce biomass and accumulate N sunflower appeared to be a promising cover crop for the transition to organic no-tillage. However, the in-depth analysis of the plant compartments revealed that the majority of N is accumulated in the leaves which is in accordance with Hocking and Steer (1983). Sunflower leaf material showed low C : N ratios with potentially detrimental effects on the long term N immobilisation as N mineralisation simulations revealed in the present study (Fig. 2.5 a-c, 2.6 a-c). In close proximity of leaf and stem material the large C content of the stem material could probably reduce the availability of mineralised leaf N for weed growth through N incorporation into microbial biomass decomposing the sunflower stems. Nevertheless, leaves would decompose quickly leading to reduced ground cover and potentially to increased weed growth. These adverse effects are also due to the low number of stems at a sunflower seeding rate of 90 viable seeds m^{-2} compared to rye and oats (300 and 350 viable seeds m^{-2}, respectively) which develop additional tillers and show therefore increased ground coverage when terminated with a roller-crimper.

The results of the present study indicate that rye or oats might be better suited as cover crop preceding no-till sown legume cash crops. Oats showed a lower stem% than sunflower at two locations (GR and KÖ) while it was similar to sunflower at PI. However oats also showed large leaf C : N ratios and the simulated proportional N mineralisation of combined stem and leaf material was similar to rye. Compared to rye the oats biomass production is often reduced (Bauer and Reeves, 1999), which makes rye the most suitable species of the evaluated non-legume species for cover cropping before no-till sown legumes.

The rye biomass production was at one location (GR) similar and at two locations (PI, KÖ) second to sunflower. However only after early seeding at the PI location with its presumed increased N availability during the cover crop growing phase, the rye biomass production was large enough to exceed the threshold of 3.9 Mg ha^{-1} which has been found to reduce the weed density of newly emerging weeds after no-till seeding by >75% (Teasdale et al., 1991). Massucati and Köpke (2010) achieved a significant reduction of the weed density in no-till sown faba beans through the application of 4 Mg ha^{-1} oats straw. In the present trials at KÖ and GR the rye biomass production remained below 3.9 Mg ha^{-1} even with additional fertilisation. Over winter the rye biomass will decompose resulting in further reduced weed suppression. Therefore the rye cover crop biomass production should exceed 3.9 Mg ha^{-1} as it was the case at the PI location to ensure sufficient ground coverage in spring.

For winter rye cover crops it has been shown that late seeding influences the potential rye biomass production negatively (Saini, 2009; Bauer and Reeves, 1999). This is consistent with the result of the present study and shows the importance of cover crop seeding immediately after harvest of the cereal grain. Early harvested cereal grains and therefore early cover crop seeding could significantly improve the cover crop biomass production.

5.3 Grain production of autumn and spring sown legume cash crop monocropped and intercropped with cereal grains after variable tillage

The implementation of spring rye cover cropping before no-till sown legume cash crops in the present study showed that under certain conditions the rye can become a problematic volunteer weed. The seeding of the cover crop was carried out in early August (similar to the preliminary trials at GR and KÖ), followed by directly seeding the cash crop into the cover crop in October. In these plots spring rye re-appeared after winter and developed into a volunteer weed, particularly at KÖ. Winter rye is known for its frost resistance but spring rye has lower frost resistance (Fowler et al., 1996), and should be terminated by frost. The rye regrowth resulted probably from its early growth stage at the beginning of October and the insufficient rye termination by the opener disk and press wheels. The rye was only damaged and regrowth occurred while the undisturbed rye in the plots of spring sown cash crops was terminated by frost. Limin and Fowler (2006) showed that vegetative growing stages of spring cereal grain genotypes can possess a substantially increased cold tolerance which explains the overwintering of rye regrowth. Nevertheless, the share of rye on the total weed biomass at BO and RG was not as high as at KÖ. This can be attributed to the large inorganic soil N resources in the no-till system at KÖ which increased the rye growth. Cash crop sowing of legumes in autumn should only be carried out if rye has reached anthesis and can be successfully terminated with a roller crimper (Mirsky et al., 2009), otherwise spring seeding of no-till cash crops into the frost terminated rye residue should be preferred.

Among the two winter and three spring legumes the normal leafed winter field pea appeared best suited for the omission of tillage since its yields were similar in the no-till, reduced and plough tillage systems. The semi-leafless spring field pea and spring faba bean appeared to be better suited for the reduced tillage system. In the reduced tillage system the weeds were removed through tillage which was advantageous for the spring field pea and faba bean with their reduced weed suppressive ability. The narrow-leafed lupin appeared not to be suited for cash cropping in the organic no-till system due to its low weed competition (Strydhorst et al., 2008). Within the no-till system the winter field pea grain yields were not consistently larger than the spring field pea yields but additionally the winter field pea displayed a tendency to better suppress weeds. The improved weed suppression of the winter field pea compared to the spring variety could be attributed to the early seeding in autumn which enabled the winter field pea to germinate in autumn and compete with weeds early in the growing season. The winter and spring field pea differed in the leaf type and growth habit (long-vined) which probably contributed to differences in weed biomass in the field pea plots because semi-leafless cultivars of peas are less competitive against weeds (Semere and Froud-Williams, 2001; Spies et al., 2011). In a recent study Gronle and Böhm (2014) found a better weed suppression of long-vined normal leafed winter field peas compared to short-vined semi-leafless winter field peas.

Intercropping of legumes and cereal grains only was successful for the spring sown legumes but even in those crops intercropping did not generally increase the weed suppression compared to monocropped plant stands. The intercropping of legumes and oats improved the weed suppression in all tillage systems at KÖ and in the tilled systems at BO. This could be attributed to the large inorganic soil N resources at KÖ and to increased N mineralisation in the tilled systems at BO which probably increased the competitive ability of the cereal intercrop component (Neumann et al., 2007). The total intercropped grain yield exceeded the MC legume yield only at one location (KÖ) in the no-till system and at two locations (KÖ and BÖ) in the reduced and plough tillage system which was probably also a result of the increased soil N resources at KÖ location and in the tilled systems at BO. This shows that the successful intercropping of legumes and cereal grains is dependent on the available inorganic soil N resources as it influences the weed competition and the grain yield of the non-legume cereal grain within the IC plant stand.

5.4 Legume cover crop biomass production and weed suppression in systems with reduced and without tillage

The field trials for the alternative transition to the no-till system after cereal grain harvest in late summer with the no-till seeding of legume cover crops revealed several important factors that need to be considered when the legume species for cover cropping are chosen. Besides the weed pressure, the inorganic soil N resources and the weather conditions are strongly influential for the cover cropping success. No-till seeding of cover crops appeared to be only suited if the weed pressure was low or moderate. In high weed density conditions the application of reduced tillage before the seeding of the legume cover crops displayed very positive effects for their biomass production and weed suppression. This can be explained by the slow legume development in their early growing stages (Giunta et al., 2009) and their susceptibility to early competition as shown for peas by (Nelson and Nylund, 1962), resulting in high competition from already established weeds in the no-till system. Reduced tillage removed the weeds and the cover crops only had to compete with emerging or re-emerging weeds which reduced the weed biomass production.

Suitable legume species for no-till cover cropping varied depending on the weather conditions. In comparatively dry conditions and with moderate weed pressure, the normal leafed field pea was best suited among the evaluated species. Its ability to resist increased weed pressure can be attributed to its intertwined long-vined growth habit and its leaf type enabling the normal leafed field pea to overgrow weeds in the inter-row space and reduce the available photosynthetically active radiation. Gronle and Böhm (2014) showed in trials with long-vined normal leafed field pea a substantial reduction of the photosynthetically active radiation transmitted towards the weed canopy which could explain the high weed suppression by the normal leafed field pea plant stands. The other cover crops appeared not to be suited for cover cropping in the presence of increased weed pressure which is in the case of faba bean and narrow-leafed lupin in agreement with the legume cash crop trial described in Chapter 3.

Under low weed pressure conditions there was in one site-year (KÖ 2010) an indication that faba bean, narrow-leafed lupin and common vetch could be better suited than field pea if precipitation is high. The reduced performance of field pea compared to faba bean, narrow-leafed lupin and common vetch at KÖ was probably due to its susceptibility to wet conditions since the emergence of field pea as well as the weed biomass at harvest I and II in the no-till system was similar to faba bean. The well performing legume species probably profited from the reduced weed biomass production at KÖ in 2010 which could be attributed to the chopping and spreading of the preceding cereal grain crop potentially increasing the weed suppression through ground coverage. However the number of weed species emerging after no-till seeding was increased in 2010 which disputes this assumption. The weed biomass production was probably mainly influenced by the available inorganic soil N resources. The large inorganic soil N resources at KÖ in 2009 likely increased the weed biomass production (Blackshaw et al., 2003) while lower inorganic soil N in 2010 resulted in lower weed growth.

The large biomass production of MC sunflower in the reduced tillage system at RG in 2009 and particularly at KÖ the same year confirmed results from an earlier study presented in Chapter 2. The further improved sunflower biomass production at the KÖ location displayed again the sunflowers' response to large available inorganic soil N resources. However, even with large inorganic soil N resources available the sunflower failed to produce sufficient amounts of biomass in the no-till system at KÖ in 2009. The N accumulation of sunflower (Fig. 4.3) in the no-till and reduced tillage system revealed that sunflower accumulated only small amounts of N. This can be attributed to the increased N accumulation by weeds (data not shown). Johnson (1971) and Kandel et al. (1997) showed that sunflower is very susceptible to weed pressure in its early growing stages. Due to the already established weeds in the no-till system the weed competition probably reduced the sunflower biomass production. This shows that sunflower should only be grown in low weed pressure conditions with potentially improved biomass if weeds are removed by tillage. The alleviation of soil compaction through tillage can potentially further improve the sunflower´s growth because of its susceptibility to soil compaction (Bayhan et al., 2002).

5.5 Conclusion

The complete omission of tillage in organic farming has proven to be difficult but the integration of no-tillage phases into organic crop rotations appears to be possible and could make organic farming more sustainable. For no-till sown legume cash crops the preliminary non-legume cover cropping after plough tillage has shown to produce large amounts of biomass potentially reducing the weed biomass in spring. The early seeding of the cover crops appeared to be important for the production of large amounts of biomass. The biomass production by the non-legume cover crops could be increased through organic fertiliser but in many cases with detrimental effects on the long term N immobilisation in cover crop biomass. The N mineralisation simulations indicated that rye could be well suited for cover crop biomass production and long term N immobilisation. The legume cash crop trials used rye as a cover crop in which the legumes were directly sown. The autumn seeding into the rye plant stand damaged the rye and resulted in rye regrowth and partially in the development into a volunteer weed. This showed that the seeding of the rye has to be carried out as early as possible to advance the phenological growth stage towards inflorescence emergence at cash crop seeding in October and that the rye needs to be terminated mechanically before cash crop seeding. Among the tested legumes the normal leafed field pea displayed the least variation between the no-till, reduced tillage and plough tillage system. This indicated that the normal leafed field pea is equally suited for all three tillage systems. The spring faba bean and narrow-leafed lupin benefitted from the weed removal by tillage in the reduced tillage system and appeared to be better suited for the reduced tillage and plough tillage system. The success of intercropping spring legume cash crops with oats appeared to be influenced by inorganic soil N and showed the importance of available inorganic soil N resources for the success of intercropping legumes and non-legumes. This was in agreement with the legume cover crop trials in the present study which showed in the reduced tillage system that IC legume and sunflower plant stands can produce larger amounts of biomass than MC legumes plant stands if sufficient amounts of inorganic soil N are available for the sunflower growth. This was not the case in the no-till system because sunflower appeared to be intolerant to the growing conditions in the no-till system. The suitability of legume species for no-till cover cropping showed some variations depending on the weed pressure and the weather conditions. For moderate weed pressure under dry conditions the normal leafed field pea appeared to be best suited for no-till cover cropping. Under wet conditions the faba bean, narrow-leafed lupin and common vetch appeared to be suited for the no-till system if the weed pressure was low. It was apparent in our trials that only a few crops were able to suppress weeds in the no-till system sufficiently. Within a crop rotation the weed pressure would probably increase and require occasional tillage to manage weeds. Nevertheless this study has shown that the implementation of no-tillage phases in organic agriculture appears to be possible. Such short term no-tillage could make organic farming more sustainable.

5.6 Further research

The partitioning of the cover crop biomass into stem and leaf material and determination of their individual C : N ratios revealed substantial differences between the tested non-legume species. The N mineralisation simulation under tillage conditions provided further information for the evaluation of the cover crops for long term N immobilisation. Yet, the N mineralisation simulation with the STICS crop model could not be carried out under no-till conditions because there were large inconsistencies for the decomposition of residues with low C : N ratios on the soil surface. The STICS model is capable of simulating the N mineralisation on the soil surface but the model needs to be fitted for plant materials with low C : N ratios. With the updated model further studies should be carried out to confirm the actual amount of N released from the cover crop residues over winter. The STICS model could prove to be a useful tool for the evaluation of cover crop and cash crop residues by the determination of their N mineralisation.

The spring faba bean and field pea displayed similar performance in the reduced tillage and plough tillage system which indicated that plough tillage is not always required before the seeding of these crops. This was also the case for oats which displayed high weed suppression in the reduced tillage system if sufficient inorganic soil N resources were available. These crops should be further investigated for seeding after reduced tillage because the reduction of tillage could further improve the sustainability of the organic farming system.

Depending on the weed pressure and weather conditions the normal leafed field pea, faba bean, narrow-leafed lupin and common vetch appeared to be suited for cover cropping in an organic no-till system and should be the basis for no-till cover crop trials with legumes in the future. Additional research with these legumes under variable weed pressure and weather conditions could improve the decision basis for no-till cover cropping in organic farming.

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* In German with English title

** In German with English abstract

*** In German with English summary

**** In German

Appendix

Fig. A 1. Prototype plot seeder with cross-slot openers.

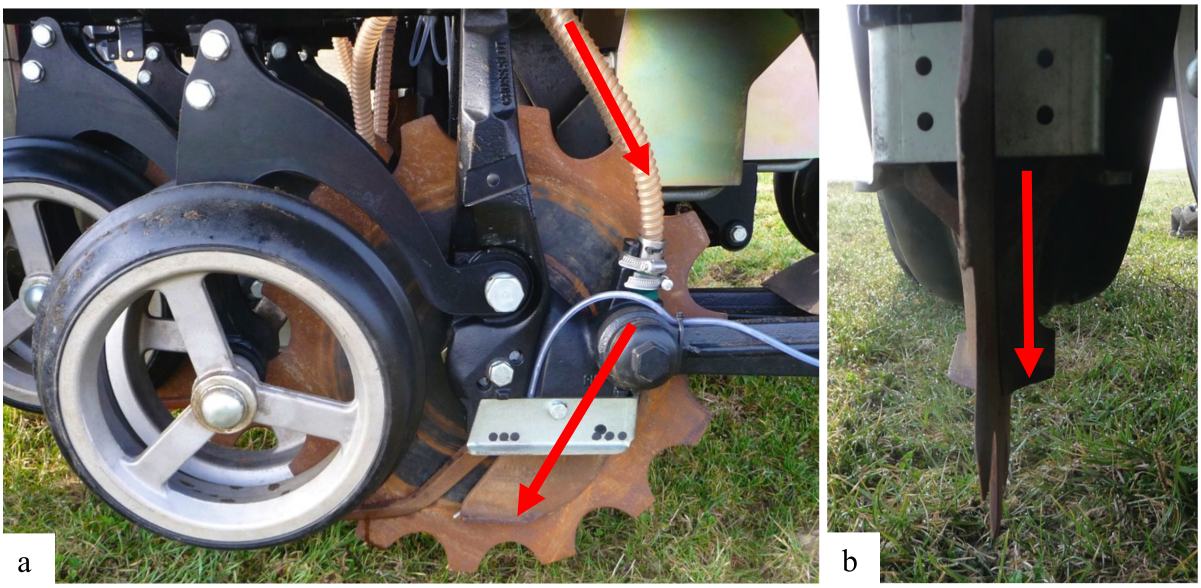

Fig. A 2a-b. Cross-Slot opener (red arrows indicating seed travel and placement).

Fig. A 3. Field pea emerging through cover crop residues in the no-till system.

Fig. A 4. Hemp cover crop in early September at the trial location Pillnitz.

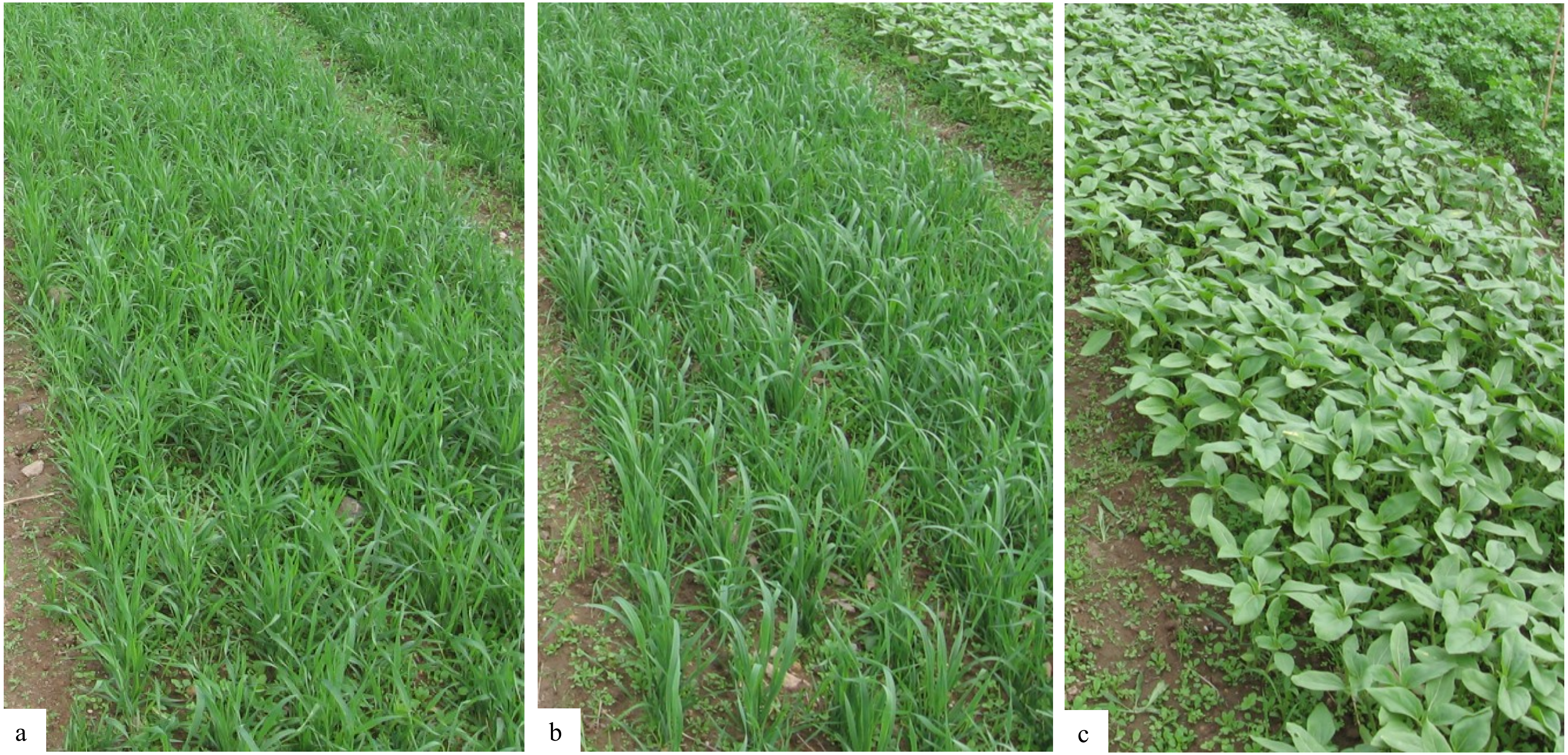

Fig. A 5a-c. Rye, oats and sunflower cover crops (respectively), in early September at the trial location Groß Radisch.

Fig. A 6a-c. Mustard, buckwheat and hemp cover crops (respectively), in early September at the trial location Groß Radisch.

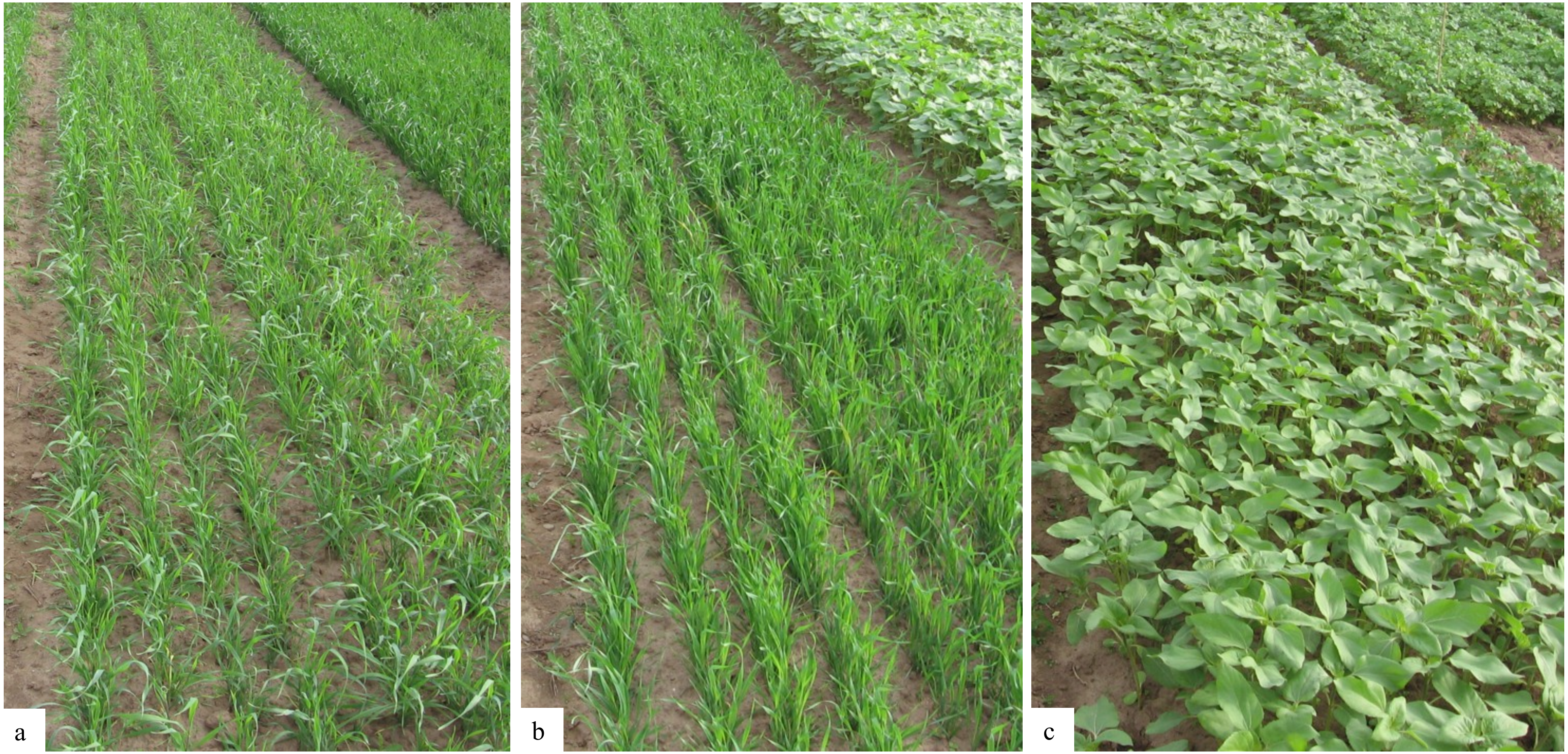

Fig. A 7a-c. Rye, oats and sunflower cover crops (respectively), in early September at the trial location Köllitsch.

Fig. A 8a-c. Mustard, buckwheat and hemp cover crops (respectively), in early September at the trial location Köllitsch.

Fig. A 9a-c. MC winter field pea at flowering in the no-till, reduced tillage and plough tillage system (respectively), at the trial location Reinhardtsgrimma.

Fig. A 10a-c. IC spring field pea at flowering in the no-till, reduced tillage and plough tillage system (respectively), at the trial location Bockelwitz.

Fig. A 11a-b. MC field pea in the no-till and reduced tillage system (respectively), in early September at the trial location Reinhardtsgrimma 2009.

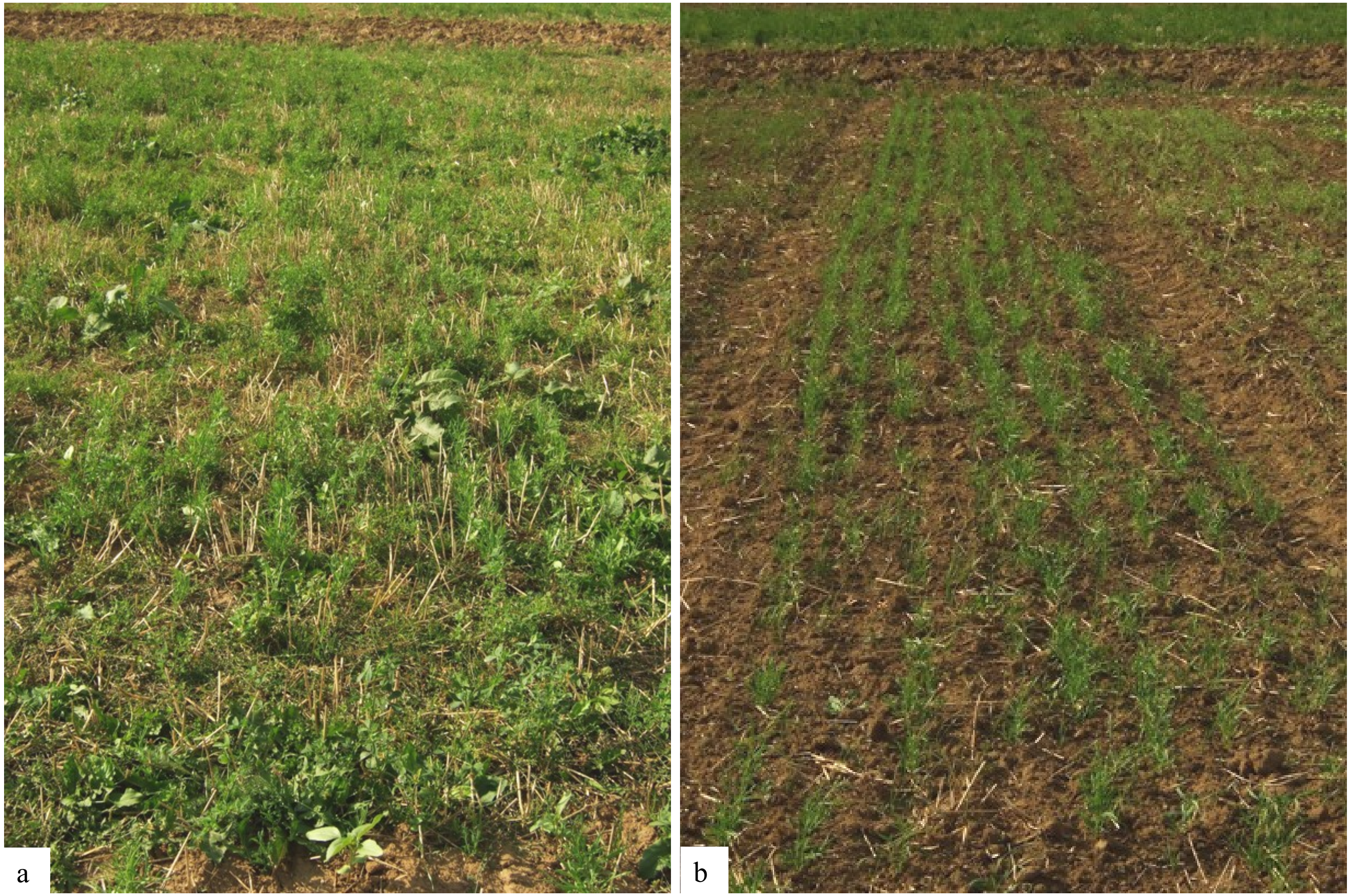

Fig. A 12a-b. MC Grass pea in the no-till and reduced tillage system (respectively), in early September at the trial location Köllitsch 2009.

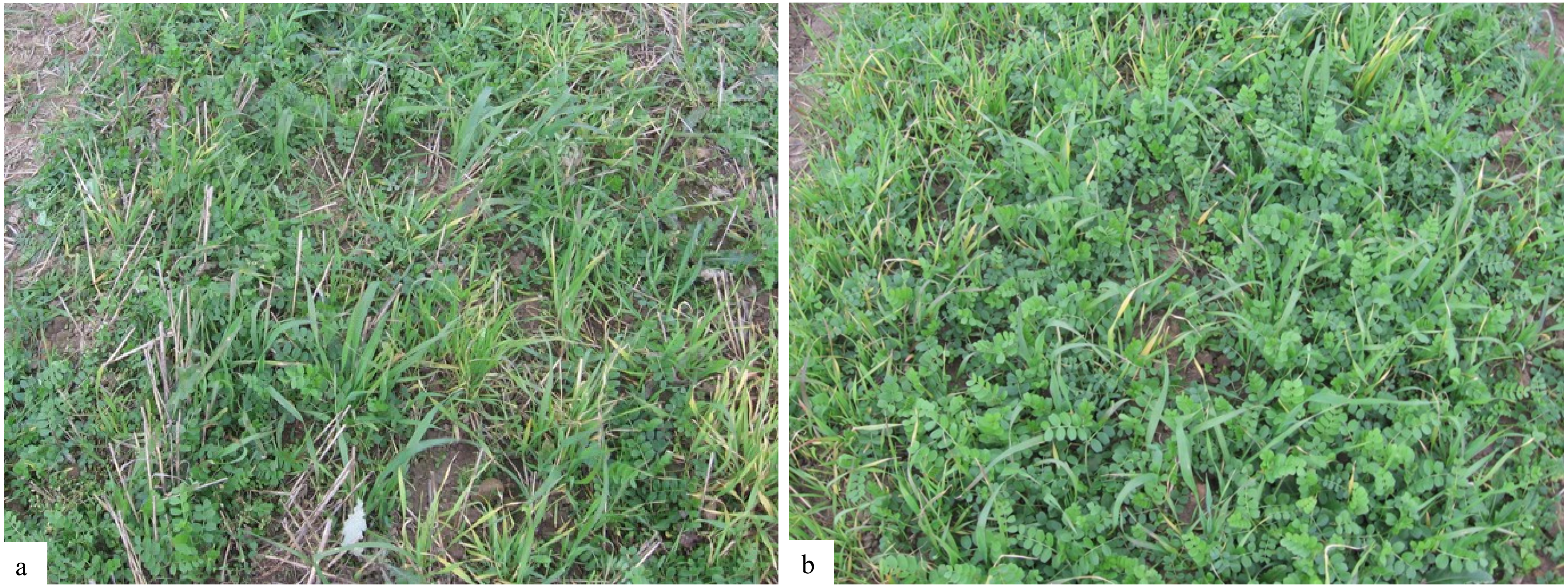

Fig. A 13a-b. MC common vetch in the no-till and reduced tillage system (respectively), in late October at the trial location Reinhardtsgrimma 2010.

Fig. A 14a-b. MC common vetch in the no-till and reduced tillage system (respectively), in late October at the trial location Köllitsch 2010.

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