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

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Abstract: Conservation tillage techniques offer considerably reduced soil erosion and improved soil structure but they are rarely used in organic farming systems due to the potentially increased weed pressure. For the use in the transition period to conservation tillage in organic farming, this study investigated the dry matter production, weed suppression and grain yield of 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). The different species were grown in no-tillage, reduced tillage and plough tillage systems at three sites in south-eastern Germany. In the no-tillage system the winter field pea grain yields of up to 3.39 Mg ha⁻¹ were 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 exceeded not 2.15 Mg ha⁻¹ in the no-tillage system. Narrow-leafed lupin displayed consistently yields below 0.65 Mg ha⁻¹ in the no-tillage system. Normal leafed winter field pea appeared 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 grown successfully 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.

Key words: Grain legume, Intercropping, No-tillage, Organic farming, Plough tillage, Reduced tillage.

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). Although this technique has been proven to control weeds very effectively it is also one of the main contributing factors for the soil erosion which reduces the soil fertility. No-tillage practices on the contrary can stabilize the soil aggregates and strongly reduce the soil erosion (Montgomery, 2007). Additionally they can increase the soil water storage (Fabrizzi et al., 2005) and the soil organic carbon content while reducing the annual CO₂ emissions (Ussiri and Lal, 2009).

Nevertheless, the adoption of the 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. 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. However, the transition period to the no-tillage system is often accompanied by a yield reduction (Reicosky and Saxton, 2007) as a result of poor crop emergence, increased weed...
pressure and reduced mineralization of the soil organic nitrogen. An organic no-tillage system approach has to address all these issues.

The use of mulch from cover crop residue for weed suppression could be a key technology for a successful transition to an organic no-tillage system. 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 immobilization and reduced weed growth. 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.

While the weed suppression increases with mulch quantity (Teasdale and Mohler, 2000) the crop seed placement is impaired by heavy residue layers. Therefore special no-tillage seeding techniques have to be used for thick cover crop residue layers. The inverted T-cross slot openers were developed for the use in high residue environments (Baker, 2007) and can improve the seed placement under those conditions.

The N immobilization caused by the cereal cover crops can lead to soil N deficiencies that reduce the weed pressure in the subsequent cash crop but it can also reduce the cash crop yield if a non-legume crop is grown. Therefore, legumes should be chosen to take advantage of their ability to symbiotically fix N₂ and compensate for the soil N deficiencies during the period of conversion to reduced or no-tillage organic agriculture. However, 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 of the IC crop stands compared with 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.

For both the faba bean and the field pea there are winter and spring cultivars available. Another high potential legume for the transition period is the spring sown narrow-leaved lupin. These legumes 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, personal communication; Urbatzka et al., 2011) yet only a few studies have been conducted in reduced or no-tillage conditions (Köpke and Schulte, 2008).

Our objective 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.

This study will provide valuable information for the development of a more sustainable organic no-tillage system.

Materials and Methods

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 (2007)) at the Teaching and Research Farm Köllitsch (KÖ, 51º30’ N, 13º06’ E, 84 m a.s.l.) and two long-term certified organic farms (based on Council Regulation (EC) No 834/2007 (2007)) located at Bockelwitz (BO, 51º12’ N, 12º55’ E, 209 m a.s.l.) and at Reinhardtsgrün (RG, 50º53’ N, 13º45’ 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 trial 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. 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. 1a). The winter period was long.
and the daily mean temperatures in January and February ranged almost constantly below 0°C (Fig. 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 CaCl₂) of 6.1 and a plant available content of 52 mg kg⁻¹ soil Mg. At the BO location the soil is a Luvisol with a pH (0.01 M CaCl₂) 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 CaCl₂) of 6.3 and a plant available content of 54 mg kg⁻¹ soil P, 110 mg kg⁻¹ soil K, and 88 mg kg⁻¹ soil Mg. The plant available Mg was extracted in 0.01 M CaCl₂ while plant available P and K were extracted using the calcium acetate lactate (CAL) method after Schüller (1969). The soil Corg content was lowest at KÖ (1.45%) and largest at RG (3.31%) while it amounted to 1.57% at BO.

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 8 to 12 cm using a stubble plough (Type Zobel, Germany), followed by the cover crop seedbed preparation (8 cm 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 m²) was conducted at a depth of 2 cm using a common seed drill (Type D9, Amazone, Germany) in August 2009 (Table 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 randomized 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 m² – 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 leaved variety with long vines while the spring field pea was a semi-leafless, short variety (Table 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, 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 trial. 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 (25 cm depth) conducted with a three-furrow plough (Type OS523A02, Vogel & Noot, Germany) while the soil was tilled without inversion (15 cm 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 (8 cm depth) with a rotary harrow (Type Erpice Rotante, Maschio, Italy). In the reduced tillage and the plough tillage system the crops

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Table 1. Field trial preparation, data measurement and sample collection dates.

<table>
<thead>
<tr>
<th>Activity / Date</th>
<th>Köttsch (KÖ)</th>
<th>Bockelwitz (BO)</th>
<th>Reinhardtsgrimma (RG)</th>
</tr>
</thead>
</table>

¹No-tillage sowing 26 March, Reduced and plough tillage sowing 30 March 2010; ²Autumn counting (1.5 m – 6 rows per plot); ³Spring counting (1.5 m – 9 rows per plot).
were sown with a plot seeder (Type HEGE 80, Wintersteiger, Austria, 16.7 cm 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 coulters, Amazone, Germany - trial preparation spring crops in 2009) and single disk coulters (RoTeC Control coulter, Amazone, Germany - trial preparation spring crops in 2010). The narrow-leafed lupin seeds were sown with a plot seeder (Type HEGE 80, Wintersteiger, Austria, 16.7 cm row spacing) with shoe openers (Baker No-Tillage Limited, New Zealand, 16.7 cm 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. 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 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.

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 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 (5 cm) 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 m² 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 (TruCSpec Macro, LECO, USA) in compliance with the VDLUFA method 4.1.2 (Bassler, 1997) 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. 

### Table 2. Crop species, cultivar, 1000 seed weight, monocropped (MC) and intercropped (IC) seeding rate (target plant population) used in the field trials.

<table>
<thead>
<tr>
<th>Crop species</th>
<th>Cultivar</th>
<th>1000 seed weight</th>
<th>Seeding rate (g per 1000 seeds⁻¹)</th>
<th>(viable seeds m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Faba bean (WF)</td>
<td>Vicia faba L.</td>
<td>655</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Faba bean (SF)</td>
<td>Vicia faba L.</td>
<td>607</td>
<td>59</td>
<td>59</td>
</tr>
<tr>
<td>Field pea (WP)</td>
<td>Pisum sativum L.</td>
<td>130</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Field pea (SP)</td>
<td>Pisum sativum L.</td>
<td>221</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Narrow-leafed lupin</td>
<td>Lupinus angustifolius L.</td>
<td>178</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>Oat (O)</td>
<td>Avena sativa L.</td>
<td>37</td>
<td>300</td>
<td>60</td>
</tr>
<tr>
<td>Winter wheat (W)</td>
<td>Triticum aestivum L.</td>
<td>49</td>
<td>280</td>
<td>56</td>
</tr>
</tbody>
</table>

Note: Winter crop; Spring crop.

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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 reduced tillage and plough tillage system lower case letters indicate significant differences between the different crops within tillage systems. 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 ($P < 0.05$) within the SAS procedure MIXED.

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 which was transformed using the arcsine transformation.

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The soil temperatures were analyzed 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). This required a separate analysis for each location, tillage system and species (Table 4, 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 ($P < 0.05$).

### Statistical Analyses

The data for the winter and spring plant populations, 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.

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

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Table 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).

<table>
<thead>
<tr>
<th>Species†</th>
<th>Crop plant population in spring (% overwintered and germinated plants of viable seeds)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Köllitsch (KÖ)</td>
</tr>
<tr>
<td></td>
<td>Bockelwitz (BO)</td>
</tr>
<tr>
<td></td>
<td>Reinhardtsgrimma (RG)</td>
</tr>
<tr>
<td></td>
<td>NT</td>
</tr>
<tr>
<td>MC faba bean (WF)</td>
<td>54 cd A</td>
</tr>
<tr>
<td>IC faba bean (WF)</td>
<td>62 bc A</td>
</tr>
<tr>
<td>MC field pea (WP)</td>
<td>52 ce A</td>
</tr>
<tr>
<td>IC field pea (WP)</td>
<td>35 fg B</td>
</tr>
<tr>
<td>MC faba bean (SF)</td>
<td>78 ab A</td>
</tr>
<tr>
<td>IC faba bean (SF)</td>
<td>84 a A</td>
</tr>
<tr>
<td>MC field pea (SP)</td>
<td>52 ce A</td>
</tr>
<tr>
<td>IC field pea (SP)</td>
<td>46 def A</td>
</tr>
<tr>
<td>MC narrow-leaved lupin (NL)</td>
<td>19 h B</td>
</tr>
<tr>
<td>IC narrow-leaved lupin (NL)</td>
<td>23 gh B</td>
</tr>
<tr>
<td>MC oat (O)</td>
<td>39 ef A</td>
</tr>
</tbody>
</table>

†Monocropped (MC) and intercropped (IC) crop species; †winter crop; †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 ($P < 0.05$).

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

Based on Tukey Kramer mean 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 ($P < 0.05$) between the tillage systems based on Tukey Kramer mean separation.

Results

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, 4). Although the seed emergence factors were not quantitatively determined in the present study, it became apparent during soil temperature 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. 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-leaved lupin at KÖ and BO which were strongly reduced in the no-tillage system compared with the tilled systems.

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 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. **Shoot dry matter production**

The shoot dry matter production of legumes, cereal grains and weeds varied with the location, tillage system and species (Fig. 3a-c, Table 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. 3a). At BO the omission of tillage reduced the crop biomass less for legumes than for cereal grains (Fig. 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 -44%, respectively while for MC oats the biomass was reduced by -91%. The described differentiated biomass production by legumes and cereal grains in the no-tillage system was also present at RG (Fig. 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. 3b-c).

The dry matter production by the winter field pea at all three locations was largely unaffected by the different tillage systems. 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. 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.

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. 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 narrow-leafed lupin. No-tillage instead of plough tillage decreased the dry matter production for the MC the 66% are calculated for the lupin content in the IC lupin + grain biomass which could lead to confusion for the reader narrow-leafed lupin by -66% at the KÖ location (Fig. 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. 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. 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. 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. 3c).

The reduction of tillage was accompanied by an increased weed pressure and weed biomass production. 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, Polygonum aviculare, Stellaria media and Matricaria inodora 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 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, Cirsium arvense and Galinsoga ciliata present in all tillage systems, Apera spica-venti and Vicia cracca 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. 4a-c, Table 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. 4a-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.

Fig. 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 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. 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).

### 4. Grain yield

The grain yields of legumes and cereal grains were influenced differently by the omission of tillage (Fig. 5a-c, Table 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. 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. 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. 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 for the IC spring field pea (–73 and –65%, respectively) and for the IC spring field pea (–36%) in the reduced tillage system (Fig. 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. 5a-b). Significantly increased total grain yields were for example shown at the KÖ location in the no-tillage system by the IC narrow-leaved 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-leaved lupin (+124%) in comparison with their respective MC crop yields.

5. Harvest index

The legume harvest index was not influenced by the omission of tillage compared with plough tillage before
seeding (Fig. 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. 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. 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).

For winter wheat and oats at Kö the harvest indices in the three tillage systems differed only slightly (Fig. 6a). However, at BO the MC winter wheat displayed a lower harvest index in the no-tillage than in the plough tillage system (Fig. 6b). At RG, the harvest indices of IC oats in the reduced tillage system were much lower than in the plough tillage system (Fig. 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-leaved lupin (Fig. 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. 3c, 6c).
Discussion

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 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-leaved lupin showed substantially lower emergences in the no-tillage system (Table 5). This can be explained by the sensitivity of the narrow-leaved lupin seedlings to obstructions above the seeds and by their epigeal seedling development. White and Robson (1989) showed that the narrow-leaved 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 systems (Table 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 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. 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 at KÖ and BO were damaged to a larger extent than in the no-tillage system (Table 4).

At BO, 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 KÖ and BO, at RG the overwintering had a tendency to be higher in the plough tillage system compared with the no-tillage system (Table 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.

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. 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\textsubscript{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. 3a-c). Nevertheless the largest biomass production in the no-tillage system at both BO and RG 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. 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 3b; Hauggaard-Nielsen et al., 2001; Hauggaard-Nielsen, 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 BO and RG, the biomass production of the winter field pea was higher than for spring field pea (Fig 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 KÖ and in the tilled systems at BO (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. Grain yield and harvest index

At KÖ, 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. 4a). The largest winter and spring legume yields were reached at BO (Fig. 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. 4c, Table 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 BO, 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. 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. 4b-c).

The weed competition in all tillage systems and the low field emergence in the no-tillage system led to the lower narrow-leaved lupin yield compared with spring field pea and faba bean (Fig. 4a-c, 5a-c). This is in agreement with results by Šarūnaitė et al. (2010) and can be attributed to the lower 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, which shows that autumn seeding was advantageous (Table 5). An additional advantage was that the winter field pea was a normal leaved 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. 5a-b). In these particular tillage systems, at the KÖ and BO locations 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, 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 fertilized 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. 4a-c).

4. 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 leaved 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-leaved lupin appeared not to be suited for conservation tillage systems in organic farming. There was increased weed competition in the no-tillage system by winter 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 leaved 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.

Acknowledgements

This study was financially supported by the Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie on behalf of the Sächsisches Staatsministerium für Umwelt und Landwirtschaft. Two anonymous reviewers are greatly acknowledged for their improvements and valuable comments on the manuscript. We also thank many undergraduate student workers for their assistance in the collection of field data, Dr. Jens Möhring (University of Hohenheim) for advice on the statistical analysis and Falk Böttcher (Deutscher Wetterdienst DWD) for providing the climate information.

References


* In German with English title.
** In German with English abstract.
*** In German with English summary.
**** In German.