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ABSTRACT

The aim of the study was to evaluate non-legume cover crops for growing no-till grain legumes in organic farming systems. Evaluated cover crops should be able to suppress weed growth, reduce plant available nitrogen in the soil and produce large amounts of biomass with slow N mineralisation. Six non-legume species; 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.) were tested. Plots with organic fertiliser (50 kg N ha^{-1}) and without fertiliser incorporation at three locations in south-east Germany were trialled and the cover crops' ability to produce biomass and accumulate N in plant compartments was evaluated. The N mineralisation from stem and leaf material was simulated using the STICS model. The 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 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.

Organic farming systems have only partially benefitted from recent advancements in conservation tillage and associated reduced soil erosion, fuel consumption, labour costs and further improved soil structure. One major reason is the status of plough tillage as one of the most efficient weed control practices (Gruber & Claupein, 2009).

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. Transitioning to organic no-tillage at the end of a crop cycle by omitting stubble tillage can increase perennial weed growth (Pekrun & Claupein, 2006) and impede the adjustment to more sustainable crop production. 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). Furthermore, weeds can be suppressed by the thick residue mulch that retains accumulated N, intercepts light and has, in some species, allelopathic properties (Barnes & Putnam, 1983; Putnam & DeFrank, 1983; Teasdale & Mohler, 2000). For a long-lasting effect, the composition of cover crop residues should delay residue decomposition and N mineralisation. Parameters for the biochemical

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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 (Abiven et al., 2005; Bending et al., 1998; Corbeels et al., 2003; Trinsoutrot et al., 2000). 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 developmental 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.

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 the 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 & Nylund, 1962).

The C:N ratio in legume plant material is usually lower than in non-legumes (Smith & Sharpley, 1990), and 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 (Clark, 2007; Creamer & Baldwin, 2000; Forentìn et al., 2011; Miyazawa et al., 2010; Stivers-Young, 1998). 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.

The measurement of biomass production is common for cover crop evaluations. A novel method is the evaluation of the 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 evaluation 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 pea 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

Table 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.

could result in improved residue cover and weed suppression in the early cash crop phase.

It was the objective of our study 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.

1. Materials and methods

1.1. Experimental study site and field trial set-up

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 subplots (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 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).

1.2. Sample collection and analysis

Soil samples were collected directly after seeding (10 sample points for each main plot) and after cover crop biomass sampling in October (4 sample points for each subplot). At both PI and KÖ, the soil samples were taken from 0 to 1.2 m (4 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 (2 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 Analytical B.V., Breda, Netherlands) based on the VDLUFA method A 6.1.4.1 (Thun & 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 m² 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 20 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 10694:199608 (DIN Deutsches Institut für Normung e.V, 1996), respectively.

1.3. 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.

1.4. 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
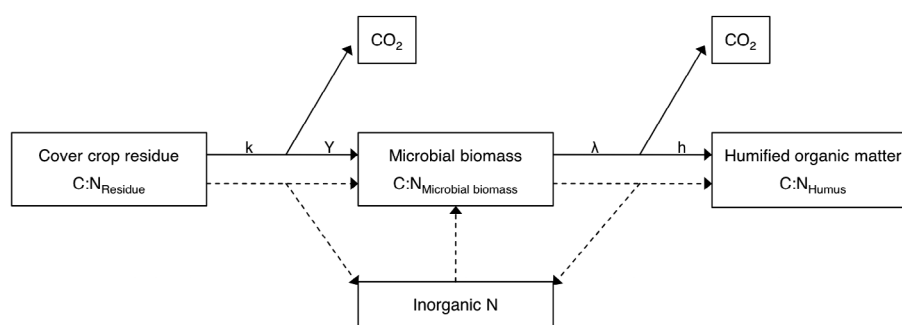
Figure 1. Conceptual diagram of the residue decomposition model (Nicolardot et al., 2001), continuous lines indicating C fluxes, dashed lines indicating N fluxes.
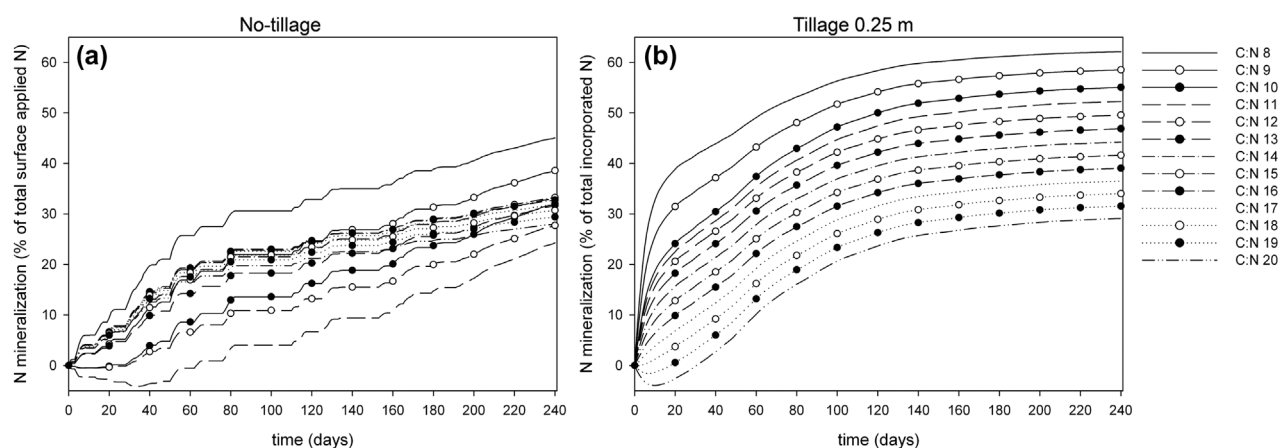

Figure 2. (a–b) Comparison of proportional net N mineralisation in no-till (a) and tilled conditions (b) from immature crop residues with fixed dry matter (1 Mg ha^{-1}) and C content (40%) as well as variable C:N ratios (8 to 20:1).

Table 2. 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).

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$_{Humus}$ (Figure 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).

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 (Figure 2(a)). 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 (Figure 2(b)), 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; Tables 1 and 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 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 assumend 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.

2. Results

2.1. 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). 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). 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

Table 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 variation	Field emergence	Shoot dry matter production					Shoot N accumulation					C:N ratio		Soil N[c]
		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 × F	n.s.	**	***	*	**	n.s.	*	n.s.	*	n.s.	n.s.	*	*	*
L × S	***	**	***	***	***	***	**	***	*	***	***	***	***	***
F × S	n.s.	n.s.	n.s.	*	***	**	n.s.	n.s.	n.s.	***	*	n.s.	n.s.	n.s.
L × F × 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 4. Cover crop field emergences (averaged across fertiliser levels).

Species	Cover crop field emergence (% germinated plants of viable seeds)		
	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 ($a < 0.05$).
Within a row, upper case letters display significant differences between locations based on Tukey–Kramer means separation ($a < 0.05$).

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.

2.2. Cover crop emergence

Precipitation before and after cover crop seeding was sufficient for high field emergences, which differed slightly between species and locations (Table 3). At all three locations, sunflower, oats and buckwheat consistently displayed the highest field emergences (between 82 and 97%, Table 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.

2.3. 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. 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 3, Figure 3). 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.

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 5). At all locations, oats displayed the lowest stem% among the species. It was noted that at PI the
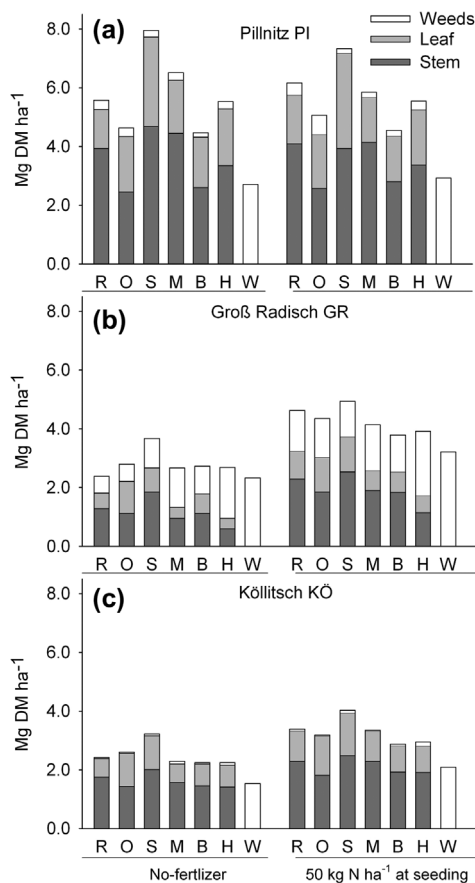
Figure 3. (a–c) Total dry matter (DM) partitioned into cover crop stem and leaf material, as well as weed biomass in plots of rye (R), oats (O), sunflower (S), mustard (M), buckwheat (B), hemp (H) and no cover crop–weeds (W), respectively. The cover crop and weed dry matter was produced without fertiliser (left side columns) and with 50 kg N ha⁻¹ fertiliser (right side columns), respectively.

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 3, Figure 3(a–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.

2.4. 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, (Figure 4). The available inorganic soil N contents at harvest showed interactions between location, additional fertilisation and cover cropping (Table 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. 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.

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

Table 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 × Species[b]	
Species	−N	+N	L × S[a]	−N	+N	L × S	−N	+N	L × 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 × S, Location × 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);.
[b]Fertiliser × 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 fertiliser treatments based on Tukey–Kramer means separation (α < 0.05).
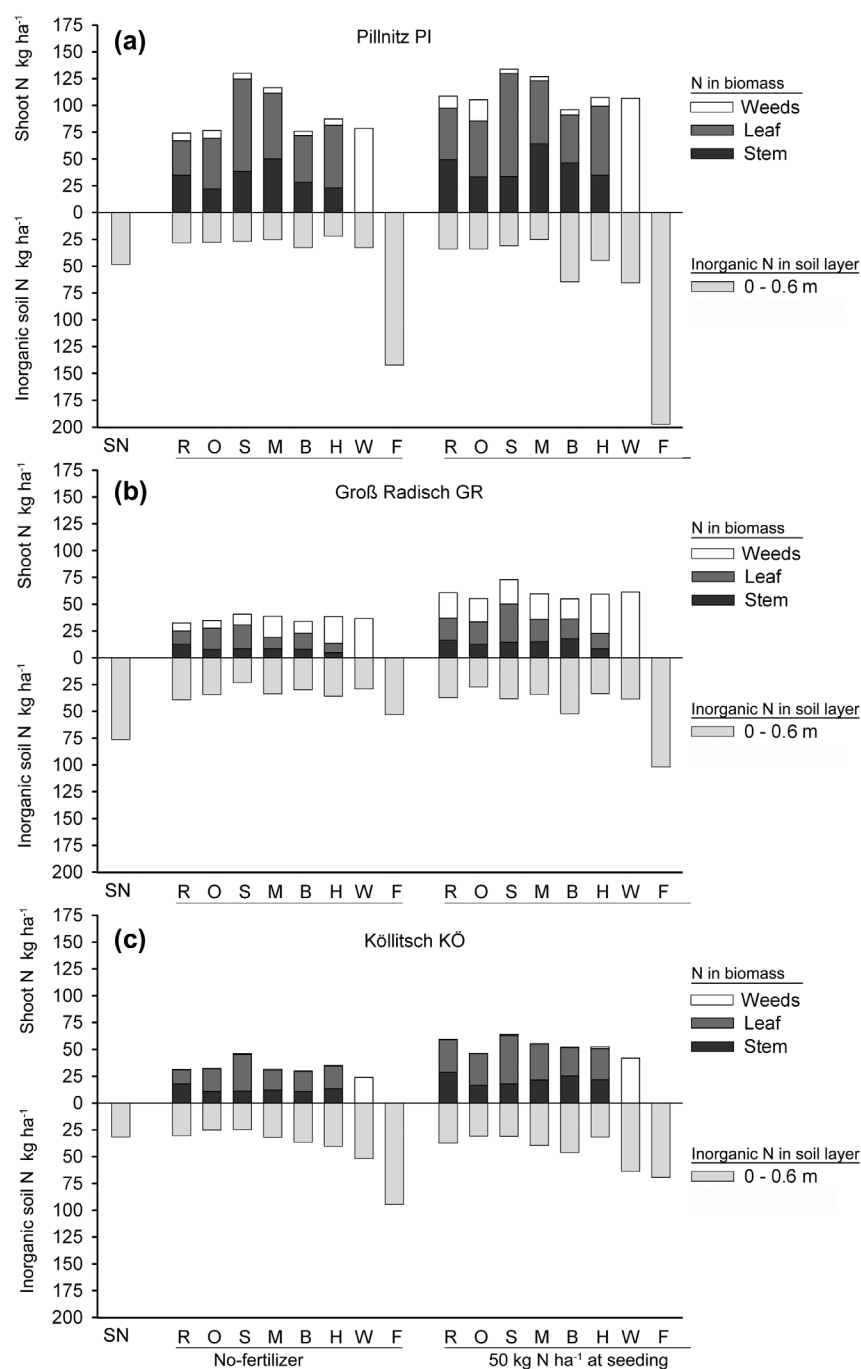
Figure 4. (a–c) Inorganic soil N at seeding (SN) and after harvest in plots of rye (R), oats (O), sunflower (S), mustard (M), buckwheat (B), hemp (H), no cover crop–weed plot (W) and bare soil fallow (F), respectively. Shoot N accumulation of the respective cover crops partitioned into stem and leaf 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.

Table 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 between cover crop species based on Tukey–Kramer means separation ($α < 0.05$).

Table 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 × S[a]	−N	+N	L × S	−N	+N	L × 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 × S, Location × Species interaction: Within a column lower case letters display significant differences between species based on Tukey–Kramer means separa-
   tion (α < 0.05), within a row, upper case letters display significant differences between locations based on Tukey–Kramer means separation (α < 0.05).

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 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%.

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.

2.5. 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 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
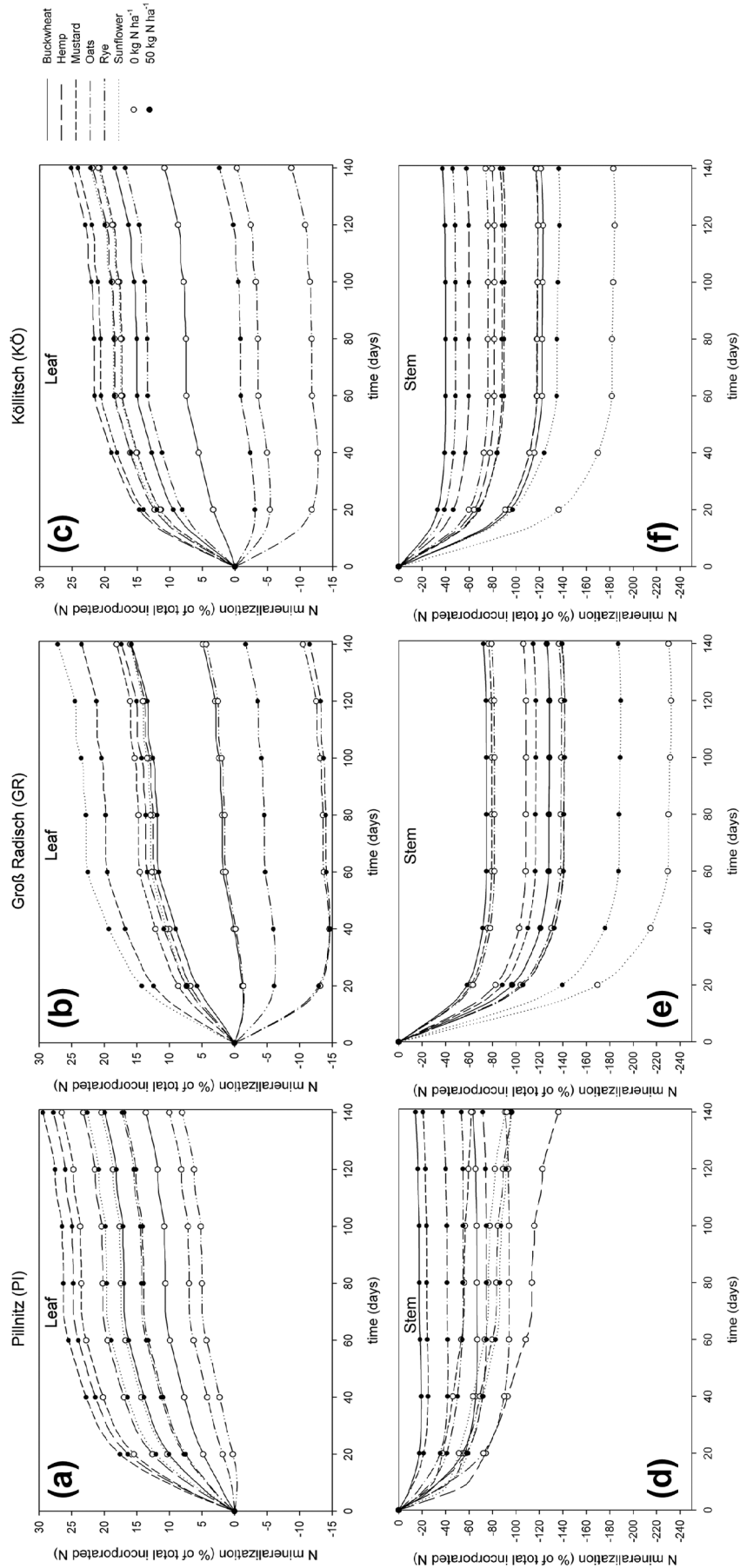
Figure 5. (a–f) Proportionate net N mineralisation of separate cover crop leaf material (a–c) and stem material (d–f) at the Pillnitz (PI), Groß Radisch (GR) and Köllitsch (KÖ) location.
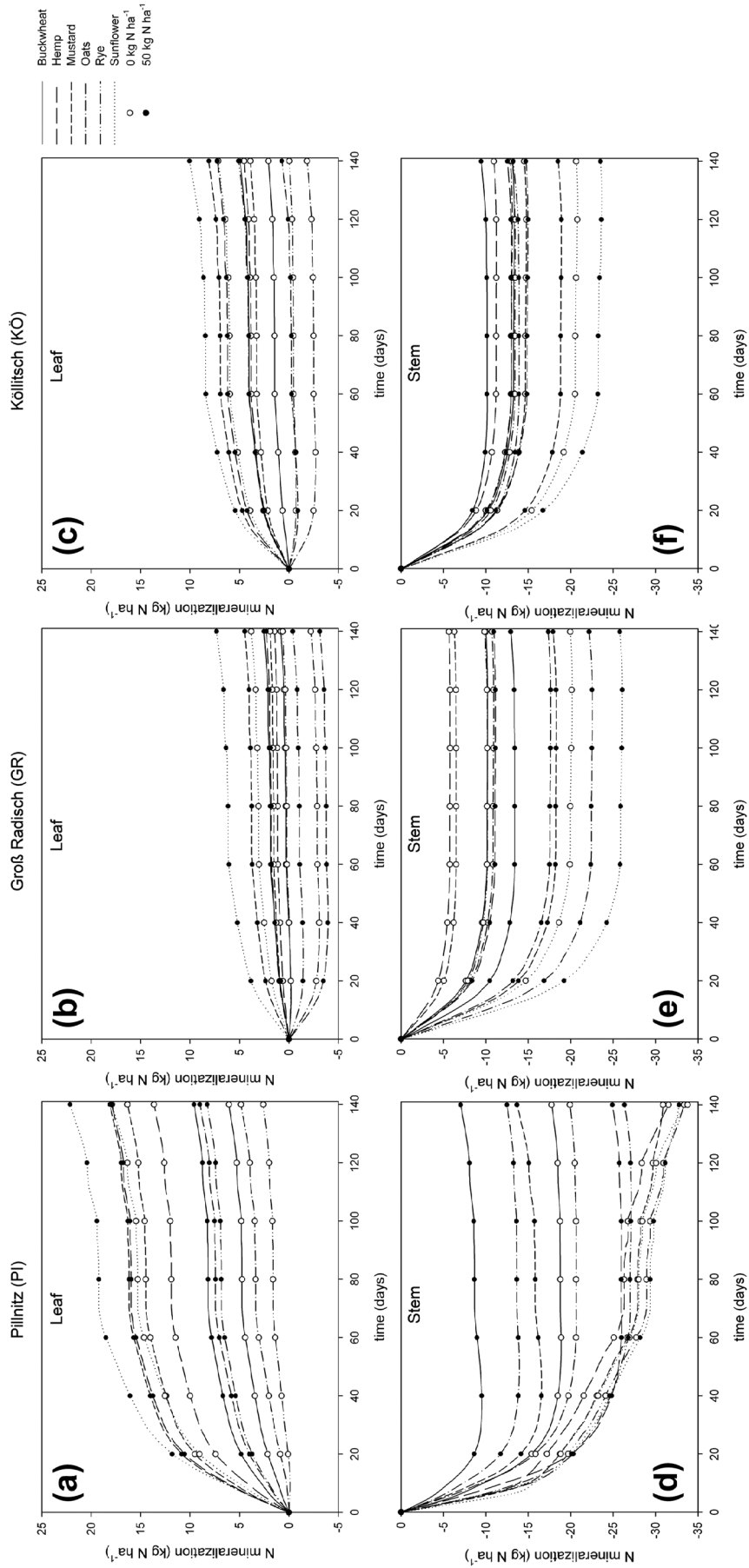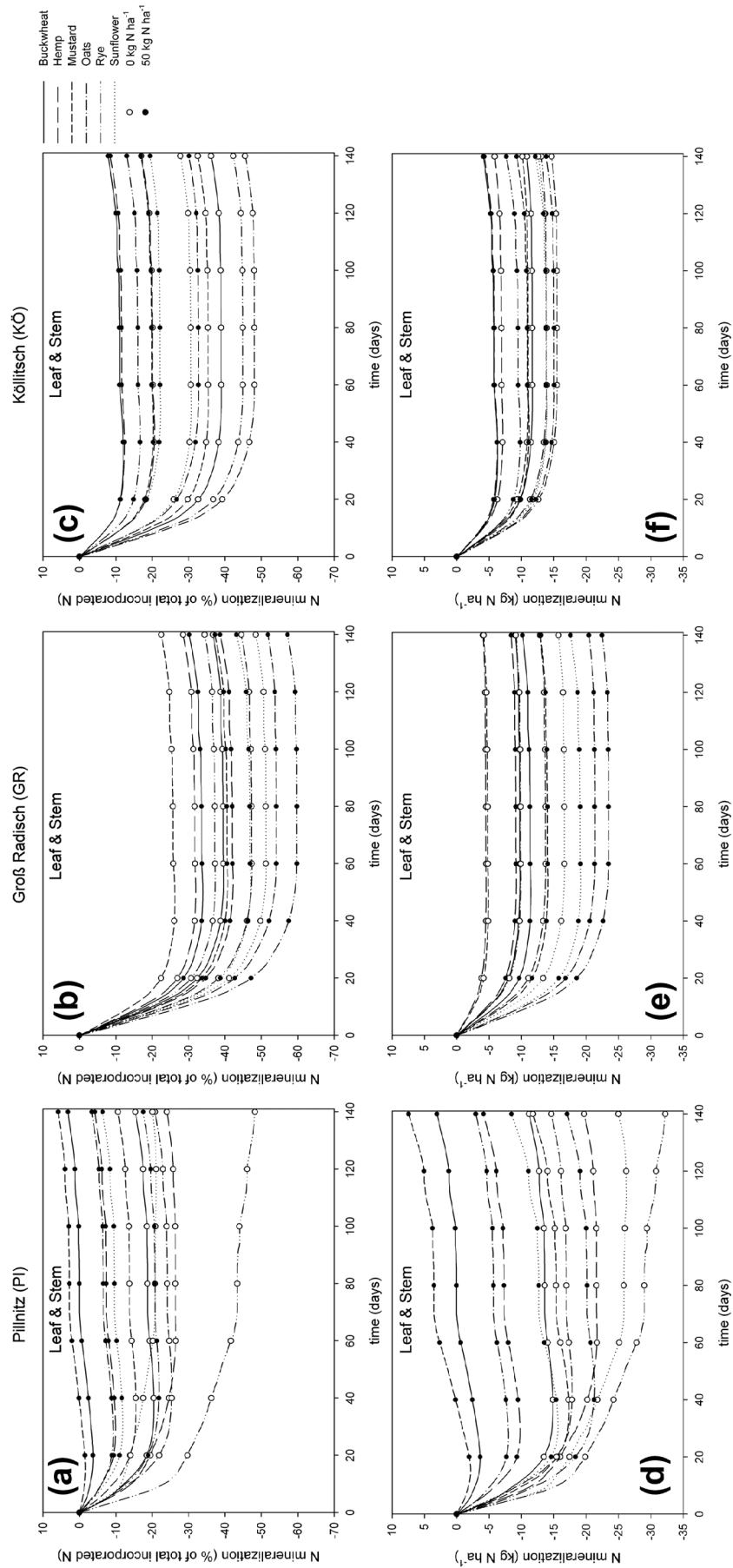
Figure 6. (a–f) Net N mineralisation of separate cover crop leaf material (a–c) and stem material (d–f) at the Pillnitz (PI), Groß Radisch (GR) and Köllitsch (KÖ) location.

Figure 7. (a–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.

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 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.

2.6. Simulated N mineralisation from cover crop residues

2.6.1. 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 7 and Figure 5(a–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 (Figure 5(b–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) (Figure 5(a–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 (Figure 5(d–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) (Figure 7(a–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.

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 (Figure 7(a–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.

2.6.2. 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 (Figure 6(a–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 (Figure 6(a–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 (Figure 6(d–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 (Figure 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.

3. Discussion

3.1. 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 (Figure 4(a)). 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 (Figure 4(a)) 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 (Figure 5(a–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 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 the 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 (Figure 3(a–c)), which at PI were similar to the sunflower biomass stated by Forentin 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 & Range, 2012). It was

higher than in a reduced tillage organic trial (Rühlemann & 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 (Figure 6(a–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 (Figure 7(e–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 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 25 July 2003 resulting in an autumn biomass production that was intermediate between the unfertilised and fertilised rye at the GR and KÖ location (Figure 3(b–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 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 (Figure 3(a–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 (Grimmer & Masiunas, 2004; Stivers-Young, 1998). 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 (Brust, et al., 2014a; Stivers-Young, 1998). 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 that could further reduce the emergence of weeds (Grimmer & Masiunas, 2005; Putnam & DeFrank, 1983).

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 & Range, 2012). Buckwheat germinates and develops quickly making it effective at suppressing weeds (Creamer & 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 & 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 (Figure 5(a–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 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 (Figure 3(b–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 (Figure 5(a–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 (Figure 3(a–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.

3.2. 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 (Figure 5(a–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).

4. 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 stem per m^2. 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.

Abbreviations

a.s.l   above sea level;

cv.   cultivar;

DM   dry matter;

DWD   Deutscher Wetterdienst (German Meteorological Service);

GR   Groß Radisch;

LfULG   Sächsisches Landesamt für Umwelt, Landwirtschaft und Geologie (Saxon State Office for Environment, Agriculture and Geology);

KÖ   Köllitsch;

PI   Pillnitz;

SBS   Staatsbetrieb Sachsenforst (Saxon State-Owned Forestry Enterprise).

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