



Cover crop composition mediates the constraints and benefits of roller-crimping and incorporation in organic white cabbage production



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ABSTRACT

Roller-crimping of cover crops grown during winter may facilitate reduced tillage efforts in organic vegetable production. A one-year field experiment was conducted twice (autumn 2015–2017) in sandy loam soil in Denmark testing two cover crop termination systems, roller-crimping (RC) without tillage before crop planting, and full incorporation by tillage (FI) of mowed cover crops in organic white cabbage (*Brassica oleracea* L. convar. *capitata* var. *capitata* f. *alba*) production. Three legume species were investigated: winter faba bean (*Vicia faba* L.), winter pea (*Pisum sativum* L.), hairy vetch (*Vicia villosa* Roth), in pure stands or in a mixture with winter rye (*Secale cereale* L.). Roller-crimping reduced total white cabbage biomass by 31% (2016) and 19% (2017). Marketable white cabbage yield was 100% (2016) or 24% (2017) lower under RC than FI, likely caused by delayed N release from cover crops and reduced soil dehydrogenase activity. White cabbage root growth was reduced by RC following pea/rye, where N availability was low. Despite reduced root growth and yield, RC still had the advantage of reducing weed growth by 63% compared with FI three weeks after cover crop termination in 2017 and of decreasing N leaching risk, indicated by reduced soil mineral N content in 0.5–1.5 m depth in autumn. Marketable yield was 35% higher following legumes compared with legume/rye mixtures in both termination systems in 2017, due to 105 kg N ha⁻¹ higher mineral soil N content in 0–2.5 m depth in the spring and faster N mineralisation from plant material with a lower C/N ratio. This yield increase corresponded with increased root growth following RC legumes. In contrast, legume/rye mixtures had the advantage of decreasing weed growth by 50–68% and N leaching risk by 22 kg ha⁻¹ in 0.5–2 m depth. Although RC demonstrated ecological benefits such as weed suppression and indicated reduced N leaching risk, the trade-off with yield losses could create a barrier to adoption. This trade-off could be mitigated by using pure legume cover crops and by improving management of supplemental N fertility.

1. Introduction

Cover crops are commonly used in organic production systems. The purpose of cover crops is to improve the production system not primarily in terms of higher crop yields, but rather regarding enhanced environmental functions such as reduced summer weed infestation (Leavitt et al., 2011; Wayman et al., 2014), improved soil structure

(Hartwig and Ammon, 2002), as well as reduced mineral nitrogen (N) leaching in the winter (Kristensen and Thorup-Kristensen, 2004).

In organic systems, termination of cover crops in the spring, prior to crop planting, is commonly conducted by mowing and incorporating the crops into the soil via tillage. Purposes of soil tillage include creation of a seedbed for planting, stimulation of mineralisation of organic matter, facilitation of root growth, and control of weeds. Soil tillage,

Abbreviations: CCC, cover crop composition; cv, cultivar; FI, full incorporation; N, nitrogen; N_{acc}, nitrogen accumulation; N-P-K, nitrogen, phosphorus, and potassium; PMN, potential mineralisation of N; RC, roller-crimping; Root intensity_{mod}, modified root intensity

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however, also leads to soil structure degradation and an increased use of fossil fuels (Triplett and Dick, 2008), both factors that intensify the reduction of tillage operations. Negative effects of tillage on soil structure can be reduced by decreasing tillage depth, avoiding soil inversion (Mäder and Berner, 2012), and running fewer tillage operations. Conservation tillage consists of a shallow working depth without soil inversion, whilst maintaining at least 30% of the soil covered by residues (Peigné et al., 2007). Reducing tillage operations is challenging for many organic vegetable farmers due to weed management difficulties in the absence of herbicide use. Where herbicide use is prohibited, termination of cover crops by roller-crimping (RC) may enable the implementation of conservation tillage practices in organic production, because weed growth can be reduced under RC (Wayman et al., 2014).

A roller-crimper consists of a steel drum with metal crimping blades arranged in a chevron pattern, which crush and crimp cover crop stems and leaves without cutting the stems (Ashford and Reeves, 2003). One crucial point of attention is that roller-crimping has been reported to reduce organic vegetable yields under a humid continental climate in New York and Minnesota, and under a Mediterranean climate in California (Mochizuki et al., 2008; Leavitt et al., 2011; Luna et al., 2012). Challenges related to RC, other than reduced crop yield, include planting in excessive cover crop residue, delayed vegetable transplanting (Luna et al., 2012), and reduced soil mineral N, which can be caused by pre-emptive competition by cover crops (Thorup-Kristensen, 1993) and immobilisation by microbial degradation (Leavitt et al., 2011). Studies of N availability after roller-crimping of cover crops are scarce, but cover crop residues left on the soil surface mineralise more slowly than if incorporated, thereby temporarily reducing the N availability for the subsequent crop (Radicetti et al., 2016). Modelling by Coppens et al. (2007) suggested that crop residues left on the surface increase the risk of N leaching over winter compared with residue incorporation.

Mineral N in the soil profile is affected by cover crop species in different ways. Non-leguminous cover crops are more effective than legumes in taking up residual N from a previous crop, thereby reducing N leaching risk over the winter (Tonitto et al., 2006). Legumes have the advantage of adding N to systems through biological N₂ fixation, which upon mineralisation becomes available to subsequent crops, thereby decreasing fertiliser need (Xie et al., 2017). Non-leguminous and leguminous species can be combined to reduce N leaching and add new N simultaneously (Tribouillois et al., 2016). However, soil mineral N was found to be lower after legume/rye mixtures than after pure legumes 2–6 weeks after cover crop termination (Wayman et al., 2014). Using pure legumes in a RC system might be a better option compared to legume/rye mixtures because N availability for the subsequent crop may be improved.

Crop root growth responds to nutrient availability and soil structure (Hefner et al., 2019). Therefore, root growth studies could reveal the effects of RC on nutrient availability and soil structure, but little is known regarding root growth in RC systems. Wheat root growth was reduced with decreasing tillage intensity early in the growing season, most likely as a result of higher soil strength in the topsoil under reduced tillage (Munkholm et al., 2008). The effect of tillage on soil microbial properties has been studied to a greater extent, however, revealing highly variable results depending on environmental and experimental factors. For instance, a recent meta-analysis showed that tillage increased the metabolic quotient only in the short-term (< 10 years), while microbial biomass carbon and enzymes activities were generally higher under no-tillage compared to tillage conditions (Zuber and Villamil, 2016). Increased levels of soil organic carbon and N at the surface of no-tillage soils may contribute to increased enzyme activity (van Capelle et al., 2012).

To the best of the authors' knowledge, RC effects on crop yield, root growth, soil mineral N, soil microbial activity, and weed emergence have not previously been studied together in organic vegetable

production. However, such comprehensive datasets are much needed for evaluating RC in a system approach, both from an agro-ecological and a farmer practitioner's perspective. In the present study, white cabbage yield was investigated the first year following different cover crop species or species mixtures, and two cover crop termination systems in a northern temperate climate. We hypothesised that: (1) weed emergence during the cropping season is reduced by RC compared with full incorporation of mowed cover crops (FI), and in legume/rye mixtures compared with pure legumes; whereas (2) the risk of N leaching during the following winter is increased by RC compared with FI, but reduced by legume/rye mixtures compared with pure legumes; (3) soil microbial activities, particularly dehydrogenase and β -glucosidase activities, are increased by RC compared with FI; (4) N accumulation (N_{acc}) of legume/rye mixtures is higher and soil mineral N at cover crop termination is lower compared with pure legumes; and (5) white cabbage yield and (6) root growth are reduced under RC, relative to FI, and following legume/rye mixtures compared with legumes.

2. Materials and methods

2.1. Field site and experimental design

Field experiments were conducted in 2015/2016 and 2016/2017, at Aarhus University Aarslev, Denmark (10°27'E, 55°18'N) in a sandy loam soil (Typic Agrudalf) (Table 1). Cumulative precipitation and annual mean temperatures during the experimental period were 614 mm and 9.3 °C in 2016 and 673 mm and 9.2 °C in 2017 (Supplementary material, Fig. S1). The experiments in the first and the second cropping year took place in two different fields that were 350 m apart. The two fields were managed since 1996 (2015/2016 field) and since 2014 (2016/2017 field) according to Danish organic farming regulations.

A split-plot randomized complete block study design was implemented with three replicates (blocks), where the cover crop termination system in the spring was a whole-plot factor. Legume species grown over winter and cover crop composition (CCC) were regarded as separate subplot factors. The two cover crop termination systems were: (1) full incorporation (FI), and (2) roller-crimping (RC). These systems had intrinsic differences in management: soil was tilled prior to cabbage transplanting, brush weeding was conducted, and fertilisation was broadcast under FI in contrast to no-tillage, no brush weeding, and fertiliser placement in a planting-band under RC. The cover crop termination systems were tested in three legume species: (1) winter faba bean (*Vicia faba* L. cultivar (cv.) Hiverna), (2) winter pea (*Pisum sativum* L. cv. James), and (3) hairy vetch (*Vicia villosa* Roth cv. Villana). These legume species were either cropped as (1) pure stands or (2) in a 50%/50% mixture with winter rye (*Secale cereale* L. cv. Livado). A bare soil subplot was included as a winter fallow control in the FI system. The subplot size was 3.2 m × 10 m in 2016 and 4.8 m × 10 m in 2017, consisting of six white cabbage (*Brassica oleracea* L. convar. *capitata* var. *capitata* f. *alba* cv. Coronet) rows in 2016 and nine rows in 2017.

Table 1
Soil properties of the experimental site.

Soil depth (m)	Clay (%)	Silt (%)	Sand (%)	P ^{ex} (mg kg ⁻¹)	Total N* (%)	Total C* (%)	SOM* (%)
0-0.25	12	15	70	0.15	0.15	1.6	2.8
0.25-0.5	15	15	69	–	–	–	–
0.5-1	19	13	68	–	–	–	–
1-1.5	18	13	68	–	–	–	–
1.5-2	18	13	69	–	–	–	–
2-2.5	18	15	66	–	–	–	–

– Not analysed.

^{ex} Phosphorous (P) was extracted with 0.5 M NaHCO₃.

* Results of P, N, C and SOM are from the current experiment, whereas soil texture was obtained from a previous experiment at the same site.

2.2. Cover crop cultivation and termination

Experimental fields were tilled to 0.2 m depth with a plough (Kverneland, Norway) prior to cover crop sowing in the autumn of 2015 and 2016. Seedbeds were prepared with a rotary harrow (Howard, Kongskilde, Denmark) with 0.1-m working depth and plots were fertilised with 200 kg ha⁻¹ (26 kg N ha⁻¹) feather meal pellets on September 9th, 2015 and September 28th, 2016. In 2015, the seeding rate was 322 kg ha⁻¹ for faba bean, 192 kg ha⁻¹ for pea, 100 kg ha⁻¹ for hairy vetch, and in the legume/rye mixtures 50 kg ha⁻¹ rye was mixed with 161 kg ha⁻¹ faba bean, 96 kg ha⁻¹ pea, and 50 kg ha⁻¹ hairy vetch. Seeding rates were representative of local agricultural practice. In order to obtain greater cover crop biomass and improved soil cover under RC in 2016/2017, faba bean and pea seeding rates were increased to 419 kg ha⁻¹ faba bean, 288 kg ha⁻¹ pea, and in the legume/rye mixtures 209 kg ha⁻¹ faba bean, and 144 kg ha⁻¹ pea. Cover crops were sown with a sowing machine (Nordsten, Kongskilde, Denmark) on October 5th, 2015 and October 9th, 2016 and terminated on June 10th, 2016 and May 30th, 2017. Cover crops were first cut, chopped once (pure legumes) or twice (legume/rye mixtures) with a flail mower (Spearhead, UK), and then incorporated into the soil with a cultivator (Kuhn, France) to 0.15-m depth in the FI system. Cover crops were passed with a roller-crimper (Soldo, Italy) in the RC system. The roller-crimper had a diameter of 0.6 m, a length of 2 m, and a weight of 932 kg. Soil cultivation (FI) and roller-crimping were repeated after 1 (2016) or 2 weeks (2017). The bare soil subplot within FI was cultivated in a similar way as the FI system.

2.3. White cabbage cultivation

A 0.25-m deep planting furrow was prepared with a harrow tooth prior to white cabbage transplanting in the RC system, whereas this was not needed in the cultivated beds of the FI system. White cabbage seedlings were delivered by an organic seedling producer in 2016, but were grown at Aarhus University under greenhouse conditions in 2017. Six-week-old seedlings were transplanted with a three-row planting machine (Cecchi & Magli Wolf, Italy) at a 0.5-m row distance and a 0.5-m plant distance on July 1st, 2016 and June 21st, 2017.

Inter-row weed control was conducted with a weed-brush machine (Rath Maschinen, Germany) in FI on July 27th–29th and August 19th in 2016 and on July 17th–19th in 2017. Inter- and intra-row weed control were carried out manually with a hoe in all plots on September 26th–30th, 2016 and August 10th–22nd, 2017. Weeding was limited to manual removal of most of the above ground biomass of large weeds in the RC system due to cover crop biomass on the soil surface.

All plots were fertilised with feather meal pellets (Monterra 13, nitrogen, phosphorus, and potassium (N-P-K): 13-0-0.4) and lupine seeds (N-P-K: 4.5-0.4-0.9). In the first cropping cycle, 50 kg N ha⁻¹ feather meal pellets were applied on August 25th, 2016. Because N deficiency symptoms were visible in white cabbage in 2016, fertilisation was increased in 2017 to 100 kg N ha⁻¹ feather meal pellets and 30 kg N ha⁻¹ lupine seeds applied on June 15th, 2017, and 80 kg N ha⁻¹ feather meal pellets applied on Aug 24th, 2017. The fertiliser was broadcast, except for the fertiliser given to RC prior to cabbage transplanting in mid-June 2017, which was placed in the furrows of the cabbage rows.

White cabbage was sprinkler-irrigated with 30 mm on August 22nd and 25 mm on September 14th, 2016. No irrigation was needed in 2017 due to sufficient precipitation for crop growth. Both years, pest control was carried out by coverage with an insect net from planting until mid-September. However, due to infestations with diamondback moths (*Plutella xylostella* L.) and large white butterflies (*Pieris brassicae* L.) in 2016, additional control was applied by spraying 1 l ha⁻¹ *Bacillus thuringiensis* (Dipel DF) against larvae on August 5th and August 11th, 2016. Soil temperature was measured biweekly in each plot during the early crop growth period (June to August) in 2016 and 2017 with a

digital multi thermometer (Amarell Electronic, Germany), which was inserted to 15 cm depth in the row between two white cabbage plants at three locations per plot.

2.4. Soil sampling

Soil samples were taken three times during the growing season (spring, mid-season and autumn) in order to relate plant growth to soil N availability before, during and after the growing season. For determination of soil mineral N, soil samples were taken 0–2.5 m depth because cabbage roots can reach this deep (Kristensen and Thorup-Kristensen, 2007). Ten sub-samples were randomly taken in each subplot by a machine-driven soil piston auger with a 14-mm inner-diameter for soil samples from 0–0.25 m, 0.25–0.5 m, 0.5–1 m, 1–1.5 m, 1.5–2 m and 2–2.5 m depth layers and then mixed into a composite sample for each depth and subplot on June 7th (2016) and June 13th (2017). Additionally, five inter-row samples and five within-row sub-samples were collected on November 30th (2016) and November 9th (2017). Nine randomized sub-samples per subplot were taken with a hand-driven soil piston auger (15-mm inner diameter) in 0–0.3 m depth at mid-season on August 17th (2016) and August 1st (2017). Soil samples were frozen until mineral N analysis, at which time they were thawed and subsamples (each, 100 g fresh weight) were extracted in 1 M KCl for 1 h (1 soil: 2 solution). The soil extract was centrifuged and the supernatant was subjected to NH₄⁺ and NO₃⁻ analyses by standard colorimetric methods in an AutoAnalyzer 3 (Bran + Luebbe, Germany).

For soil microbial enzyme analyses and determination of potential mineralisation of N (PMN) in the soil, nine randomized sub-samples per subplot of field-moist soil were taken with a hand-driven soil piston auger (15-mm inner diameter) from 0–0.3 m depth in hairy vetch, hairy vetch/rye, pea, and pea/rye subplots in both termination systems on August 17th (2016). Pea and pea/rye were sampled on August 1st (2017). Subplots containing hairy vetch were not sampled in 2017 due to poor overwintering of hairy vetch. Debris was removed from soil surfaces before sampling. Soil was stored at 1 °C for a maximum of 6 days and passed through a 5-mm mesh sieve prior to incubation for soil PMN and analysis of microbial enzyme activities.

2.5. Soil microbial activity

Soil microbial activity was measured by β-glucosidase and dehydrogenase enzyme activities, which are considered suitable indicators of the impact of management on soil microbial quality (Moeskops et al., 2010). Mid-season (August) soil samples in 0–0.3 m depth from selected treatments of pea and pea/rye were analysed. Treatments were selected based on white cabbage yield and laboratory capacity. For β-glucosidase 1 ml 25 mM p-nitrophenyl-β-D-glucoside solution and 4 ml of modified universal buffer were added to two technical replicates of 1 g sieved soil (fresh weight) and the samples were incubated at 37 °C for 1 h. P-nitrophenyl-β-D-glucoside solution was added to the control samples after incubation. Subsequently, 1 ml of 0.5 M CaCl₂ and 4 ml Tris-buffer pH 12 were added to the samples, which were then filtered immediately through Whatman no. 5 papers. Released p-nitrophenol in the extract was determined by measurement of optical density with a Varian Cary 50 spectrophotometer at 400 nm. β-glucosidase activity was determined as the difference between experimental and control samples. For determination of dehydrogenase activity, 2 ml 3% triphenyl tetrazolium chloride solution (TTC) and 2 ml Tris-buffer pH 7.6 was added to 5 g sieved soil (fresh weight); 4 ml Tris-buffer was added to the control samples. Samples were incubated at 37 °C for 24 h, after which 20 ml methanol was added, and then the samples were shaken at 125 rev min⁻¹ for 2 h. After filtering the samples through Whatman no. 5 paper, each extract was diluted with methanol to obtain a 50 ml solution. Triphenyl tetrazolium chloride reduction rate to triphenyl tetrazolium formazan was estimated by measuring optical density at 485 nm. Dehydrogenase activity was determined as the difference

between samples with and without added triphenyl tetrazolium chloride.

2.6. Soil potential mineralisation of N (PMN)

Soil PMN was determined in the pea and pea/rye treatments in RC and FI from mid-season (August) soil samples in 0–0.3 m depth as described by De Neve and Hofman (2000). Cover crop debris was removed from soil surfaces in RC treatments prior to soil sampling. Polyvinyl chloride tubes (7-cm in diameter and 15-cm long) were filled with 323 g sieved soil (fresh weight) in 2016 and 266 g in 2017. Four tubes per treatment were used to allow for destructive sampling during incubation. The soil in each tube was compacted to obtain a dry soil bulk density of 1.4 g cm^{-3} in 2016 or 1.15 g cm^{-3} in 2017 and moisture content was adjusted to and kept constant at 50% water-filled pore space throughout the incubation experiment. Tubes were covered with gas permeable polyethylene (30 μm) and incubated in the dark at $15 \text{ }^\circ\text{C}$ for three months. An initial sample was used to determine the initial mineral N content. Tubes were sampled destructively after 28 days, 56 days, 84 days, and 112 days. The 28-day samples were lost in 2016. Soil samples were analysed for NH_4^+ and NO_3^- , as described for soil mineral N.

2.7. Root growth

Cabbage root growth was measured in the pea and pea/rye treatments using minirhizotrons, i.e. 3-m long transparent plastic tubes installed shortly after transplanting. The minirhizotrons were prepared by drawing observation windows ($0.04 \times 0.04 \text{ m}$ crosses) along the tube surface. The tubes were inserted into the soil as described by Kristensen and Thorup-Kristensen (2004) at a 30° angle from the vertical and reached a depth of 2.4 m. Two tubes per subplot were installed in the white cabbage rows in the pea and pea/rye treatment areas. Roots growing along the tube margins were filmed with a mini-video camera two times during the crop growth period on August 24th, and November 8th, 2017. Root frequency was recorded as the presence or absence of roots crossing each observation window, which is used to quantify the soil volume occupied by the root system. The intensity of root colonisation was obtained by counting the total number of roots crossing each observation window, given as root intensity. Root depth was registered as the deepest recorded root in the minirhizotron tube observation windows, not necessarily crossing the counting grids.

2.8. Plant sampling

To assess cover crop biomass production, a 1-m^2 area of cover crops was cut above ground prior to termination on June 2nd, 2016 and on May 24th, 2017. White cabbage was hand-harvested on November 15th, 2016 and November 3rd, 2017 (two rows \times 4.5 m per subplot). Plant samples were divided into marketable yield and crop residues, and then weighed. Marketable yield was evaluated by cabbage head size and damage by pests or diseases according to the market standard. Plant material was chopped, mixed well, weighed, oven-dried at $80 \text{ }^\circ\text{C}$ for 20 h, weighed again, and analysed by the combustion method for total plant N content according to VDLUFA (1991), wherein plant material was first combusted at $950 \text{ }^\circ\text{C}$ and molecular N was then measured by a LECO TruSpec CN (St. Joseph, MI). Total organic carbon content was determined by Dumas' dry combustion method, wherein plant material was combusted at $1000 \text{ }^\circ\text{C}$ and total organic carbon content measured by an ELTRA Helios C/S-analyzer (Haan, Germany).

Above ground weed biomass was harvested from a 1-m^2 area of each subplot on May 31st, 2016 and May 24th, 2017 and oven-dried at $80 \text{ }^\circ\text{C}$ for 20 h before obtaining a dry matter weight. Weed density was evaluated by counting the number of individual weed plants (seedling to mature) in four 0.25-m^2 squares prior to the first weeding event on July 27th, 2016 and July 13th, 2017.

2.9. Data processing and statistical analysis

Cover crop biomass was calculated as dry weight per area, and cabbage yield as fresh weight per area. Above ground N accumulation (N_{acc}) of plant material was determined by multiplication of total plant dry matter per area and N content. Soil mineral N was calculated per unit area from measured N concentrations in 0–0.25 m, 0.25–0.5 m, and in 0.5-m depth increment layers down to 2.5 m, and the corresponding bulk densities. Bulk densities for the 0–0.25 m depth were measured on August 31st, 2016 by extracting undisturbed soil cores by use of a steel auger with 0.04-m diameter and 0.3-m length; drying and weighing the soil. Average bulk density values of RC and FI treatments were used for soil mineral N calculation in the autumn. Results of bulk density measurements below 0.25 m depth and in the spring were from a previous study (Kristensen and Thorup-Kristensen, 2004).

Results were analysed separately for each year because over-wintering of cover crops and fertiliser strategies differed between years. White cabbage yield and N_{acc} , soil mineral N in the autumn, soil PMN, and enzyme activities were analysed with a Gaussian linear mixed model containing three fixed effects (legume species, CCC and termination system), interactions between these effects, and a random component representing the block and the whole-plot accounting for the split-plot design. The model for analysis of soil mineral N in the spring, cover crop biomass and N_{acc} did not include termination system as a factor, since termination was not conducted yet. The bare soil treatment was included as a control in the analyses of the primary effects of cover crops. Soil PMN and autumn soil mineral N data were logarithmically transformed to meet assumptions of homogeneity of variance and normal distribution of residuals. The transformation did not help to fulfil the assumption of homogeneity of variance for soil mineral N data in 0.5–1 m depth in autumn 2016 and these data were therefore subjected to analysis with a non-parametric Kruskal-Wallis test. For soil PMN, two subplots were removed since there was oxygen deficiency during incubation (grey colouring of soil). Soil mineral N was analysed for each soil layer separately. Root frequency and intensity were summed for every 0.25-m depth interval and analysed for each such layer separately. Root frequency was modelled as a Bernoulli distributed response variable in a generalised linear mixed model defined with a logistic link function and two fixed effects (CCC and termination system). The modified root intensity (root intensity_{mod}) analysis method used was described in detail elsewhere (Hefner et al., 2019). In short, root intensity was modelled with a generalised linear mixed model defined by a Poisson distribution and two fixed effects (CCC and termination system). The model included a logarithmic link function, and the logarithm of root numbers as an offset. It can be shown that the exponentially transformed fixed effect parameters of the model above are proportional to the length of the root system in the region around the observational window (see details in Hefner et al., 2019), which resulted in a quantifier of the root intensity_{mod} expressed in an arbitrary unit. For modelling of root frequency and root intensity_{mod}, observations from the same minirhizotron obtained on the same date were included as a random component, in addition to a random component representing the block and the whole-plot.

The statistical analyses were performed in R software, version 3.4.2 (R Core Team, 2017). The mixed models were defined with the R-package lme4 (Bates et al., 2015), using likelihood based inference (i.e., maximum likelihood, and not restricted likelihood, inference for the fixed effects, see Demidenko, 2013). Significant interactions between fixed factors were detected using likelihood ratio tests for generalised linear mixed models implemented in the 'anova()' R-function, which allow to compare nested models (e.g., a large model containing all interactions and a reduced model containing additive main effects or lower order interactions). Post-hoc analyses were conducted using the correction for multiple comparisons based on the method of control of False Discovery Rate (FDR, see Benjamini and Yekutieli, 2001) with the R-package 'pairwiseComparisons' (available at <http://home.math.au>).

Table 2Dry matter, N_{acc} and C/N ratio of cover crops, and soil mineral N in 0–2.5 m depth in May/June prior to cover crop termination.

Treatment	Dry matter (Mg ha ⁻¹)		N_{acc} (kg N ha ⁻¹)		C/N ratio		Soil mineral N (kg N ha ⁻¹)		
	2016	2017	2016	2017	2016	2017	2016	2017	
Legume species									
Faba bean	3.6 ± 0.4 ^c	4.4 ± 1.2 ^{ab}	71 ± 6 ^b	57 ± 6 ^{bc}	102 ± 24 ^{ab}	22 ± 3	23 ± 4	81 ± 8	176 ± 23
Pea	4.6 ± 0.2 ^b	5.3 ± 1.0 ^a	85 ± 10 ^b	99 ± 12 ^{ab}	113 ± 18 ^a	24 ± 4	23 ± 4	85 ± 10	168 ± 32
Hairy vetch	5.7 ± 0.3 ^a	3.7 ± 1.5 ^b	113 ± 11 ^a	11 ± 3 ^c	88 ± 5 ^{ab}	21 ± 2	23 ± 5	89 ± 14	154 ± 25
CCC									
Legumes	4.2 ± 0.4 ^b	1.8 ± 0.4 ^b	104 ± 9 ^a			16 ± 0 ^b	13 ± 0 ^b	106 ± 4 ^b	219 ± 12 ^b
Legumes/rye	5.1 ± 0.3 ^a	7.0 ± 0.4 ^a	75 ± 6 ^b			29 ± 1 ^a	33 ± 1 ^a	64 ± 5 ^c	114 ± 10 ^c
Bare soil								170 ± 19 ^a	326 ± 12 ^a
P-values									
Legume species	< 0.001	0.05	< 0.001			0.073	0.073	0.703	0.399
CCC	0.001	< 0.001	< 0.001			< 0.001	< 0.001	< 0.001	< 0.001
Legume species × CCC	0.182	0.07	0.158	0.035		0.08	0.08	0.425	0.19

Note: N_{acc} = N accumulation, CCC = cover crop composition. Mean values are followed by standard error (legume species, n = 6, CCC, n = 18, N_{acc} in 2017, n = 3), except for soil mineral N in 2016, where values are displayed as medians followed by confidence intervals. Different superscript letters indicate significant differences among treatments for years separately (Post-hoc analysis using the control of false discovery rate method to adjust for multiple comparisons).

dk/astatlab/software/pairwisecomparisons). Differences between treatments ($P < 0.05$, $P < 0.01$, and $P < 0.001$) are indicated by different lower-case letters in figures and tables. Mean values are reported with standard errors, except for root intensity_{mod}, where estimates are reported with 95% confidence intervals.

3. Results

3.1. Cover crop growth and soil mineral N at termination

The biomass and C/N ratio of legume/rye mixtures were higher than those of pure legumes in both years (Table 2). Hairy vetch biomass was highest, followed by pea and faba bean in 2016, whereas pea biomass was higher than hairy vetch biomass in 2017. Nitrogen accumulation of pure legumes was higher than of legume/rye mixtures in 2016, but CCC interacted with legume species in 2017, where N_{acc} did not differ between CCC for faba bean and pea, but was lower for pure hairy vetch than hairy vetch/rye. Soil mineral N in spring was highest in bare soil, followed by pure legumes and legume/rye mixtures in both years.

3.2. Weed growth

Weed dry matter at cover crop termination was, on average, 68% lower under legume/rye mixtures compared with pure legumes in 2017 (Table 3). Weed biomass was lowest under pure hairy vetch in 2016, but highest under pure hairy vetch in 2017. Weed biomass correlated negatively with cover crop biomass in both years (Fig. 1). Roller-crimping reduced weed density by 63% compared with FI three weeks after cover crop termination in 2017 (Table 3). Likewise, weed density was lower under RC than FI for all cover crop species except faba bean/rye and pea/rye in 2016.

Soil temperature was reduced by 0.2–1 °C under RC in June and July in both years, with a greater effect under legumes/rye than pure legumes (Supplementary material, Table S2).

3.3. Microbial activity

β-glucosidase activity did not differ between treatments in both years, whereas dehydrogenase activity was generally increased under FI compared with RC, except for pea in 2016, where no difference between FI and RC was found (Table 4). Dehydrogenase activity was higher in pea than in pea/rye soils under RC in 2016 (Table 4).

3.4. White cabbage yield, N_{acc} and N concentration

Roller-crimping reduced total white cabbage biomass by 31% in 2016 and 19% in 2017 (results not shown) and marketable white cabbage yield completely in 2016 and by 24% compared with FI in 2017 (Table 5). Moreover, roller-crimping reduced white cabbage N_{acc} in legume/rye mixtures, but not in pure legumes in 2016. An indication ($P = 0.068$) of reduced white cabbage N_{acc} by RC was also found in 2017. Total plant N concentration was higher under RC than FI in 2017. Pea resulted in higher marketable white cabbage yield than hairy vetch in 2017. White cabbage N_{acc} and to a lesser extent marketable yield were positively correlated to soil mineral N in the spring 2017 (Fig. 2). Marketable white cabbage yield, N_{acc} and N concentration were reduced following legume/rye mixtures by 26%, 38% and 14%, respectively, compared with pure legumes in 2017. Similarly, legume/rye mixtures reduced white cabbage N concentration compared with pure legumes in 2016, except for FI hairy vetch/rye, which had comparable N concentration to all pure legumes, excluding FI pure hairy vetch (Table 5).

3.5. White cabbage root growth

Root frequency was not affected by termination system or CCC (results not shown). Roller-crimping reduced white cabbage root intensity_{mod} following pea/rye in 0–0.25 m depth and 0.75–1 m depth in August 2017, and in 1–1.25 m depth in November 2017, whereas RC increased root growth following pea in 0.75–1 m depth in August 2017 (Fig. 3). Effects of CCC were found in 0.75–1 m depth in August, and in 0.75–1.25 m depth in November 2017, where cabbage root intensity_{mod} was reduced under RC pea/rye compared with RC pea (Fig. 3). Root intensity_{mod} was further decreased following pea/rye compared with pea in 1–1.25 m depth in August 2017. Root depth did not differ between treatments in August and November and reached an average of 1.88 m depth at harvest in 2017 (results not shown).

3.6. Soil mineral N at mid-season and harvest

Potential mineralisation of N (PMN) was higher in pea than pea/rye soil from start to day 84 in 2016 and at day 28 in 2017 (Fig. 4). Full incorporation increased PMN compared with RC for pea/rye throughout the 112-day incubation period in 2016, for pea until the 84th day of incubation in 2016, and at incubation start in 2017 (Fig. 4).

Pure legumes left 4, 14, and 22 kg ha⁻¹ more soil mineral N than legume/rye mixtures in 0–0.5 m depth, in 1.5–2.5 m depth in 2016 and in 0.5–2 m depth in 2017, respectively (Fig. 5). Furthermore, soil

Table 3
Weed dry matter at cover crop termination in May/June and weed density three weeks after termination.

Treatment	Dry matter (Mg ha ⁻¹)		Density (number m ⁻²)		
	2016	2017	2016		2017
Legume species x CCC			FI	RC	
Pure faba bean	0.99 ± 0.21 ^a	1.35 ± 0.09 ^b	644 ± 31 ^{ab}	240 ± 43 ^{def}	761 ± 354 ^{ab}
Pure pea	0.83 ± 0.13 ^a	1.17 ± 0.24 ^b	707 ± 41 ^a	298 ± 45 ^{def}	761 ± 468 ^{ab}
Pure hairy vetch	0 ± 0 ^b	2.10 ± 0.27 ^a	528 ± 64 ^{bc}	222 ± 69 ^{ef}	948 ± 422 ^a
Faba bean/rye	0.34 ± 0.03 ^{ab}	0.50 ± 0.03 ^c	396 ± 40 ^{ce}	214 ± 52 ^{ef}	665 ± 384 ^b
Pea/rye	0.49 ± 0.14 ^{ab}	0.45 ± 0.08 ^c	399 ± 39 ^{ce}	276 ± 16 ^{d^{ef}}	623 ± 481 ^b
Hairy vetch/rye	0.44 ± 0.33 ^{ab}	0.51 ± 0.13 ^c	440 ± 38 ^{cd}	161 ± 24 ^f	585 ± 320 ^b
Termination					
FI	n. a.	n. a.			1058 ± 256 ^a
RC	n. a.	n. a.			390 ± 154 ^b
P-values					
Termination					< 0.001
Legume species × CCC	0.004	0.002			0.016
Legume species × termination	n. a.	n. a.			0.227
CCC × termination	n. a.	n. a.			0.304
Legume species × CCC × termination	n. a.	n. a.		0.015	0.142

Note: FI = full incorporation, RC = roller-crimping, CCC = cover crop composition. Mean values are followed by standard error (n = 3, except for plant density in 2017: legume species x CCC, n = 6, and termination, n = 18). P-values of ANOVA are given. Different superscript letters indicate significant differences among treatments for years separately (Post-hoc analysis using the control of false discovery rate method to adjust for multiple comparisons). n.a. = not applicable.

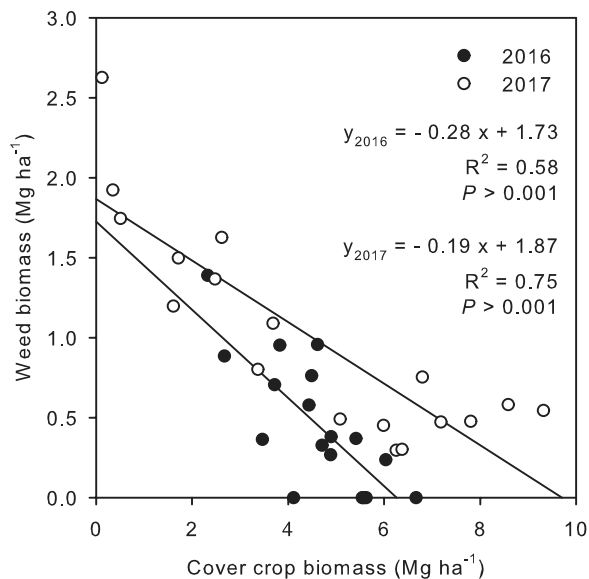


Fig. 1. Weed biomass related to cover crop biomass at cover crop termination in May/June for all cover crop species and compositions in 2016 and 2017. Data points represent individual subplots. Lines show the linear regression for 2016 and 2017.

mineral N was higher under FI pure legumes than all other treatments in 0.5–1.5 m depth in 2016. Roller-crimped pea and hairy vetch left more soil mineral N than FI pea and hairy vetch in 0–0.25 m depth in November 2017 (results not shown). Soil mineral N was by indication ($P = 0.050$ and $P = 0.058$) lower under RC than FI in 0.5–1.5 m depth in November 2017.

4. Discussion

4.1. Cover crop growth and soil mineral N at termination

The lower soil mineral N content in 0–0.25 m depth under legume/rye mixtures compared with pure legumes in May 2016 and June 2017 corresponded to a higher biomass of legume/rye mixtures (Table 2), indicating that legume/rye mixtures took up more soil mineral N than

Table 4
Enzyme activities in 0–0.3 m soil depth in August.

Termination	Dehydrogenase ($\mu\text{g TPF g}^{-1} \text{ day}^{-1}$)		β -glucosidase ($\mu\text{g PNP g}^{-1} \text{ h}^{-1}$)	
	2016	2017	2016	2017
	Pea	Pea/rye		
FI	14 ± 5 ^{ab}	20 ± 7 ^a	39 ± 3 ^a	86 ± 3
RC	20 ± 7 ^a	11 ± 3 ^b	21 ± 4 ^b	84 ± 5
P-values				
CCC		0.152	0.253	0.508
Termination		0.024	0.528	0.299
CCC × termination	0.02845	0.137	0.539	0.108

Note: FI = full incorporation, RC = roller-crimping, CCC = cover crop composition, TPF = triphenyl tetrazolium formazan, PNP = p-nitrophenol. Mean values are followed by standard error (dehydrogenase in 2016, n = 3; all other cases, n = 6). P-values of ANOVA are given. Different superscript letters indicate significant differences among treatments for years separately (Post-hoc analysis using the control of false discovery rate method to adjust for multiple comparisons).

pure legumes. These results are in line with a French study, where soil mineral N in 0–0.9 m depth was lower under legume/non-legume mixtures than under pure legumes at cover crop termination (Tribouillois et al., 2016). An Austrian study also found higher biomass (6 Mg ha^{-1}) of legume/non-legume mixtures than pure legumes (3.5 Mg ha^{-1}) (Rinnofner et al., 2008). Apart from a higher mineral N uptake from the soil, Rinnofner et al. (2008) attributed the higher biomass of legume/rye mixtures to enhanced biological N_2 fixation by the legume in the mixture. Moreover, a Swiss study found a land equivalent ratio value of greater than one when growing legumes and non-legumes in mixtures, revealing that these mixtures used abiotic resources more efficiently than pure cover crops to acquire N (Tribouillois et al., 2016).

In 2016, N_{acc} of pure legumes was higher than of legume/rye mixtures, but this difference was not found in 2017. In contrast, N_{acc} of pure hairy vetch was lower than N_{acc} of hairy vetch/rye. These different patterns in N_{acc} may be connected to a generally lower soil mineral N content in 2016 compared to 2017, as legumes may increase biological N_2 fixation at low N availability. In accordance, biological N_2 fixation by legumes was higher at low fertiliser application of 50 kg N ha^{-1} compared with 450 kg N ha^{-1} in a Swiss study (Nyfeler et al., 2011). The N_{acc} of legume/rye mixtures was not higher than of pure legumes in our study. This was probably the result of low soil mineral N in 2016,

Table 5
White cabbage marketable yield, and N_{acc} and N concentration in marketable yield and residue at harvest.

Treatment	Marketable yield (Mg ha ⁻¹)	Total plant N_{acc} (kg N ha ⁻¹)		Total plant N concentration (g kg ⁻¹)	
2016					
Legume species x CCC		FI	RC	FI	RC
Pure faba bean	4 ± 1			24 ± 2 ^{bc}	20 ± 1 ^{cd}
Pure pea	8 ± 4			29 ± 2 ^{ab}	20 ± 0 ^{cd}
Pure hairy vetch	3 ± 1			31 ± 2 ^a	26 ± 1 ^{ab}
Faba bean/rye	4 ± 4			16 ± 1 ^d	16 ± 1 ^d
Pea/rye	1 ± 1			16 ± 1 ^d	16 ± 1 ^d
Hairy vetch/rye	0			24 ± 2 ^{bc}	18 ± 0 ^d
CCC x termination					
Legumes		66 ± 15 ^b	62	± 7 ^b	
Legumes/rye		102 ± 8 ^a	52	± 6 ^b	
Bare soil	37 ± 5 ^{**}	226 ± 24 ^{**}		18 ± 0 ^{**}	
P-values					
Legume species x CCC	0.199	0.157			
Legume species x termination		0.008			
CCC x termination		0.002			
Legume species x CCC x termination		0.534		0.004	
2017					
Legume species					
Faba bean	54 ± 4 ^{ab}	168 ± 14		20 ± 1	
Pea	58 ± 4 ^a	179 ± 17		20 ± 1	
Hairy vetch	50 ± 4 ^b	155 ± 10		20 ± 1	
CCC					
Legumes	62 ± 2 ^a	206 ± 8 ^a		22 ± 1 ^a	
Legumes/rye	46 ± 3 ^b	128 ± 6 ^b		18 ± 0 ^b	
Termination					
FI	61 ± 2 ^a	172 ± 10		19 ± 1 ^b	
RC	47 ± 3 ^b	162 ± 13		22 ± 1 ^a	
Bare soil	64 ± 1 ^{**}	185 ± 1 ^{**}		20 ± 1 ^{**}	
P-values					
Legume species	0.004	0.054		0.806	
CCC	< 0.001	< 0.001		< 0.001	
Termination	0.002	0.397		0.013	
Legume species x CCC	0.254	0.052		0.345	
Legume species x termination	0.290	0.203		0.196	
CCC x termination	0.08	0.068		0.127	
Legume species x CCC x termination	0.501	0.925		0.560	

Note: FI = full incorporation, RC = roller-crimping, CCC = cover crop composition. Mean values are followed by standard error (2016, n = 3, CCC x termination, n = 9; 2017: Legume species, n = 12, CCC, n = 18, and termination, n = 18). P-values of ANOVA are given. Different superscript letters indicate significant differences among treatments for years separately (Post-hoc analysis using the control of false discovery rate method to adjust for multiple comparisons). *Marketable yield under RC was zero for all cover crop species in 2016 and was not included in the analysis. ** Bare soil was not included in the statistical analyses.

limiting N uptake by rye, and a small share of legume biomass in the legume/rye mixtures in 2017, which was indicated by the generally low pure legume biomass in Table 2, limiting biological N₂ fixation.

Cover crop biomasses ranged between 1.8 and 7 Mg ha⁻¹ in this study, which was comparable to 5 Mg ha⁻¹ obtained at termination in early to mid-June in the coastal region of Norway (Brandsaeter et al., 2008). However, hairy vetch biomass was very low in 2017, possibly due to damage by frost or flea beetle larvae (*Phyllotreta* species) in late winter. C/N ratios of legume/rye mixtures were higher than of pure

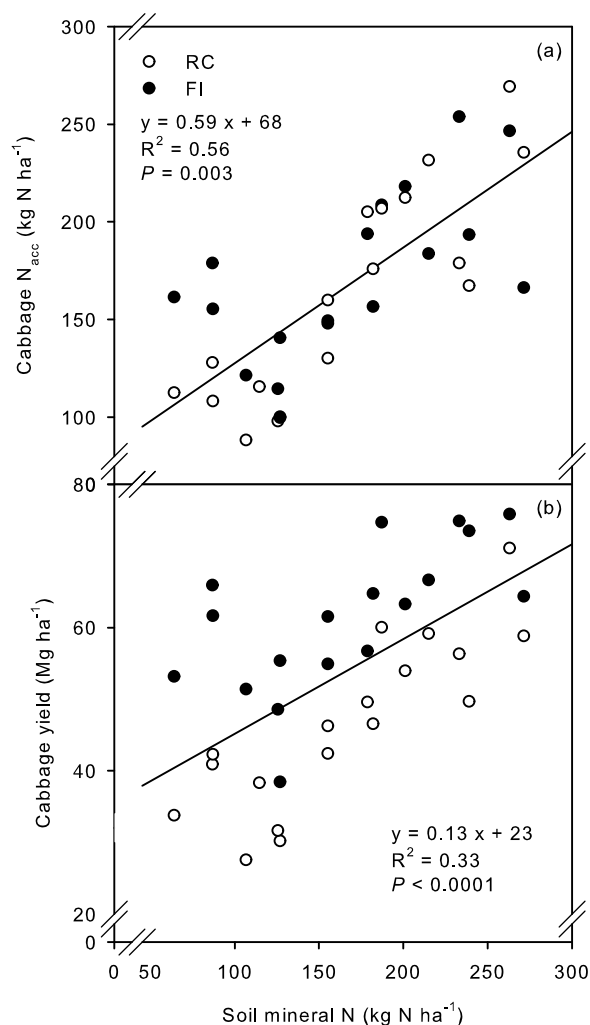


Fig. 2. (a) Cabbage N accumulation and (b) marketable yield at harvest related to soil mineral N in 0–2.5 m depth in the spring in 2017. Data points represent individual subplots. The line shows the linear regression.

legumes, which was also found in a French study (Tribouillois et al., 2016).

The fourth hypothesis that N_{acc} of legume/rye mixtures is greater than of pure legumes was rejected, most likely due to low soil N availability or a low share of legume biomass in the legume/rye mixtures. The second part of the fourth hypothesis that soil mineral N at cover crop termination was reduced under legume/rye mixtures compared with pure legumes was supported in both years.

4.2. Weed growth

The negative regression coefficient between cover crop biomass and weed biomass in both years (Fig. 1) indicates that weed biomass was reduced with increased cover crop biomass. Hairy vetch had a high biomass in 2016, eliminating weed growth completely (Tables 2 and 3) by forming a dense ground cover. In contrast, low hairy vetch biomass in 2017 resulted in the highest weed biomass among cover crop species (Tables 2 and 3). Including rye in the cover crop mixture increased cover crop biomass (Table 2), thereby reducing weed growth at cover crop termination in 2017 (Table 3). The greater persistence of rye, indicated by the higher C/N ratio (Table 2), may be responsible for the improved weed suppression of legume/rye mixtures compared with pure legumes three weeks after FI in 2016 (Table 3).

In line with our findings, a Swiss study showed that weed suppression by cover crops is strongly related to biomass production and

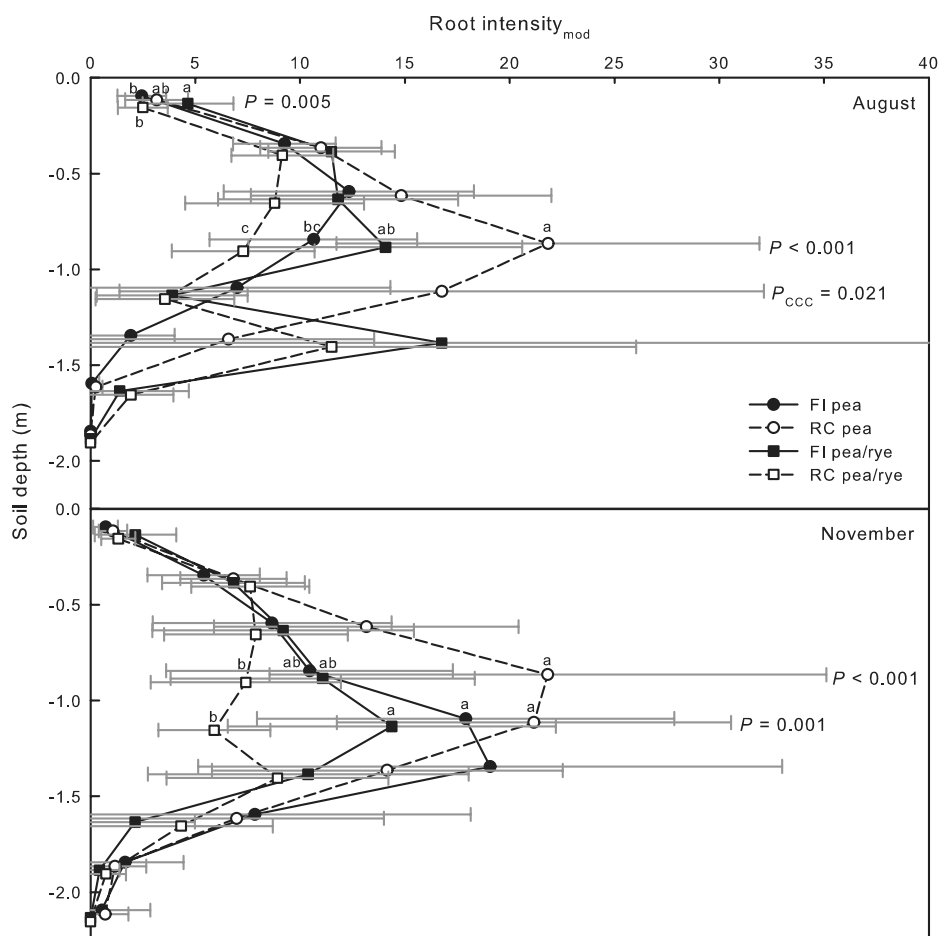


Fig. 3. White cabbage root intensity_{mod} in 0–2.4 m depth in August and November 2017. FI = full incorporation, RC = roller-crimping, CCC = cover crop composition. Data points were jittered to avoid overlap. Bars indicate 95% confidence intervals (n = 3). Statistical differences between treatments were tested for each soil layer separately and are indicated with different lower-case letters.

early soil cover of the cover crops (Dorn et al., 2015). Greater cover crop biomass is likely suppressing weed growth physically through direct competition for light, water and nutrients with weeds (Creamer et al., 1996). Teasdale and Mohler (1993) showed that light transmittance through rye residue was smaller than through hairy vetch residue

with increasing time after termination, thereby providing longer lasting weed suppression.

Weed density was suppressed by RC compared with FI three weeks after termination in both years, except for pea/rye and faba bean/rye in 2016 (Table 3). Tillage under FI may have stimulated weed seeds to

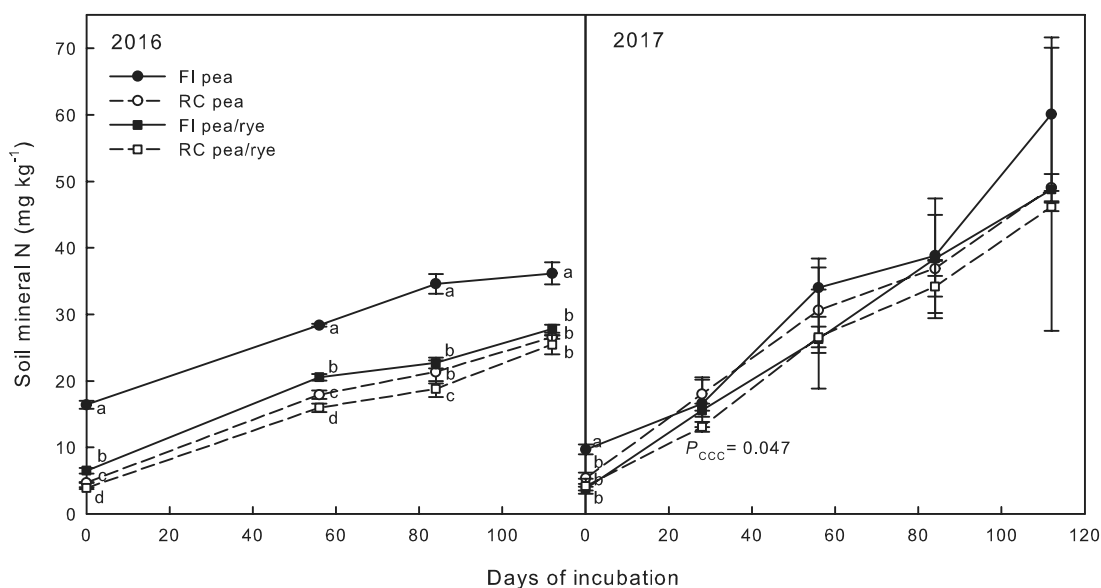


Fig. 4. Potential mineralisation of N during 112-days of incubation in soil samples taken in 0–0.3 m depth in August 2016 and 2017. FI = full incorporation, RC = roller-crimping, CCC = cover crop composition. Bars indicate standard error (n = 3). Different lower case letters indicate significant differences among treatments for each sampling time separately (Post-hoc analysis using the control of false discovery rate method to adjust for multiple comparisons).

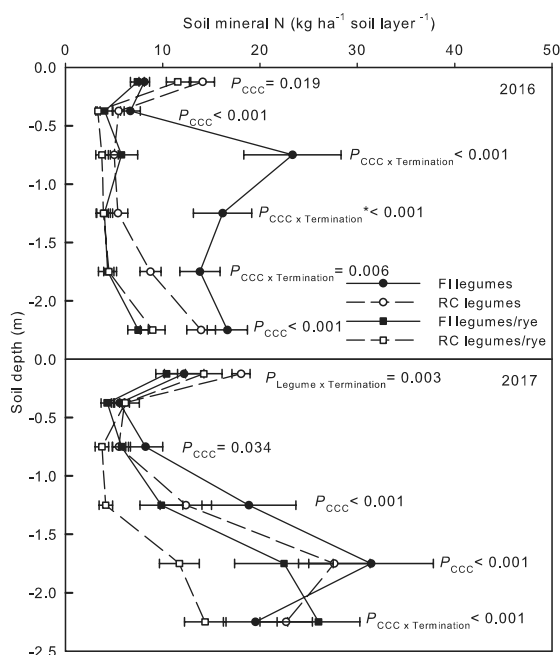


Fig. 5. Soil mineral N in 0–2.5 m depth in November 2016 and 2017. FI = full incorporation, RC = roller-crimping, CCC = cover crop composition. Bars indicate standard error ($n = 9$). Statistical differences between treatments were tested for each soil layer separately. * Statistical difference was tested with Kruskal-Wallis due to lack of variance homogeneity.

germinate in contrast to no-tillage under RC. A marginally lower soil temperature under RC, sometimes only following legumes/rye in June and July (Supplementary material, Table S2), could contribute to reduce germination of weed seeds. Teasdale and Mohler (1993) also assigned the reduced germination of weed seeds after RC to the physical barrier of plant residues, which decreased soil temperature and light transmittance at the soil surface.

Differences in weed suppression in this study disappeared later in the growing season (visual observation), as cover crops decomposed under RC while weed control was carried out with a weed-brush under FI. Therefore, weed management can still be a challenge under RC late in the growing season under a northern humid climate. To conclude, our findings support the second hypothesis that weed growth is reduced by legume/rye mixtures and by RC early in the growing season.

4.3. Microbial activity

Dehydrogenase activity, which is involved in the biological oxidation of soil organic matter, was higher under FI than RC, whereas β -glucosidase, which is essential to complete the hydrolysis of cellulose to glucose, was not affected by treatments. In contrast to these findings, a meta-analysis showed that long-term no-tillage generally increased dehydrogenase and β -glucosidase enzyme activities compared with tilled systems (Zuber and Villamil, 2016), which is likely an effect of improved quantities and qualities of soil organic carbon in the upper 0–0.1 m soil depth with no-tillage (van Capelle et al., 2012). Dehydrogenase is generally considered as an indicator of soil microbial activity as it is found only in viable cells. The higher dehydrogenase activity under FI indicates a stimulation of the growth and activity of the microbial community in response to the incorporation of organic carbon. The soil organic matter content and the subsequent soil microbial activity under RC might have been reduced compared with FI because roller-crimping was only conducted for one season, and plant debris was removed from soil surfaces in the RC treatments prior to soil sampling. In line with our findings, Moeskops et al. (2010) found that dehydrogenase and β -glucosidase activity were correlated to soil

organic carbon. Unlike dehydrogenase, β -glucosidase is an extracellular enzyme and its activity exists in the soil regardless of the viable microbial biomass, explaining the absence of significant response to management practices in the short term (Nannipieri et al., 2018). In contrast to our hypothesis, RC did not increase microbial activity in the current one season experiment.

4.4. White cabbage yield affected by termination system

Marketable yield of white cabbage ranged between 44–67 Mg ha⁻¹ in 2017 (Table 5), which was comparable to 48–77 Mg ha⁻¹ white cabbage yield obtained in another organic cropping study at the same site (Thorup-Kristensen et al., 2012). Marketable yields in 2016 reached only 0 to 37 Mg ha⁻¹, indicating poor crop development in the first experimental year across all treatments. Possible explanations for low marketable yields in 2016 include poor plant quality at planting, low initial soil mineral N content (Table 2), as well as low and late (August) fertiliser application, resulting in zero marketable yield under RC. In 2017, initial soil mineral N was higher (Table 2), white cabbage was fertilised at planting, and fertiliser was applied in the planting-furrow under RC, resulting in improved crop growth in all treatments. In-soil fertiliser placement through banding has been recommended for reduced tillage systems due to changes in microclimate and microbial activity (Malhi et al., 2001), possibly resulting in improved N supply under RC in 2017.

White cabbage N_{acc} and to a lesser extent marketable yield showed a positive correlation to spring soil mineral N in 2017 (Fig. 2), which did not level off at high soil mineral N, indicating that N was limiting crop development in both termination systems. The positive correlation points towards the importance of early soil mineral N content for crop N uptake and yield. However, the grouping of RC values below the regression line (Fig. 2b) indicates that besides soil mineral N content in the spring, other factors related to RC affected marketable yields. Higher white cabbage N concentration at harvest, but lower marketable yield together with an indication of lower white cabbage N_{acc} ($P = 0.068$) in 2017 (Table 5) suggest that N availability was delayed under RC. The delayed N availability could have caused inferior plant establishment, translating into reduced biomass and, later in the season, when N availability increased, in higher cabbage N concentration. Another explanation could be that cabbage plants in the lower-yielding stands had less competition for soil N, resulting in increased N concentration. Limited N availability under RC was further evident by lower PMN in 2016 and lower soil mineral N content following pure pea at incubation start in 2017 (Fig. 4). Apart from delayed soil N availability, white cabbage yield reduction under RC could also have been influenced by other factors, such as a compact topsoil (visual observation) and marginally lower topsoil temperature in the early part of the growing season (Supplementary material, Table S2).

Yield reductions by RC have also been observed in other studies. Roller-crimped rye reduced white cabbage yield by 19% compared with rye stubble cultivation in New York, USA (Mochizuki et al., 2008), and a 20% vegetable yield reduction under no-tillage systems was found in a meta-analysis (Pittelkow et al., 2015). Yields are reduced under RC as a result of slower mineralisation and N release from cover crops, which was found for mowed cover crop material left on the soil surface in contrast to incorporated cover crops (Radicetti et al., 2016). In addition, white cabbage yield in Wisconsin was reduced by no-tillage compared with conventional tillage partly due to greater soil compaction in 0.3 m soil depth under no-tillage (Bulan et al., 2015).

In conclusion, RC reduced white cabbage yield compared with FI, supporting the fifth hypothesis. However, RC pure pea was an exception, as white cabbage yield (62 Mg ha⁻¹, result not shown) was comparable to bare soil (64 Mg ha⁻¹) in 2017. Thus, RC pure pea is a promising treatment for implementation of RC systems in organic farming.

4.5. White cabbage yield affected by cover crop composition (CCC)

The positive correlation of white cabbage N_{acc} and soil mineral N in 0–2.5 m depth in the spring 2017 (Fig. 2) displays the indirect effect of CCC on white cabbage N_{acc} , as soil mineral N was lower following legume/rye mixtures (Table 2), resulting in lower N_{acc} of white cabbage (Table 5). The greater soil mineral N reduction by legume/rye mixtures (Table 2) indicates a greater pre-emptive competition effect (Thorup-Kristensen, 1993), as N taken up by legume/rye mixtures reduced the N supply for the following cash crop. In addition to the greater depletion of soil mineral N, N release from legume/rye mixtures was slower than from pure legumes, evidenced by lower PMN 28 days after incubation start in 2017 (Fig. 4) and indicated by the higher C/N ratio of the plant material (Table 2). Similar effects of legume/rye mixtures have been found in other studies, where cereals depleted soil mineral N more effectively (Tonitto et al., 2006), and N mineralisation rates after incorporated vetch/rye were lower compared with vetch only (Rosecrance et al., 2000). Likewise, maize yield was decreased following cover crops with a high C/N ratio in Pennsylvania, USA (White et al., 2017).

Consequently, white cabbage yield and N_{acc} were reduced following legume/rye mixtures compared with pure legumes in 2017 due to a lower soil mineral N content in the spring and slower N mineralisation from legume/rye mixtures during the growing season caused by high C/N ratios, supporting the fifth hypothesis.

4.6. White cabbage root growth

Root frequency did not differ between treatments (results not shown), indicating that the soil volume occupied by white cabbage roots was equal among treatments. However, root intensity_{mod} was higher under FI pea/rye, suggesting that white cabbage produced more roots locally, but did not explore other areas of the soil. This illustrates that white cabbage under FI pea/rye was a stronger competitor for nutrients that are not easily mobilized. The reduced root intensity_{mod} under RC pea/rye can be ascribed to the combined effects of increased soil strength in RC (visual observation) and reduced soil mineral N content in the spring after pea/rye (Table 2), both affecting root growth development negatively. The lower root intensity_{mod} under RC pea/rye corresponded to reduced white cabbage yield and N concentration (Table 5) and reduced soil mineral N content following legume/rye mixtures in the spring (Table 2). This suggests that above- and below-ground crop growth following RC legume/rye mixtures were linked and affected by soil mineral N content in the spring (Fig. 2), which could not be counteracted by N release during the season from the similar input of pea/rye and pure pea biomass N_{acc} (Table 2). In agreement, root growth response to soil mineral N distribution was ascribed to the overall performance and N nutritional status of the crop (Kristensen and Thorup-Kristensen, 2007). In line with these results, Bulan et al. (2015) found that soil strength was greater in the plough layer (0–0.25 m depth) of no-tilled compared with conventionally tilled soil immediately after tillage, confirming the compacting effect of RC. Consequently, the sixth hypothesis that legume/rye mixtures and RC reduces root growth was supported for the combination of these factors.

4.7. Nitrogen leaching risk

The higher soil mineral N content under RC than FI following pea and hairy vetch in 0–0.25 m depth in November 2017 indicated that the delayed N release from cover crops under RC was not synchronised well with cabbage N uptake, leaving more soil mineral N in 0–0.25 m under RC. Similarly, modelling of cover crop decomposition suggested that crop residues left at the soil surface might increase N leaching compared with incorporated residues (Coppens et al., 2007). However, soil mineral N content did not differ between termination systems in 0.25–2.5 m depth in both years (Fig. 5) and was by indication lower

under RC than FI in 0.5–1.5 m depth in 2017, suggesting that N leaching risk was not increased by RC.

Increased N leaching risk following pure legumes compared with legume/rye mixtures was indicated by the higher soil mineral N content following legumes in deeper depths (0.5–2 m) in 2017, likely the result of faster N mineralisation due to the lower C/N ratio of legumes (Table 2). Similar results were found in a Swiss study (Tribouillois et al., 2016), and increased N leaching risk after vetch compared with vetch/rye was ascribed to faster mineralisation of vetch biomass (Rosecrance et al., 2000). Consequently, the second hypothesis that N leaching risk is lower following legume/rye mixtures compared with pure legumes was supported, whereas no increase in N leaching risk by RC was suggested.

4.8. Assessment of the RC system

Advantages of the RC system compared with the FI system included improved weed suppression in the early part of the growing season (Table 3), and indicated reduction of N leaching risk in autumn (Fig. 5), making this an environmentally sound management system. However, 24% yield reduction under RC (Table 5) is unacceptable from a grower's perspective if not counterbalanced by cost reduction. White cabbage root growth was reduced by RC following pea/rye (Fig. 3), but not pea, indicating that RC affected root growth to a greater extent under low soil mineral N content. Moreover, dehydrogenase activity (Table 4) was reduced or at best maintained under RC, suggesting limitations in terms of nutrient release. Nevertheless, appropriate white cabbage yield (62 kg ha⁻¹) was obtained following RC pea in 2017 (results not shown). This suggested that the RC system could still be relevant if adjustments are made to fit the changes in ecosystem processes, e.g. choosing the right cover crop species and adapting fertilisation time and placement in order to synchronise N availability for the crop. Choice of cover crop composition is important for appropriate RC management, as a trade-off occurred between improved weed suppression, and reduced N leaching risk following legume/rye mixtures (Table 3 and Fig. 5) on the one hand and increased N availability and white cabbage yield following pure legumes on the other hand (Table 2 and Table 5). Similarly, legume/non-legume mixtures represented a compromise between providing N and preventing N leaching compared with their respective mono crops (Tribouillois et al., 2016; White et al., 2017). Considering the importance of early N availability for crop growth shown in the present study, legumes may be the preferred choice in the RC system, where N release during the growing season was delayed and may be limited (Radicetti et al., 2016). Implementation of RC in the long-term, resulting in a no-tillage system suitable for organic production, could lead to a build-up of N and soil fertility due to the slow decomposition of roller-crimped cover crops and the absence of tillage. Vegetable yields increased in the third year after no-tillage implementation in a meta-study (Pittelkow et al., 2015), indicating that soil N mineralisation potential and soil fertility were enhanced in this medium-term study, which could be further enhanced in the long-term. However, long-term no-tillage also carries the risk of increased weed and disease occurrence, particularly in humid climates, which may depreciate yields (Pittelkow et al., 2015).

5. Conclusion

Roller-crimping reduced marketable white cabbage yield, and root growth following pea/rye, compared with FI, partly as a result of delayed N release from cover crops, lower microbial activity indicated by dehydrogenase activity, as well as other factors. Despite the observed yield reduction under RC, this management system may still be promising for vegetable production if fertilisation placement and timing is adjusted, compensating for the change in ecosystem processes, and if pure legumes are used as cover crops, as they increased soil mineral N in spring and N availability to crops. Promising results have been

obtained by RC pure pea, which obtained comparable white cabbage yield to bare soil. Legume/rye mixtures, however, were better at suppressing weed growth and reduced N leaching risk over winter. Long-term implementation of the RC system may have further beneficial effects on the build-up of soil N and the mineralisation potential.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.agee.2020.106908>.

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