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Aboveground and Root Decomposition of Cereal Rye and Hairy Vetch Cover Crops

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Synchronizing cover crop decomposition and nutrient release with cash crop uptake can provide benefits to agroecosystems but can be difficult to implement. The objectives of this study were to quantify the aboveground and belowground decomposition and nutrient release of two cover crops, hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.), after termination with herbicides through a 16-wk period during the cash crop growing season using litterbags and intact root cores. Plant Root Simulator probes monitored mineral N in the soil. Hairy vetch aboveground (k = 0.4505) and root (k = 0.6821) biomass decomposed at a faster rate than aboveground (k = 0.1368) and root (k = 0.1866) biomass of cereal rye. Hairy vetch had higher initial N content in aboveground (41.9 g kg^{-1}) and root (16.5 g kg^{-1}) biomass than cereal rye (11.5 and 8.3 g kg^{-1}, respectively). Hairy vetch had a lower C to N ratio than cereal rye in both aboveground (9.52 vs. 34.72) and root biomass (17.31 vs. 40.31) contributing to decomposition differences. Hairy vetch rapidly decomposed after cover crop termination in the spring, therefore growers should consider delaying termination of this cover crop until close to cash crop planting to decrease the risk of N loss. Cereal rye residues decompose much slower and may also immobilize N because of its high C to N ratio. A better understanding of how aboveground and belowground cover crop characteristics influence decomposition will help to optimize cover crop nutrient release with cash crop uptake.

Abbreviations: ARC, Agronomy Research Center; PRS, Plant Root Simulator.

Core Ideas

- **Hairy vetch decomposed faster than cereal rye.**
- **Hairy vetch released N within two weeks of termination.**
- **Biomass belowground decomposed more quickly than aboveground.**
- **Cover crop N release occurred earlier than maximum crop uptake due to late planting.**

Cover crops are often grown with the intention for nutrients either produced or accumulated by cover crops to be released after termination for cash crop uptake. This nutrient release can be variable depending on environmental conditions and inherent plant residue quality. Nitrogen is typically the most limiting nutrient in crop production, but has the most potential for environmental impact from losses. One goal when planting cover crops should be to coordinate cover crop N release during decomposition with peak cash crop uptake needs. To establish this synchrony, cover crop decomposition and nutrient release between species must be evaluated in order for farmers to most effectively implement cover crops into their crop production system.

Plant decomposition and nutrient release can be affected by substrate quality, soil temperature, moisture, or aeration, and microbial and faunal heterotrophs (Stump and Binkley, 1992; Robertson and Paul, 2000; Vazquez et al., 2003). Incorporation of residues can also increase decomposition rates (Poffenbarger et al., 2015). Plant substrate quality can differ greatly among closely related species (Cobo et al., 2002; Dauer et al., 2007), among plant parts (leaves, stems, roots; Hackney and De La Cruz, 1980; Scheffer and Aerts, 2000; Cobo et al., 2002; Murungu et al., 2011a), or even within species based on age or height (Harre et al., 2014). Higher initial plant nutrient content (lower C to N ratios) has been shown

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to increase decomposition rates and N release rates, but physical protection by cellulose, hemicellulose, or lignin (structural polysaccharides) can reduce microbial attack (Luna-Orea et al., 1996; Ranells and Wagger 1996; Rosecrance et al., 2000; Cobo et al., 2002; Vazquez et al., 2003; Aulen et al., 2011; Lindsey et al., 2013). One literature review highlighted that calcium concentrations and C to N ratios together explained between 83 and 87% of the variability in root decomposition rates globally, and root substrate quality appeared to be a dominant factor controlling decomposition rates (Silver and Miya, 2001). However, quality parameters of N content, lignin to N ratio, and C to N ratio were poorly correlated with weed biomass decomposition in Harre et al. (2014). Environmental factors, such as weather, climate, and soils, can influence decomposition and nutrient release rates overall (Vazquez et al., 2003; Jani et al., 2016). Precipitation that leads to optimal soil moisture can increase decomposition (Ranells and Wagger, 1996; von Haden and Dornbush, 2014). An increase in the number of litter-ingesting organisms, such as earthworms, or greater soil contact may also increase decomposition (Vazquez et al., 2003).

The purpose of this study was to investigate cover crop decomposition and nutrient release in a southern Illinois agronomic field after termination. The objectives of this study were to determine the biomass production, decomposition rates, and N release rate of aboveground and belowground biomass of cereal rye (*Secale cereale* L.) compared with hairy vetch (*Vicia villosa* Roth). These two cover crops are among the most planted cereal or legume cover crops in the North Central region (CTIC, 2017) and therefore provide a useful comparison for regional growers. Results from this research can help inform Midwestern farmers utilizing cover crops in corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production systems to understand likely nutrient release from preceding cover crops.

Table 1. Dates of 2015 field activities at the Kuehn Farm, West Unit, and Agronomy Research Center for the decomposition and nutrient release experiment. Corn and soybean growth stages throughout the experiment at the ARC are also listed.

Date	Activity	Growth stage: Corn	Growth stage: Soybean
	Kuehn Farm		
15 April	Cereal rye herbicide burndown	–	–
	West Unit		
23 April	Hairy vetch herbicide burndown	–	–
	Agronomy Reserach Center		
17 April	All cover crops herbicide burndown	–	–
24 April	Installed PRS probes	–	–
5 May	Installed decomposition study; Week 0 collection	–	–
19 May	Week 2 collection	–	–
2 June	Week 4 collection	–	–
4 June	Planted corn	–	–
12 June	Planted soybean	–	–
16 June	Week 6 collection	V3	VE
30 June	Week 8 collection; Fertilized corn with N†	V6-V7	V1-V2
28 July	Week 12 collection	R1-R2	R2
25 August	Week 16 collection	R5	R5

† 168 kg ha^{-1} of N was applied as 32% urea ammonium nitrate as a sidedress application to corn.

MATERIALS AND METHODS

Field Site

The field site for this study was located at the Agronomy Research Center (ARC) in Carbondale, IL (37°42′10.3968″ N, 89°14′25.3314″ W) primarily on a Hosmer silt loam soil (fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs) located within a tillage by cover crop field experiment. The field was arranged in a split split-plot design as a replicate of a larger study (Dozier et al., 2017) but with minor modifications. Portions of this larger study were chosen for the decomposition experiment. The whole-plot cash crop treatment was divided into a north and south block that rotated each year into corn or soybean. In the year of this study (2015), corn was in the north block and soybean in the south block. Within each cash crop, there were subplot treatments for tillage (Till vs. No Till) with cover crop species as the split plot within tillage (Supplemental Fig. S1). For this decomposition experiment, no-till hairy vetch and no-till cereal rye cover crop plots were utilized. Each research plot was 3 m by 12 m, and treatments were replicated four times; thus, there were four hairy vetch plots (preceding corn) and four cereal rye plots (preceding soybean) for this decomposition study.

Biomass Collection

Cover crop biomass was collected in Spring 2015 from two locations (Table 1) to supply the required quantity for this experiment and reduce impact on the experimental plots. Cereal rye was collected from a stand that was drilled in Fall 2014 at the Kuehn Farm (37°56′0.7728″ N, 89°14′39.9696″ W), a research farm of Southern Illinois University Carbondale located near Elkville, IL. The cereal rye was planted on a Hoyleton silt loam (Fine, smectitic, mesic Aquollic Hapludalfs) by a no-till seed drill at a rate of 144 kg ha^{-1}. Rye was terminated on 15 April 2015. Hairy vetch biomass was collected at the West Unit of the ARC (37°42′39.366″ N, 89°16′24.8844″ W), on Southern Illinois University Farms on a Hosmer silt loam soil (fine-silty, mixed, active, mesic Oxyaquic Fragiudalfs). The hairy vetch cover crop was drilled at 28 kg ha^{-1} in Fall 2014. Aboveground biomass was clipped to the soil line and air-dried in the lab for 1 wk. Root biomass was collected using a slide-hammer to collect root cores in 5-cm diameter by 15-cm length plastic sleeves (AMS Suppliers). After sampling, root cores in plastic sleeves were capped and stored at approximately 4°C until placement in experimental plots. Both cover crops were collected after glyphosate herbicide burndown application at each location, specifically after the plant material began to become chlorotic and wilted (approximately 3 to 4 d).

Litterbags and Intact Cores

Ten grams of air-dry aboveground cover crop biomass, based on methods by Harmon et al. (1999), was placed into 20-cm by 20-cm nylon mesh litterbags, with 5-mm mesh on the upper side and 2-mm mesh on the bottom (PL311YJ, EFE & GB Nets, Bodmin, Cornwall, UK). This would scale up to a greater quantity of aboveground biomass than was actually present (Table 2), but was required to have sufficient sample to collect throughout the sampling period. Aboveground material for each cover crop was dried, ground, and analyzed for initial lignin, acid detergent fiber, neutral detergent fiber, C content, and N content. Root decomposition was evaluated using the intact root core method (Dornbush et al., 2002; Sun et al., 2013a). The intact root core method is beneficial because it does not disrupt the root environment as in the buried litterbag method. A limitation of the intact root core method is that initial root biomass per core is unknown, therefore a larger sample size of root cores is necessary to compensate for the variability of root biomass per core. A total of 14 litterbags, either hairy vetch or cereal rye, were randomly placed into their respective plots, with two litterbags collected per plot at each sampling time, and four replications of each cover crop. Root cores remained in plastic liners with the ends of the root cores wrapped with size 16-mesh and inserted into the ground, making sure that they were not inverted. The top of each core was approximately 5 cm below the soil surface.

Sampling

A "Week 0" initial sampling was collected on installation of litterbags and cores into the field on 5 May 2015. Litterbags and intact root cores that were part of the Week 0 sampling were taken to the field during installation, placed on the ground to simulate installation, and returned to the lab on the same day to adjust for any handling loss that may have occurred through transport or handling of the materials. At each sampling time thereafter, two root cores and two litterbags were collected from each plot and taken back to the laboratory. The biomass in the litterbags was dried in the oven at 40°C until constant weight. After drying, the weight was recorded for each sample, then samples were composited and ground to pass through 1-mm mesh using a Wiley Mill (Standard Model 3, Arthur H. Thomas, Co., Philadelphia, PA). Intact soil-root cores were separated using the washed-soil core method, with cores being mixed with water and poured over a size 16-mesh screen. Roots were then collected from the screen using tweezers and dried in the oven at 40°C. The oven-dry weight was recorded, and then roots were ground to pass through 0.595-mm mesh using a smaller Wiley Mill (Arthur H. Thomas, Co., Philadelphia, PA). All plant samples were analyzed for N, C, and ash content. Samples were analyzed for total N and C using dry combustion (Flash 2000 Elemental Analyzer, Thermo Scientific, Cambridge, UK) and ash content (Isotemp Programmable Muffle Furnace Model 650-126, Fisher Scientific) by loss on ignition (Nelson and Sommers, 1996). Initial (Week 0) plant samples were additionally analyzed for lignin, acid detergent fiber, and neutral detergent fiber. Two cores and two litterbags were collected at 2, 4, 6, 8, 12, and 16 wk. At each sampling event, the corn and soybean growth stage was noted in each plot, as well as percent volumetric water content using a Field Scout soil moisture probe (Field Scout TDR 200 soil moisture probe 64365FS, Spectrum Technologies, Inc., Bridgend, UK).

Plant Root Simulator Probes

To measure plant available soil N, ion resin exchange Plant Root Simulator (PRS) probes (Western Ag, Saskatoon, Canada) were exchanged at two or four week intervals over a period of 18 wk. A set of probes includes one anion and one cation probe. The first set of probes was installed at the time of herbicide burndown at the ARC location on 24 April 2015. Four 10-cm wide by 15-cm deep PVC pipes were installed in each plot, and within each PVC pipe there was one set of N-only PRS probes meaning that they only capture either ammonium or nitrate ions. The PVC pipe was placed in the field to prevent any outside weed or cash crop roots from entering the area of the PRS probes. The pipe was leveled with the soil surface during installation to ensure adequate drainage. Standing water in the pipe area could promote denitrification, and thus, an inaccurate measurement of N. All four sets of probes within each plot were analyzed together to result in one ammonium and nitrate reading per plot. These probes were placed at a distance away from the litterbags and root cores to ensure measurement of N release from only the in situ plot cover crop residue.

Table 2. Oven-dry biomass equivalent (kg ha^{-1}) for the 10 g of air-dry cover crop residue placed in litterbags ("shoots") and the root biomass ("roots") collected from intact root cores for the cover crop decomposition experiment and in situ biomass production and percent N content for the cover crops.

Crop	Plant part	Biomass equivalent			C to N ratio
		kg ha^{-1}	g N kg^{-1}	kg N ha^{-1}	
			Decomposition experiment		
Cereal rye	Shoots	1277	12	14.7	34.7
Cereal rye	Roots	3613	8	30.0	40.3
Hairy vetch	Shoots	2203	42	92.3	9.5
Hairy vetch	Roots	1202	17	19.8	17.3
			In situ cover crops		
Cereal rye	Shoots	578	23	13.5	17.4
Hairy vetch	Shoots	791	27	21.4	15.6

Tea Bag Decomposition

Because a cover crop study was previously established in the field, and the existing plots could not be rearranged, cereal rye and hairy vetch were not in the same crop block as they were rotated each year based on a rotation of corn–cereal rye–soybean–hairy vetch. To identify any decomposition differences across plots, a simplified litterbag experiment was implemented using tetrahedron-shaped synthetic bags filled with tea (Lipton, Unilever). The sides of the bags were 5 cm containing approximately 2 g of either green or black tea (*Camellia sinensis* L.). The mesh size of the bags was 0.25 mm. This tea bag index method was developed to collect uniform decomposition data across ecosystems (Keuskamp et al., 2013) and allows for comparison of decomposition rates between north and south crop blocks. Green and black tea bags were buried pairwise at a depth of approximately 8 cm in each cover crop plot. Over the 16-wk decomposition experiment, tea bags were collected at the same sampling times as the cover crop litterbags and intact root cores, including an initial set of tea bags that were used as initial mass measurements. After retrieval from the field, tea bags were gently washed and oven-dried at 40°C. After drying to constant weight, the tea bags were cut open and the contents weighed to determine mass loss. After weighing, samples were analyzed for ash content. These results help evaluate whether a difference in hairy vetch and cereal rye decomposition rates would be a result of plot location in separate crop blocks of the field or because of plant material itself.

Calculations and Statistical Analysis

Initial hemicellulose content was determined by subtracting acid detergent fiber from neutral detergent fiber and cellulose content was determined by subtracting lignin from acid detergent fiber (Lindsey et al., 2013). Cover crop chemical composition is shown in Table 3. The percentage of ash-free mass remaining (MR, %) and N remaining (NR, %) at any given time (t, wk) was calculated as:

$$\text{MR or NR} = 100 \times (X_t/X_0) \quad [1]$$

where X was the mass or nutrient at each time or week (t), and X_0 was the initial mass or N content at Week 0. Decomposition rates of cover crops over a 16-wk period were derived from the three-parameter single negative exponential model with an asymptote, as in Harmon et al. (2009), by the nonlinear regression function in JMP (JMP Pro v.12; SAS Institute, 2007):

$$\text{MR or NR} = ae^{-kt} + Y_0 \quad [2]$$

where MR or NR is a result of the estimated asymptote (Y_0), the y-intercept (a), and the decomposition constant (k). Decomposition curves for each cover crop (aboveground and belowground) and each type of tea were determined and curves were subjected to an equivalence test. The equivalence test compares decomposition curves and their parameter estimates to a chosen reference curve and calculates a ratio describing the relationship to the reference curve (SAS Institute, 2015). In this case, only two curves were being compared at one time so the cereal rye decomposition curve was chosen as the reference curve. A ratio of ~1 means the curves are practically equivalent. Curves are considered statistically significantly equivalent ($\alpha = 0.05$) if the ratio is between 0.8 and 1.25, meaning the curves can be equivalent as long as any differences between the curves were 25% or less. Soil moisture readings and PRS probe N capture in each cover crop plot were compared at each week throughout the experiment using a t test to compare means of cereal rye and hairy vetch plots per week. All statistical analyses were performed using the JMP statistical analysis package (JMP Pro v.12; SAS Institute, 2007).

RESULTS AND DISCUSSION

Cover Crop Decomposition

Moisture is a key factor in the decomposition process (Robertson and Paul, 2000). However, because there was only 1 wk that the volumetric water content of the soil was significantly higher in cereal rye plots, and this was at Week 12 (Fig. 1) when most decomposition had already happened, it does not seem likely that moisture affected aboveground or belowground decomposition in this study. Soil moisture between the 2-wk sampling points could have varied, and a continuous soil moisture sensor would have provided more detailed measurements. It should be noted that because cover crop residues were placed in separate crop blocks, factors such as micro-climate temperature due to the difference in canopy among cash crops may have affected decomposition rates, though we expect these differences to be relatively small after canopy closure. Parameter estimates for all aboveground and belowground mass loss and N loss are listed in Table 4. The aboveground cover crop mass loss over time data

Table 3. Initial chemical content of plant material before decomposition. Plant parts are cover crop residue ("shoots") and root tissues collected from intact root cores ("roots").

Crop	Plant part	Total C	Total N	C:N	Lignin	Acid detergent fiber	Neutral detergent fiber	Cellulose	Hemicellulose
		g kg^{-1}			g kg^{-1}				
Cereal rye	Shoots	398.6	11.5	34.7	24.1	340.8	611.5	316.7	270.7
Cereal rye	Roots	334.6	8.3	40.3	57.3	534.2	858.1	476.9	323.9
Hairy vetch	Shoots	399.2	41.9	9.5	58.2	289.9	353.6	231.7	63.7
Hairy vetch	Roots	285.6	16.5	17.3	104.1	635.0	778.6	530.9	143.6
Black tea		457.0	35.7	12.8	64.5	181.8	205.1	117.3	23.3
Green tea		452.4	31.6	14.3	39.0	124.5	139.2	85.5	14.7

showed that the estimated parameters of asymptote and decomposition constant were not equivalent (Table 5). The estimated intercepts were equivalent, which would be expected because all initial biomass should be present at Week 0. Therefore, we can conclude that the decomposition rates for cereal rye and hairy vetch were significantly different, as can be observed by their decomposition curves (Fig. 2). It is interesting to note that the asymptotes of the two decomposition curves were not equivalent. This could mean that each type of cover crop had a different amount of labile versus recalcitrant chemical compounds in its biomass (Wider and Lang, 1982; McDaniel et al., 2014).

Many studies suggest that initial C to N ratio and lignin content can be the driver of decomposition rates (e.g., Wider and Lang, 1982; Ibewiro et al., 2000; Lupwayi et al., 2004). For the material used in our litterbags, cereal rye had a higher initial C to N ratio in its aboveground biomass (35:1) than hairy vetch (10:1), and cereal rye decomposition rate was lower (k = 0.1368) than hairy vetch (k = 0.4505). It appears that the C to N ratio may have been a driver in the decomposition rates of our cover crops, but lignin content was not. Higher lignin contents should result in lower k values (slower decomposition), however, in this study cereal rye had lower initial lignin content than hairy vetch (Table 2), but cereal rye had a higher k value. Harre et al. (2014) suggested that for plants not grown to full maturity (i.e., cover crops), lignin content may not be the best predictor of decomposition rates. Nitrogen content has also been found to positively correlate with decomposition rates (Vazquez et al., 2003; Lupwayi et al., 2004), which is related to C to N ratio. Hairy vetch biomass had a higher percentage of N than cereal rye biomass in our study for the material collected for use in the litterbags, but interestingly the in situ cereal rye and hairy vetch N contents were similar. Another indicator of decomposition rates is neutral detergent fiber, with high values of neutral detergent fiber having been shown to result in slower decomposition rates (Cobo et al., 2002; Harre et al., 2014). In our study, cereal rye biomass had higher neutral detergent fiber values than hairy vetch biomass, with cereal rye decomposing slower than hairy vetch.

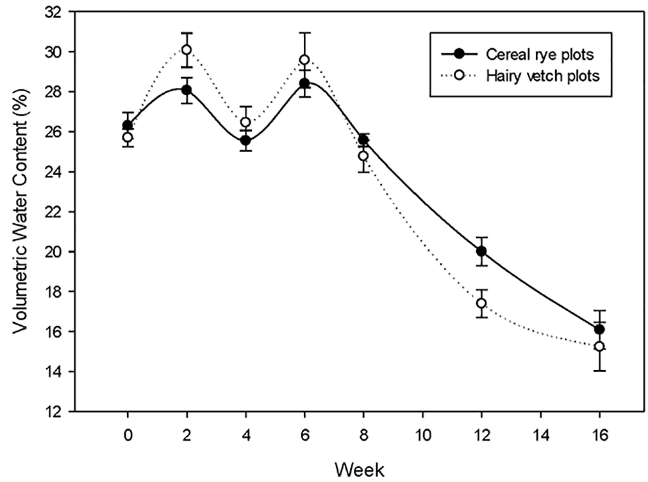

Fig. 1. Volumetric water content in each cover crop plot over the 16 wk of residue decomposition and nutrient release sampling. Cereal rye (South block, soybean) and hairy vetch (North block, corn) plots were significantly different from each other in volumetric water content only at Week 12 (P < 0.0165). Error bars are one standard error of the mean.

Root decomposition from cereal rye and hairy vetch differed for all estimated parameters, which can be observed by their curves (Fig. 2; Supplemental Table S1). Similar to aboveground biomass, the decomposition rate for cereal rye roots (k = 0.1866) was slower than hairy vetch roots (k = 0.6821). Depending on location and additional N applied, hairy vetch

Table 4. Parameter estimates for the asymptotic exponential model used to describe the dry mass loss and N loss of cereal rye, hairy vetch, black tea, and green tea in each cover crop plot over 16 wk of residue decomposition. Plant parts are cover crop residue placed in litterbags ("shoots"), black or green tea, and root tissues collected from intact root cores ("roots").

		Parameter estimates†				
Crop	Plant part	k	a	Y_0	RMSE‡	R^2
			Percentage of mass remaining			
Cereal rye	Shoots	0.1368 a§	85.63 a	10.80 a	4.88	0.9787
Hairy vetch	Shoots	0.4505 b	87.96 b	11.31 a	2.74	0.9952
Cereal rye	Roots	0.1866 a	94.00 a	3.32 a	13.55	0.8928
Hairy vetch	Roots	0.6821 b	90.68 b	8.35 b	8.79	0.9557
Cereal rye	Black tea	0.5047 a	51.50 a	47.99 a	2.22	0.9908
Hairy vetch	Black tea	0.5866 b	53.52 a	46.11 a	2.39	0.9902
Cereal rye	Green tea	0.7061 a	70.66 a	29.07 a	2.79	0.9924
Hairy vetch	Green tea	0.8333 b	70.02 a	29.74 a	4.26	0.9823
			Percentage of nitrogen remaining			
Cereal rye	Shoots	0.0703 a	110.28 a	−15.16 a	8.40	0.9364
Hairy vetch	Shoots	0.6148 b	93.10 b	6.49 b	2.94	0.9951
Cereal rye	Roots	0.1928 a	83.78 a	15.05 a	12.54	0.8866
Hairy vetch	Roots	0.6052 b	87.25 b	11.57 b	8.97	0.9504

† Asymptotic exponential model is XRM = $Y_0 + ae^{-kt}$, where XRM is the percent mass or percent nutrient remaining at time (t), Y_0 is the estimated asymptote, a is the y-intercept, and k is the decomposition constant.

‡ RMSE, root mean square error.

§ Different lowercase letters represent significant differences between cereal rye and hairy vetch parameters (α = 0.05) for each cover crop part based on the equivalence test.

Table 5. Estimated N release and C to N ratio per 2- or 4-wk interval for aboveground ("shoots") and belowground ("roots") hairy vetch and cereal rye cover crops throughout the 16-wk decomposition study.

		Cereal rye				Hairy vetch			
		Nitrogen release			C to N ratio	Nitrogen release			C to N ratio
Date	Week	Shoots	Roots	Shoots + Roots		Shoots	Roots	Shoots + Roots	
		kg N ha^{-1}				kg N ha^{-1}			
5 May	0	0.00	0.00	0.00	35.8	0.00	0.00	0.00	9.7
19 May	2	3.59	11.35	14.94	34.4	58.16	14.00	72.16	12.4
2 June	4	1.59	−3.55	−1.96	34.5	11.39	−0.97	10.42	14.2
16 June	6	−0.15	12.18	12.03	28.8	5.40	4.56	9.96	15.7
30 June	8	0.92	2.27	3.19	20.7	2.57	−0.06	2.51	14.5
28 July	12	4.31	0.25	4.56	21.1	3.49	0.03	3.52	15.5
25 August	16	0.29	1.22	1.51	18.7	−0.27	0.91	0.64	16.3
Total loss		10.55	23.72	34.27		80.74	18.47	99.21	

roots decomposed (k = 0.43–0.69) at similar rates in Jani et al. (2016). Decomposition rates for belowground biomass were faster than each crop's respective aboveground biomass likely due to greater contact with soil microorganisms (Kurka et al., 2000; Dornbush et al., 2002). The root mass remaining at each time interval did not follow the typical decomposition curve as seen in aboveground biomass. Hairy vetch root-mass loss dropped rapidly from Week 0 to Week 2, similar to aboveground mass loss, but Week 4 showed an increase in mass remaining for both cover crops. Jani et al. (2016) also saw an increase in root mass remaining for hairy vetch roots buried in litterbags at their Goldsboro site, except this was around Week 8. The initial rapid loss of mass during the first 4 wk was following by a bump in mass remaining at Week 8 and then an increase in decomposition again for the remaining weeks. This was attributed to greater microbial activity. However, the bump in mass remaining at Week 8 specifically was not addressed. Our results could be due to the inherent variability in root biomass of the cores as root ingrowth was excluded. Collection and utilization of additional root cores could have reduced the variability of root biomass in each treatment. Similar to aboveground decomposition, cereal rye roots had a much more gradual decomposition curve likely due to a higher initial C to N ratio of cereal rye roots (40:1) compared with the roots of hairy vetch (17:1), rather than initial lignin content (Ostertag and Hobbie, 1999; Silver and Miya, 2001).

Cover Crop Nitrogen Release

Nitrogen release curves for aboveground cereal rye and hairy vetch (Fig. 3; Supplemental Table S1) differed in asymptote, intercept, and the decomposition constant (Table 4). Nitrogen release curves for belowground cereal rye and hairy vetch also differed in asymptote, intercept, and decomposition constant. Cumulative N release over the 16-wk period for each cover crop showed that hairy vetch released more N at a faster rate than cereal rye (Fig. 4; Table 5). Total (aboveground + belowground) estimated N release over the decomposition period was 99.21 kg N ha^{-1} from hairy vetch and 34.27 kg N ha^{-1} from cereal rye. Most of the N loss (72.16 kg N ha^{-1}) for hairy vetch was estimated to have been lost between Week 0 and Week 2. However, cereal rye appeared to immobilize N initially because estimated N release at Week 4 was negative (−1.96 kg N ha^{-1}). These results are supported in Poffenbarger et al. (2015), which illustrated that most N was released from hairy vetch residue

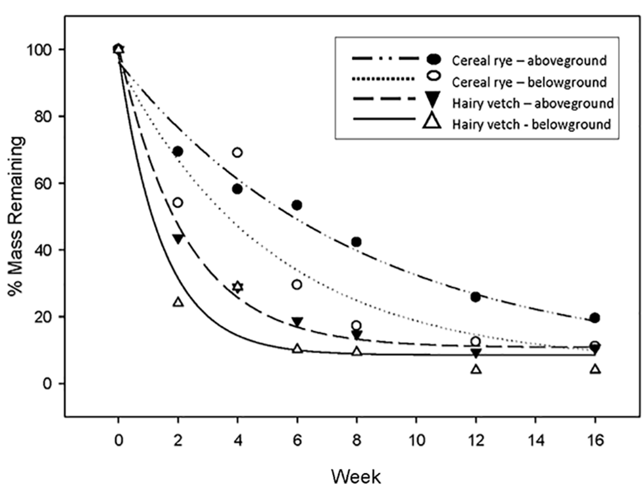

Fig. 2. Percentage of mass remaining for aboveground and belowground plant material for cereal rye and hairy vetch over 16 wk of decomposition.

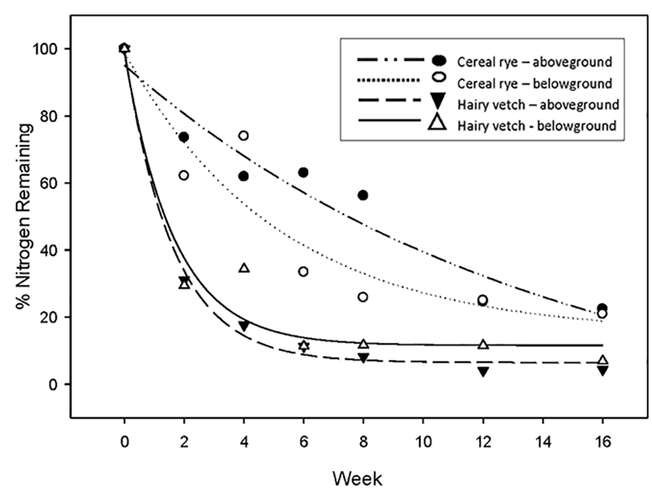

Fig. 3. Percentage of nitrogen remaining in aboveground and belowground cereal rye and hairy vetch cover crops throughout 16 wk of residue decomposition.

in the first 4 wk, while cereal rye residue released N slowly and even immobilized N. Nitrogen release from our cover crops is likely related to initial N content. Hairy vetch aboveground (4.19%) and belowground (1.65%) biomass had higher initial N contents compared with cereal rye aboveground (1.15%) and belowground (0.83%) biomass. These were similar to N contents found in grazing vetch (4%; *Vicia dasycarpa* L.) and oats (0.9%; *Avena sativa* L.) in South Africa (Murungu et al., 2011b), where grazing vetch (a legume) mineralized N at a higher rate than oats (a non-legume). In another decomposition study, black oats (*Avena strigosa* Schreb) residue immobilized N as opposed to rapid mineralization of hairy vetch residues (Ferreira et al., 2014).

Higher initial neutral detergent fiber and hemicellulose contents in cereal rye appeared to be related to its slower N release rate compared with hairy vetch, as has been seen previously with weed residue N release (Harre et al., 2014). However, lignin, acid detergent fiber, and cellulose initial content did not appear to be significant predictors of N release, as was the case in Harre et al. (2014). Cereal rye in our study had a much higher initial C to N ratio in its shoots (35:1) and roots (40:1) compared with hairy vetch shoots (10:1) and roots (17:1), which can be negatively correlated to N-release rate (Cobo et al., 2002; Lindsey et al., 2013). In Rosecrance et al. (2000), prior to cover crop kill, significantly less N was leached into the soil from rye and rye-vetch mixtures compared with vetch in a packed soil core experiment. After kill, substantially more N was leached from vetch cores, and rye and rye–vetch mixtures had even lower amounts of N leached than the fallow treatment due to immobilization of N in the rye litter. Low initial N content and possible N immobilization in our study at Week 4 may explain why cereal rye released N more slowly and steadily, while hairy vetch had a steep initial drop in N within the first month.

At Week 4, there was an increase in percent N content in cereal rye and hairy vetch roots. In Luna-Orea et al. (1996), N increases in the biomass of *Desmodium adscendens* (Sw.) DC. and *Pueraria phaseoloides* (Roxb.) Benth. tropical legume cover crops were attributed to retention of N in the microbial biomass on the plant residue. However, since there was an increase in the percentage of mass remaining also at Week 4 in our study, which was likely a reflection of variability in the intact root cores, the increase in percent N remaining is likely a reflection of the higher percentage of mass remaining at the time period, and not the result of increased microbial biomass retaining N. However, total N release from hairy vetch roots was faster (k = 0.6052) than hairy vetch roots in a cover crop termination study (k = 0.35–0.55) discussed in Jani et al. (2016).

Maximum N uptake of corn typically occurs between the V9 and V18 vegetative growth stages (Scharf and Lory, 2006). A common practice when applying split applications of N to corn in Illinois is to “sidedress” fertilize around V6. The corn crop at the ARC was at the V6 to V7 growth stage around Week 8 (3 June) of the decomposition study. It would be ideal to synchronize the bulk of cover crop N release around this time period to reduce

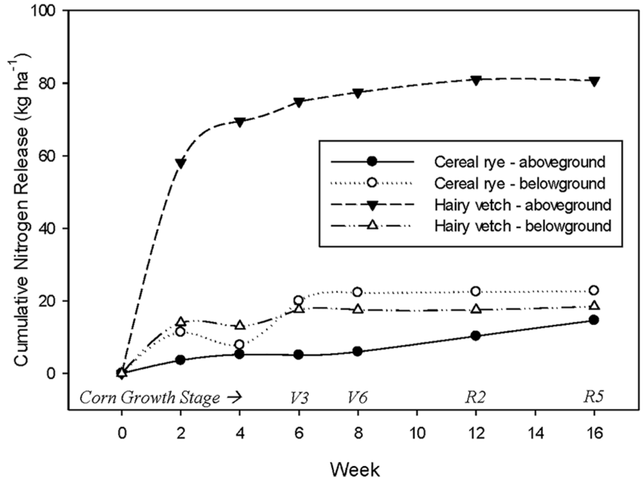

Fig. 4. Estimated cumulative nitrogen release of cereal rye and hairy vetch residue over 16 wk of decomposition with corn growth stages.

off-site N loss and better utilize captured N to reduce fertilizer N input levels. During our study, the peak N release for hairy vetch residues occurred between Week 0 and Week 4 (Table 5). Following the same aboveground estimated N loss as the decomposition experiment, the in situ hairy vetch would have only released 18 kg N ha^{-1} between Week 0 and Week 4 versus the hairy vetch litterbags which released the equivalent of 70 kg ha^{-1} between Week 0 and 4. This is assuming that percent N remaining in the in situ cover crop biomass would follow the same trend as the litterbag experiment biomass. The in situ cereal rye would have released 5 kg N ha^{-1} between Week 0 and Week 4, and similarly cereal rye litter was estimated to have released 5 kg N ha^{-1} in the first 4 wk. These estimates were calculated to illustrate the difference between in situ cover crops and cover crop litter in the decomposition experiment, as well as to illustrate how nutrient release may vary dependent on initial nutrient content. Nutrient release and uptake may have been better synchronized if cover crop termination had been closer to corn planting. Hairy vetch was terminated 17 April, and corn was planted 2 mo later due to weather delays, leading to asynchrony. A cover crop with a slower N release may be beneficial in years when cash crop planting occurs later than initially planned. It should be noted that some cover crop N will remain unavailable in the soil for the initial cash crop. Cash crops have previously been found to recover 30 to 50% of fertilizer N applied compared with <25 to 30% of the N from leguminous material (Crew and Peoples, 2005). A better understanding of cover crop nutrient release and cash crop uptake will be required to optimize crop synchrony. Future research could investigate multiple cover crops, varying plant growth stages, or even simulation of different termination timings and methods to better synchronize cover crop nutrient release with cash crop uptake.

Plant Root Simulator Nitrogen Release

Ammonium and nitrate concentrations captured by the PRS probes showed N release from the in situ cover crops (Fig. 5). Total N was approximately 99% NO_3–N while ammonium concentrations were often below the detection limit, therefore total N levels are reported rather than reporting both NO_3–N and NH_4–N separately. Total N levels captured by the PRS probes were the same for hairy vetch and cereal rye plots at Week 0 ($P = 0.8235$) and Week 16 ($P = 0.8464$). Cereal rye total N capture was fairly consistent throughout the entire time period, while N capture in the hairy vetch plots continued to climb until a spike at Week 12 (coinciding with corn stage R1-R2), before rapidly falling at Week 16, which coincided with the reproductive plant stage of R5 for both corn and soybean. Probes in hairy vetch plots captured significantly more N than probes in cereal rye plots at Week 2, Week 4, Week 6, Week 8, and Week 12, coinciding with litterbag N-release results. Since in situ aboveground biomass production of hairy vetch was similar to cereal rye ($P < 0.0001$), higher PRS probe N in hairy vetch is likely due to cereal rye residue immobilizing N initially or releasing N at a slower rate than hairy vetch residues. Rosecrance et al. (2000) also illustrated N immobilization by rye and substantial N release from hairy vetch residues in their packed core experiment. Additionally, the spike at Week 12 was likely due to the fertilizer N (32% urea ammonium nitrate at 168 kg N ha^{-1}) applied at Week 8 in hairy vetch plots (which proceeded corn). Cereal rye plots were planted before soybean, which is not typically fertilized with N in Illinois.

Tea Decomposition

Black tea in cereal rye plots and black tea in hairy vetch plots had similar decomposition curves (Fig. 6) and decomposition constants (Table 3), supporting our assumption that treatment plots had similar edaphic conditions affecting decomposition. Green tea followed a similar pattern. Though the curves appear very similar within each tea type (Fig. 6), it appears that the tea in the hairy vetch plots had a slightly higher decomposition rate compared with tea in cereal rye plots. This could indicate that decomposition rates of the hairy vetch cover crop may be overestimated compared with cereal rye. Slight differences may have been due to crop rotation effects which may influence microbial populations (McDaniel et al., 2014) or soil temperature (Robertson and Paul, 2000). It could be possible that higher N availability in hairy vetch plots may have affected decomposition rates of tea, causing faster decomposition due to higher N availability (Vazquez et al., 2003). However, in Jani et al. (2016), root decomposition and N release for hairy vetch, pea (*Pisum sativuum*), and clover (*Trifolium incarnatum*) was not affected by soil inorganic N levels, but it was assumed that decomposition rates were affected by possible increased microbial populations in vetch plots versus non-cover cropped plots.

CONCLUSIONS

In general, decomposition of hairy vetch and cereal rye residues were different when evaluated by the percentages of dry mass remaining and N remaining. Cereal rye residues were slower to decompose and released N more gradually. Hairy vetch rapidly decomposed and released N within the first 2 wk, but tended to slow down in decomposition and nutrient release from Week 4 (early June) to Week 16 (late August). The reasons for this are likely due to initial crop C to N ratios and initial N content. Greater understanding of cover crop decomposition will allow growers to better synchronize cash crop uptake with cover crop N release. Depending on management goals, a grower may be able to utilize certain cover crops based on the timing of their N needs. A cover crop like cereal rye would be beneficial before a crop with low N needs based on its slow decomposing residues and slower release of N. However, a cover crop like hairy vetch will contain more N its biomass and have the ability to release a larger amount of N than cereal rye more quickly. The disadvantage of a cover crop like hairy vetch is that most if its N is released in the first 2 wk after termination, and therefore that N could be lost due to leaching or denitrification if the cash crop is not planted in a timely manner or able to reach a growth stage to take up this N.

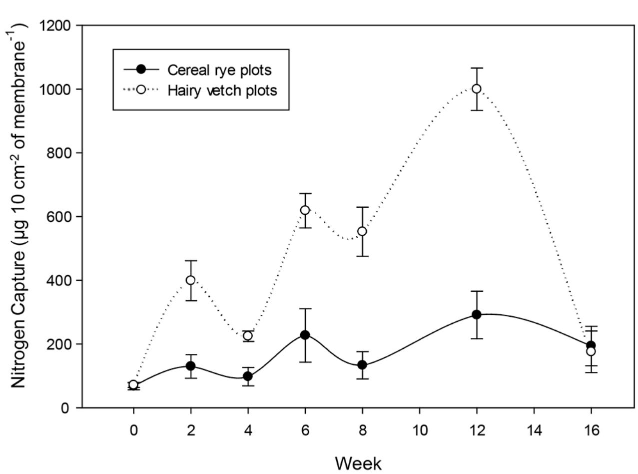

Fig. 5. Plant Root Simulator probe nitrogen capture over 16 wk of residue decomposition. Error bars are one standard error of the mean. Nitrogen capture in cereal rye plots versus hairy vetch plots was significantly different at Week 2 ($P = 0.101$), Week 4 ($P = 0.0087$), Week 6 ($P = 0.0078$), Week 8 ($P = 0.0032$), and Week 12 ($P = 0.0004$).

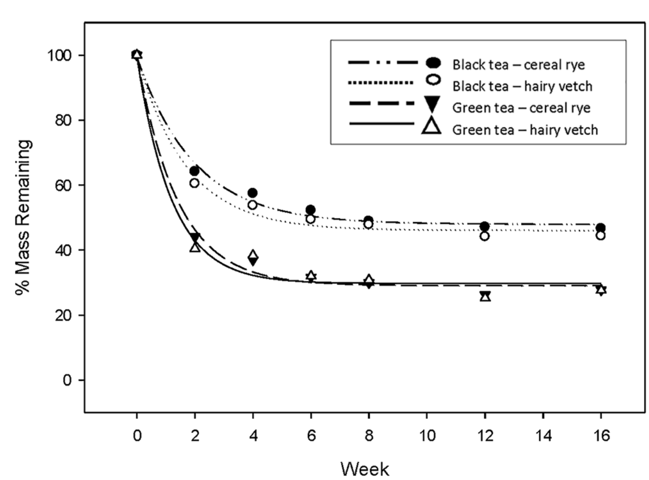

Fig. 6. Black tea and green tea percentage of mass remaining over 16 wk of decomposition in either cereal rye or hairy vetch decomposition plots.

SUPPLEMENTAL MATERIAL

Supplemental material is available with the online version of this article. Supplemental Table S1 contains aboveground and belowground mass and nitrogen data for each week of sampling. Supplemental Fig. S1 is a schematic representation of the experimental layout.

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