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Legume Proportion, Poultry Litter, and Tillage Effects on Cover Crop Decomposition

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ABSTRACT

Cover crop residues and animal waste products can be important sources of N in cropping systems. The objectives of this research were to determine, under field conditions, the effects of hairy vetch (legume; *Vicia villosa* Roth)/cereal rye (grass; *Secale cereale* L.) proportion and pelletized poultry litter (PPL) management (no PPL, subsurface banded, broadcast, or incorporated with tillage) on the extent and rate of cover crop residue mass loss and N release during a subsequent growing season. Measuring cover crop residues placed in mesh litter bags, or residues+PPL in litter bags for the broadcast treatment, we found that increasing hairy vetch proportion led to greater proportional mass loss and N release (cumulative mass loss ranged from 40 to 80% and N release ranged from 0–90% of initial), as well as greater rates of mass loss in all PPL treatments. Nitrogen release rates were generally unaffected by species proportions; however, N release rates for pure cereal rye residue in all PPL treatments except broadcast could not be estimated due to minimal N release. Incorporation of residues and PPL increased the rates of mass loss and N release for pure hairy vetch and hairy vetch–cereal rye mixtures. Although broadcast PPL application and incorporation affected decomposition patterns, subsurface banded PPL application did not. Results suggest that cereal rye provides the greatest mulch persistence, hairy vetch provides the greatest N release, and mixtures provide moderate delivery of these two services. Subsurface banding is the recommended PPL application method to conserve surface residues.

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Cover crops can play an important role in mediating N retention and supply in agroecosystems. Small-grain cover crops, such as cereal rye, take up residual soil mineral N in the fall, winter, and spring when it would otherwise be susceptible to leaching (Meisinger et al., 1991; Shipley et al., 1992; Staver and Brinsfield, 1993). Winter annual legumes, such as hairy vetch, are less effective N scavengers than grasses but fix atmospheric N_2 and release biologically fixed N during decomposition, which can reduce fertilizer N requirements for crops the following season (Decker et al., 1994; Stute and Posner, 1995; Clark et al., 1997a). Mixtures of cereal rye and hairy vetch offer the potential to provide both N scavenging during the fall, winter, and spring, and N release during the following summer.

Efficient N delivery from a legume cover crop requires synchrony between N release and crop demand. In the case of corn (*Zea mays* L.), some plant-available nitrogen (PAN) is required at planting, but the majority of N uptake begins at the six-leaf stage (Abendroth et al., 2011). If mineral N is released from cover crops too early or too late, it can be lost by leaching or denitrification (Crews and Peoples, 2005). Hairy vetch can generally provide between 50 and 150 kg PAN ha^{-1} during the subsequent growing season, an amount which typically meets some, but not all, of a corn crop's N requirements (Ebelhar et al., 1984; Clark et al., 1997a; Cook et al., 2010). Nitrogen from hairy vetch is released rapidly during decomposition, particularly when hairy vetch is incorporated with tillage, making N susceptible to early-season losses (Varco et al., 1993; Rosecrance et al., 2000; Sarrantonio, 2003). Mixing cereal rye with hairy vetch may provide better synchrony of N release for crop demand because cereal rye has a higher C/N ratio than hairy vetch, which results in a slower rate of N release (Ranells and Wagger, 1996). Previous studies evaluating the mass loss and/or N release of hairy vetch–grass mixtures in the field have considered only one or two mixture proportions of residue left on the soil surface (Ranells and Wagger, 1996; Ruffo and Bollero, 2003; Starovoytov et al., 2010). However, to optimize

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Abbreviations: GDD, growing degree day; PAN, plant-available nitrogen; PPL, pelletized poultry litter.

cover crop management for N use efficiency, a greater range of hairy vetch/cereal rye mixture proportions under both till and no-till systems must be evaluated.

Recent research has been directed toward developing cover crop-based no-till grain production systems, which use mechanical termination of mature cover crops by a roller/crimper to form a thick unidirectional mulch (Reberg-Horton et al., 2012; Mirsky et al., 2012; Teasdale et al., 2012). This mulch provides water conservation (Teasdale and Mohler, 1993; Clark et al., 1997b) and weed control (Teasdale and Daughtry, 1993; Smith et al., 2011) during the season immediately following cover crop termination. It has been observed that the time of cover crop termination can affect the decomposition of hairy vetch and cereal rye due to changes in residue quality with increasing maturity (Wagger, 1989a). However, studies on hairy vetch and cereal rye decomposition have generally been initiated in mid-April to early May, when cover crops can be killed by herbicides or tillage, but are usually not mature enough for mechanical termination (Stute and Posner, 1995; Ranells and Wagger, 1996; Ruffo and Bollero, 2003).

Even though additional N is often needed to supplement legume N in a corn growing season, little research has been conducted on the interactive effects of animal and green manures on cover crop decomposition. Mineral N additions often have a stimulatory effect on decomposition of litter <2-yr old, although they can also inhibit decomposition, particularly once easily-decomposable compounds have been used by microbes and decomposition becomes regulated by lignin (Knorr et al., 2005). Poultry litter is a widely available organic waste product in the mid-Atlantic United States and other locations with poultry production, and contains 30 to 40 kg total N Mg^{-1} of fresh material (Robinson and Sharpley, 1995). In conventional tillage systems, this product is usually incorporated, but in no-till systems, it is generally broadcast-applied before corn planting. These application methods deliver N in close proximity to decomposing cover crop residue, which may increase the extent and/or rate of cover crop mass loss if decomposition is limited by N availability. Recent developments in subsurface banding technology may soon provide farmers the option of localized subsurface application of dry animal waste products in no-till cropping systems, a practice that significantly reduces NH_3 volatilization and nutrient run-off losses relative to broadcast application (Pote et al., 2011). The delivery of poultry litter N below the soil surface may reduce the potential stimulatory effect of added N on decomposition of surface residue, providing greater mulch persistence throughout the corn growing season.

The objectives of this research were to determine, under field conditions, the effects of hairy vetch/cereal rye proportion and PPL management (no PPL, subsurface banded, broadcast, or incorporated with tillage) on the extent and rate of cover crop residue mass loss and N release during a subsequent growing season. This study is the first, to our knowledge, to quantify the interactive effects of hairy vetch/cereal rye proportion and PPL management on decomposition patterns in a field setting.

MATERIALS AND METHODS

Site Description

A field experiment was conducted at the Beltsville Agricultural Research Center in 2011–2012 and in 2012–2013. The 2011–2012 experiment was performed on the North Farm (39.03 N, 76.93 W), which has been managed organically since 2000 and certified by the Maryland Department of Agriculture according to National Organic Program requirements since 2003. The 2012–2013 experiment was performed on the South Farm (39.02 N, 76.94 W), which follows a similar crop rotation as the North Farm, but receives mineral fertilizers and herbicides. Soils on the North Farm are classified as fine-loamy, mixed, mesic Typic Endoaquults (Hatboro series); soils on the South Farm are classified as fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts (Codorus series).

Experimental Design and Field Management

The field experiment consisted of five hairy vetch/cereal rye sown proportions: 0:100, 20:80, 60:40, 80:20, and 100:0 planted in the fall of 2011 and 2012. The monoculture hairy vetch and cereal rye seeding rates were 34 and 168 kg ha^{-1}, respectively, and the mixture sown proportions represented proportions of each species' monoculture seeding rate. Dates of cover crop planting and other field operations are presented in Table 1. Additional details pertaining to cover crop planting and information about previous field management are provided in Poffenbarger et al. (2015).

Pelletized poultry litter treatments were laid out in strips perpendicular to cover crop sown proportions in the spring of 2012 and 2013, forming a split-block design with three replicate blocks each year. Each cover crop sown proportion × PPL treatment × block formed a field plot. The PPL treatments included two traditional application methods–broadcast PPL (broadcast) and broadcast PPL with incorporation (incorporated) at planting, sidedressed subsurface banded PPL (subsurface banded), and a no PPL control (no PPL). The PPL treatments were all applied at a P-based rate of 3.6 Mg PPL ha^{-1} in 2012 (moisture

Table 1. Dates of field operations for the cover crop decomposition study.

	2011–2012					2012–2013				
PPL treatment†	Cover crop planting	Cover crop termination	Corn planting	PPL application	Corn harvest‡	Cover crop planting	Cover crop termination	Corn planting	PPL application	Corn harvest‡
No PPL	7 Oct.	17 May	17 May	None	14 Sept.	25 Sept.	22 May	22 May	None	18 Sept.
Subsurface banded	7 Oct.	17 May	17 May	3 July	14 Sept.	25 Sept.	22 May	22 May	25 June	18 Sept.
Broadcast	7 Oct.	17 May	17 May	17 May	14 Sept.	25 Sept.	22 May	22 May	22 May	18 Sept.
Incorporated	7 Oct.	8 May	17 May	17 May	14 Sept.	25 Sept.	16 May	22 May	22 May	18 Sept.

† PPL = Pelletized poultry litter.

‡ Plots were harvested by hand at physiological maturity.

content = 10.7% of fresh weight) and 3.4 Mg PPL ha^{-1} in 2013 (moisture content = 13.8% of fresh weight), except the no PPL treatment. These rates corresponded to 67 kg PAN ha^{-1}, assuming 50% mineralization of organic N during the corn growing season and that 90% of PPL NH_4^+–N was plant available (University of Maryland Extension, 2009, 2011).

Cover crops were terminated using a roller/crimper (I &J Manufacturing, Gap, PA) in the no-till plots (i.e., no PPL, subsurface banded, and broadcast treatments). In 2012, hairy vetch was in full flower and cereal rye was in the soft dough stage at the time of rolling; in 2013 hairy vetch was 50% flowering and cereal rye was in the milk stage. In the incorporated treatment, cover crops were flail-mowed and disked 6 or 9 d before rolling of the no-till plots (Table 1). Pelletized poultry litter (Perdue Agricycle, LLC, Seaford, DE) was broadcast just before corn planting in the incorporated treatment using a Stoltzfus fertilizer spreader (W-Chain Sower spreader, Morgantown, PA), and hand applied just after planting in the broadcast treatment. The incorporated treatment was power spaded (Imants 27sx, Reusel, the Netherlands) to 20 cm and cultimulched after PPL application and just before planting. Corn (Blue River 53R57 104d in 2012, TA522-22DP 105d in 2013) was planted for the no-till and incorporated treatments on the same day that the cover crops of the no-till plots were rolled. All PPL treatments received PPL starter fertilizer at ~10 kg PAN ha^{-1}. In the subsurface banded treatment, PPL was sidedressed at the same rate as the broadcast and incorporated treatments using a custom-fabricated prototype subsurface banding applicator (Fig. 1) at the eight-leaf growth stage in 2012 and at the five-leaf growth stage in 2013. In 2012, weed control was accomplished through high-residue cultivation for the no-till plots and a combination of blind cultivation and between-row cultivation for the incorporated plots. In 2013, Round-up {glyphosate [*N*-(phosphonomethyl)glycine]; Monsanto, St. Louis, MO} was applied twice after corn planting, at a rate of 2.8 kg a.i. ha^{-1} for each application. North Farm was irrigated with 2.5 cm on 5 July 2012; South Farm received 4.0 cm at each of three irrigation events (27 June, 29 July, and 8 Sept. 2013).

Litter Bag Methods

We used nylon mesh "litter bags" (0.30 by 0.30 m dimensions, 1-mm mesh size) filled with fresh cover crop residues, or fresh cover crop residues+PPL for the broadcast treatment, placed in the field, and collected over time, to study cover crop decomposition. To determine the dry weights and corresponding fresh weights of each species to place in the litter bags, we collected at least two 0.50 by 0.50 m aboveground biomass samples from each cover crop sown proportion 5 d before mowing the incorporated plots. The samples were weighed fresh and then dried at 60°C for 4 d to determine dry mass and moisture content. The targeted total dry biomass levels, based on average field cover crop biomass, were 8.0 Mg ha^{-1} in 2012 and 9.0 Mg ha^{-1} in 2013. The targeted hairy vetch/cereal rye dry biomass proportions for the litter bags were: 0:100, 25:75, 50:50, 75:25, and 100:0, approximately corresponding to the five cover crop sown proportions in the field experiment. Cover crop biomass and N content data for each sown proportion are reported in Poffenbarger et al. (2015).

To prepare litter bags for the incorporated treatment, we first harvested non-decomposing hairy vetch and cereal rye material from experimental border areas just before mowing the

Fig. 1. Prototype subsurface banding applicator used to sidedress pelletized poultry litter.

incorporated plots. For each litter bag, fresh material was cut to 10 cm lengths (the approximate length of flail-mowed residues), weighed to obtain the appropriate biomass proportion and total mass, mixed, and placed in the bag. Eighteen litter bags were prepared for each cover crop biomass proportion, providing three replicate sets of six litter bags. Each set, which included one bag for each of six sampling times, was placed in the plot with the corresponding cover crop sown proportion and block identification. The litter bags were buried immediately after mowing and disking the incorporated plots. A burial depth of 20 cm was used so that the litter bags were within the depth of cover crop incorporation by disking, but below the depth of the interrow cultivator. The buried litter bags were removed during spading and immediately re-buried. Note that we did not include PPL in the litter bags for the incorporated treatment because we assumed that the PPL N was evenly distributed in the soil surrounding the bags after incorporation, and that soluble N from the PPL could move with the soil solution into the litter bags.

Litter bags for the no-till plots were prepared in the same way using freshly collected plant material just before rolling, only the material was cut to 25 cm to lay flat in the bag. Litter bags in the broadcast PPL treatment received PPL within the bag at the same rate as applied to the larger plots to mimic the interaction that would occur between the residues left on the soil surface and PPL broadcast on top of them, and to ensure that all bags were exposed to an equal amount of PPL. For the subsurface banded treatment, residues on the soil surface did not directly interact with PPL because it was delivered below the soil surface, so PPL was not included in the litter bags for this treatment. Immediately after corn planting, residue was removed from a 0.30 by 1.8 m section of each of the no-till plots, and six bags were pinned directly against the soil surface in this bare area. During broadcast PPL application, the litter bags within the broadcast treatment were covered so that they would not receive the PPL amendment in addition to what was already contained within the bags. The litter bags remained in place throughout the season, except when they were temporarily removed during subsurface banding of PPL and high-residue cultivation.

Soil temperature and moisture sensors logged hourly readings in a representative subset of plots (0:100, 60:40, and 100:0 hairy vetch/cereal rye sown proportions at 20-cm depth in the incorporated treatment and at 5-cm depth in the subsurface banded treatment) from the time of corn planting through corn maturity (Decagon, 5TE soil moisture, temperature, EC sensors, Pullman, WA). Hourly temperature readings were also collected from sensors placed on the soil surface just under the mulches and adjacent to the litter bags in the 0:100, 60:40, and 100:0 hairy vetch/cereal rye sown proportions for all of the no-till PPL treatments (Onset, StowAway Tidbit temperature data logger, Cape Cod, MA).

One litter bag was collected from each plot at each of six sampling times, corresponding approximately to: cover crop termination, corn emergence, corn three-leaf stage, eight-leaf stage, silking and physiological maturity. The litter bag contents were oven-dried, weighed, and ground to pass a 1-mm sieve. The ground litter bag contents were analyzed for C and N concentrations by dry combustion analysis (Leco CHN analyzer, St. Joseph, MI). Soil contamination was accounted for by ashing a 1-g subsample at 500°C for 4 h and adjusting dry matter and C and N contents to an ash-free basis.

Calculations and Statistics

Initial Litter Bag Properties

The effects of targeted cover crop biomass proportion, PPL treatment, and their interaction on litter bag initial total biomass and initial C and N concentrations were evaluated using analysis of variance. Linear mixed models were constructed separately for each year using the lme function in R package nlme (Pinheiro et al., 2014; R Core Team, 2014); block was a random effect. Residue N concentrations were log-transformed to meet the homogeneity of variance assumption (means and 95% confidence intervals were back-transformed for presentation). Means were computed using the lsmeans function in R (Lenth, 2014), and multiple comparisons were made using the glht function (package multcomp; Hothorn et al., 2008).

Exponential Decay Models

The proportions of mass and N remaining for each cover crop biomass proportion and PPL treatment were modeled over growing degree days (GDD), calculated by summing the mean daily temperatures above 0°C (Honeycutt et al., 1988). The GDD for the incorporated litter bags were calculated using average daily soil temperatures at 20-cm depth in the incorporated PPL treatment, and the GDD for the no-till treatments were calculated using average daily temperatures measured under the cover crop mulches. Since temperatures were only logged in the 0:100, 60:40, and 100:0 hairy vetch/cereal rye sown proportions, the GDD for the 60:40 sown proportion were assumed to be representative of all mixture sown proportions within each of the PPL treatments.

A two-component asymptotic exponential decay function was used to model proportion of mass and N remaining over GDD. The first component represents readily decomposable compounds that disappear rapidly, and the second represents resistant compounds:

$$P(t) = P\exp^{-kt} + (1 - P) \quad [1]$$

where $P(t)$ is the proportion of mass or N remaining at a given time, (in units of GDD), P is the proportion of the initial mass or N content that decomposes at rate k (i.e., the decay constant), and $(1 - P)$ is the proportion of initial mass or N content that is resistant to further decay. Model fitting was done separately for each cover crop biomass proportion × PPL treatment × year using the nlme function in R. A random block effect on the decay constant was included in the models. Estimates for P and k, coefficients of determination (R^2), and root mean square errors for exponential decay models are presented in Supplements 1 and 2.

Relationships between Experimental Factors and the Extent and Rate of Decomposition

The cumulative proportional mass loss and mass and N decay constants were analyzed using linear regression that included the effects of initial cover crop biomass proportion, PPL treatment, year, and their interactions. We used the difference between the proportion of mass and N remaining at corn maturity and one, the proportion present at cover crop termination, rather than P estimated from model fitting, to provide a better estimate of "cumulative" proportional loss for a single corn growing season. Initial residue total ash-free dry mass was not included as a covariate in the model due to its lack of significance in a preliminary analysis. Quadratic terms for cover crop biomass proportion were included in the models as needed. Interactions between year and other factors were included as random effects in the models if the term was significant when tested as a fixed effect. Linear mixed effects model fitting was performed using the lmer function in R package lme4 (Bates et al., 2013).

The cumulative proportional nitrogen release (N_p) was modeled using a rectangular hyperbolic model, which provided a better fit to the data than a linear model based on root mean square errors:

$$N_p = N_r + [sva/(a + sv)] \quad [2]$$

Table 2. Monthly mean temperature and cumulative precipitation, including irrigation, in 2012 and 2013 corn growing seasons. Thirty-year average monthly temperatures and rainfall totals (1980–2010) are also presented.

Month	Mean temperature			Precipitation		
	2012	2013	30-yr avg	2012	2013	30-yr avg
	°C			mm		
May	20	17	17	57	71	114
June	23	23	22	66	180	91
July	27	26	24	90	87	94
Aug.	24	23	23	47	57	81
Sept.	20	19	19	51	75	91
Total				311	470	471

where N_r is the y intercept, s is a shape parameter representing the initial slope of the curve, v is the initial hairy vetch/cereal rye biomass proportion, and a is an asymptote parameter. Estimates for N_r, s, and a were made for each PPL treatment within a single full model, and a random year effect on the intercept N_r was included. The rectangular hyperbolic model was fit using the nlme function in R. Contrast statements were used to determine the significance of linear and hyperbolic model parameter estimates and to compare parameter estimates among treatments using the glht function in the R package multcomp (Hothorn et al., 2008).

RESULTS

Environmental Conditions

The 2012 corn growing season had higher temperatures and less rainfall than 30-yr averages for all months (Table 2). The 2013 season was cooler and wetter than 2012, with temperatures and total rainfall largely consistent with 30-yr averages. Approximately 3000 and 2500 GDD accumulated between cover crop termination and corn physiological maturity in 2012 and 2013, respectively (Fig. 2 and 3). Soil volumetric moisture content ranged from 10 to 30% in 2012 and from 18 to 40% in 2013, with more temporal variability at 5-cm depth in the subsurface banded treatment than at 20-cm depth in the incorporated treatment (Fig. 2 and 3). Soil moisture was particularly high during the month of June in 2013.

Initial Litter Bag Properties

The litter bags contained an average initial ash-free dry mass of 7.3 Mg ha^{-1} in 2012 and 8.4 Mg ha^{-1} in 2013 (Tables 3 and 4). Adding PPL to the litter bags in the broadcast treatment increased the average mass to 9.5 Mg ha^{-1} in 2012 and 10.6 Mg ha^{-1} in 2013. Litter bag initial mass decreased with increasing hairy vetch/cereal rye biomass proportion for all PPL treatments in 2012 ($P < 0.05$). Inconsistency in the total ash-free dry mass among cover crop biomass proportions may have arisen due to slight inaccuracy of moisture content estimates used to determine the fresh mass of hairy vetch and cereal rye to place in each bag. However, statistical models indicated that initial litter bag mass was not a significant source of variation in the extent or rate of cover crop decomposition. Imprecision of moisture content estimates also caused the actual cover crop biomass proportions to deviate slightly from the targeted biomass proportions. Nitrogen concentrations of the litter bag contents increased with increasing hairy vetch/cereal rye biomass proportion in all PPL treatments in both years ($P < 0.05$). The broadcast PPL amendment increased N concentrations of litter bags

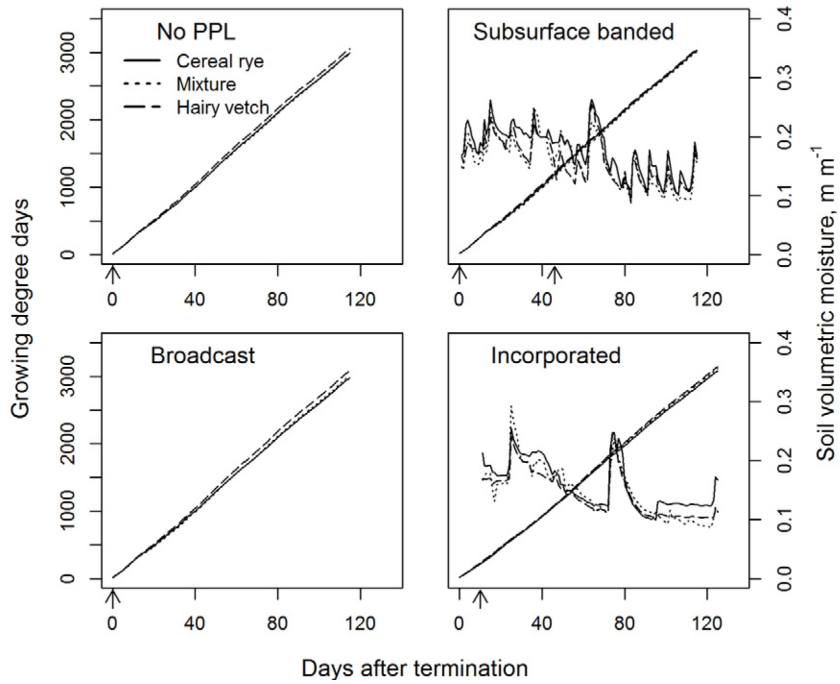

Fig. 2. Cumulative growing degree days (0°C base temperature) and daily soil volumetric moisture content between cover crop termination and corn maturity in 2012. Each line represents the average of three replicates. Moisture and temperature readings for the cover crop mixtures were collected in the 60:40 hairy vetch/cereal rye sown proportion. Moisture readings were collected only in the subsurface banded and incorporated treatments. The first arrow on each x axis marks corn planting; the second x axis arrow on the subsurface banded plot marks sidedress subsurface banded pelletized poultry litter application.

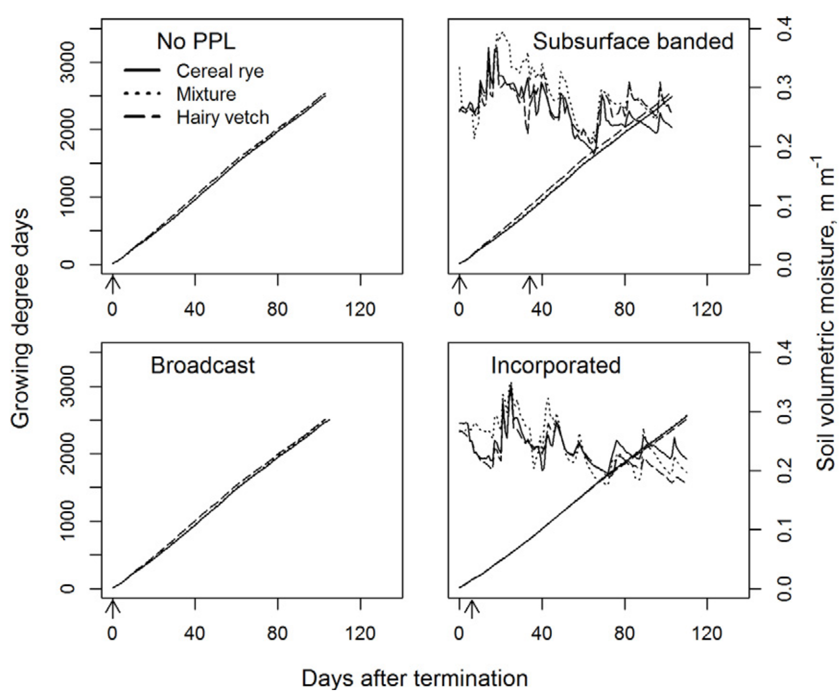

Fig. 3. Cumulative growing degree days (0°C base temperature) and daily soil volumetric moisture content between cover crop termination and corn maturity in 2013. Each line represents the average of three replicates. Moisture and temperature readings for the cover crop mixtures were collected in the 60:40 hairy vetch/cereal rye sown proportion. Moisture readings were collected only in the subsurface banded and incorporated treatments. The first arrow on each x axis marks corn planting; the second x axis arrow on the subsurface banded plot marks sidedress subsurface banded pelletized poultry litter application.

Table 3. Hairy vetch (HV)/cereal rye (CR) biomass proportions, total dry mass, N concentrations, and C concentrations of cover crop residue and pelletized poultry litter (PPL; for broadcast treatment only) placed in litter bags at initiation of the 2012 decomposition study. Total dry mass, N concentrations, and C concentrations are presented on an ash-free basis. Ninety-five percent confidence intervals are shown in parentheses.

HV/CR target	HV/CR actual	Dry mass	N concentration	C concentration
		Mg ha^{-1}	g kg^{-1}	
		No PPL and subsurface banded treatments		
0:100	0:100	8.24 (7.70–8.78)	5.3 (5.0–5.8)	460 (454–465)
25:75	20:80	8.02 (7.48–8.56)	11.8 (11.0–12.8)	460 (454–466)
50:50	42:58	7.54 (7.00–8.08)	21.3 (19.8–23.0)	462 (456–468)
75:25	67:33	6.83 (6.29–7.37)	31.1 (28.9–33.5)	470 (464–476)
100:0	100:0	5.89 (5.35–6.43)	48.2 (44.7–51.9)	471 (465–477)
		Broadcast (includes PPL)		
0:100	0:100	10.56 (9.97–11.15)	13.9 (12.5–15.5)	459 (450–467)
25:75	20:80	10.12 (9.53–10.71)	23.0 (20.7–25.5)	457 (448–465)
50:50	42:58	9.82 (9.23–10.41)	25.5 (22.9–28.3)	465 (456–473)
75:25	67:33	8.92 (8.33–9.51)	37.6 (33.8–41.8)	479 (471–487)
100:0	100:0	8.21 (7.62–8.81)	47.6 (42.8–52.9)	468 (460–476)
		Incorporated		
0:100	0:100	8.54 (7.95–9.13)	5.5 (5.0–6.1)	458 (450–467)
25:75	22:78	8.05 (7.46–8.64)	13.7 (12.3–15.2)	459 (451–468)
50:50	39:61	7.44 (6.85–8.03)	24.0 (21.6–26.7)	461 (453–470)
75:25	64:36	6.82 (6.23–7.41)	35.8 (32.2–39.8)	467 (459–476)
100:0	100:0	5.67 (5.08–6.26)	52.7 (47.4–58.5)	473 (465–481)

containing the 0:100 hairy vetch/cereal rye biomass proportion in 2012 and 2013, and the 25:75 hairy vetch/cereal rye biomass proportion in 2012 ($P < 0.05$). Nitrogen concentrations were slightly, but not significantly, greater in the incorporated litter bags than in the no PPL and subsurface banded litter bags in 2012, and tended to be greater in the no PPL, subsurface banded, and incorporated treatments in 2013 than in 2012.

Exponential Decay Predictions

The exponential decay function provided an excellent fit to the proportion of mass remaining over GDD (all $R^2 > 0.88$, Fig. 4 and 5). The proportion of initial residue mass remaining at any given time decreased with increasing hairy vetch/cereal rye biomass proportion. For example, in 2012, exponential decay models predicted 50% of pure hairy vetch mass remained in the no PPL treatment at 997 GDD (38 d), while predicting 67 and 86% for the 50:50 mixture and the pure cereal rye

Table 4. Hairy vetch (HV)/cereal rye (CR) biomass proportions, total dry mass, N concentrations, and C concentrations of cover crop residue and pelletized poultry litter (PPL; for broadcast treatment only) placed in litter bags at initiation of the 2013 decomposition study. Total dry mass, N concentrations, and C concentrations are presented on an ash-free basis. Ninety-five percent confidence intervals are shown in parentheses.

HV/CR target	HV/CR actual	Dry mass	N concentration	C concentration
		Mg ha^{-1}	g kg^{-1}	
		No PPL and subsurface banded treatments		
0:100	0:100	8.32 (7.80–8.84)	7.5 (6.9–8.2)	456 (450–463)
25:75	25:75	8.35 (7.86–8.84)	17.2 (15.9–18.7)	456 (450–462)
50:50	50:50	8.15 (7.67–8.64)	27.8 (25.7–30.2)	459 (453–465)
75:25	75:25	8.04 (7.56–8.53)	39.7 (36.6–43.0)	461 (455–467)
100:0	100:0	7.67 (7.18–8.15)	50.5 (46.5–54.7)	461 (455–467)
		Broadcast (includes PPL)		
0:100	0:100	10.49 (9.85–11.12)	12.9 (11.5–14.5)	461 (454–468)
25:75	25:75	10.74 (10.10–11.38)	21.4 (19.1–24.0)	460 (453–467)
50:50	50:50	10.77 (10.13–11.41)	29.7 (26.5–33.3)	457 (450–464)
75:25	75:25	10.82 (10.18–11.46)	35.7 (31.9–40.0)	458 (451–465)
100:0	100:0	9.93 (9.29–10.57)	49.7 (44.4–55.7)	464 (456–471)
		Incorporated		
0:100	0:100	9.18 (8.54–9.82)	6.9 (6.2–7.8)	454 (447–461)
25:75	23:77	9.25 (8.61–9.89)	17.1 (15.2–19.1)	459 (452–466)
50:50	47:53	9.03 (8.39–9.66)	25.6 (22.9–28.7)	460 (452–467)
75:25	72:28	8.64 (8.00–9.28)	38.6 (34.5–43.3)	462 (455–469)
100:0	100:0	8.34 (7.70–8.98)	50.3 (44.9–56.3)	466 (459–473)

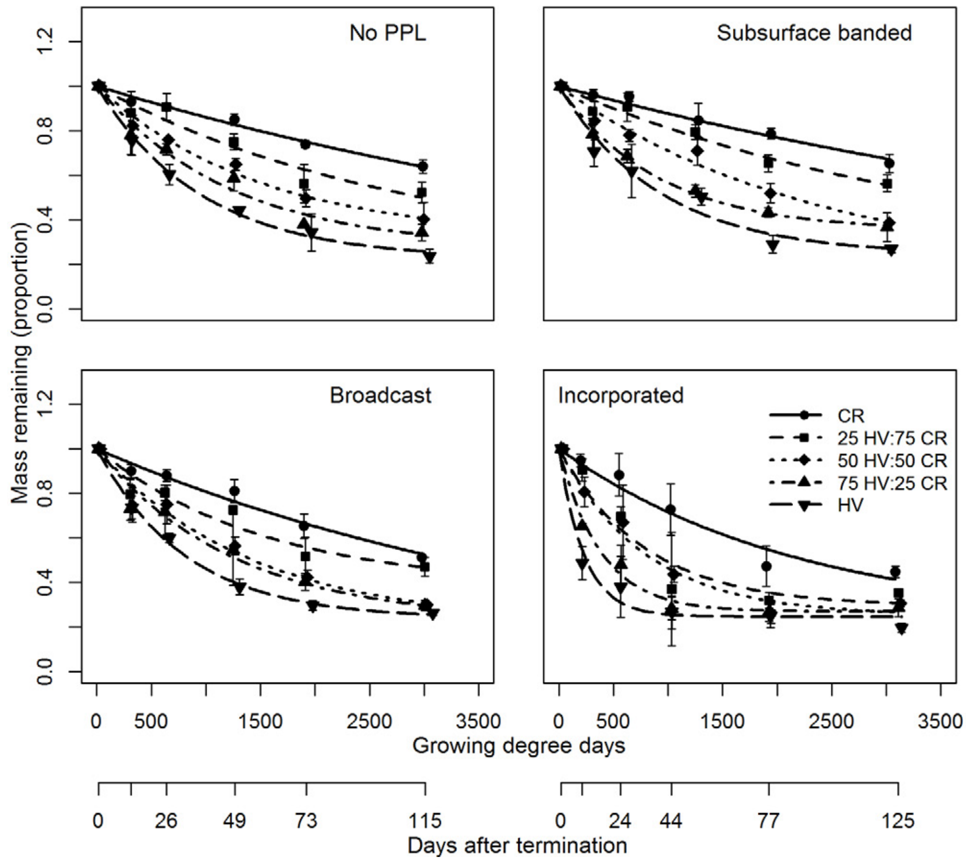

Fig. 4. Proportion of mass remaining in litter bags containing a range of hairy vetch (HV)/cereal rye (CR) biomass proportions and subjected to different pelletized poultry litter (PPL) management during the 2012 corn growing season. Each point represents the mean of three replicates of a particular cover crop biomass proportion and PPL treatment at a given time. Curves are exponential decay models fit to each cover crop biomass proportion within each PPL treatment. Error bars are ± 1 SD. The secondary *x* axis on the bottom left panel shows days after termination that litter bags were collected for the no-till PPL treatments, while the secondary *x* axis on the bottom right panel shows days after termination that litter bags were collected for the incorporated treatment. Noise was added to the *x* coordinates for points and their error bars to avoid excessive overlapping.

mass, respectively (Fig. 4, top left panel). In 2013, a similar pattern was observed, but mass loss proceeded more rapidly overall. The biomass decomposition patterns for the subsurface banded treatment were similar to the no PPL treatments in both years. For litter bags with high cereal rye composition, broadcast PPL application decreased the proportion of mass remaining at any given time relative to the no PPL and subsurface band treatments, resulting in prediction curves that were more similar among cover crop biomass proportions for broadcast than for other treatments (Fig. 4 and 5, bottom left panels). Incorporation of residues and PPL with tillage tended to decrease the mass of cover crop residue remaining relative to the no PPL and subsurface banded treatments for all cover crop biomass proportions, particularly in the first 1000 GDD, except for pure cereal rye in the first 500 GDD of the 2013 season (Fig. 4 and 5, bottom right panels).

Coefficients of determination for the exponential decay function fit to the proportion of N remaining over GDD ranged from 0.63 to 0.99, with 76% of R^2 values at or above 0.90 (Fig. 6 and 7). The exponential decay function was not fit to the proportion of N remaining over GDD in pure cereal rye for the no PPL, subsurface banded, and incorporated treatments because it tended to oscillate around 1.0, rather than decline exponentially. As with the proportion of mass remaining, increasing hairy vetch/cereal rye biomass proportion resulted in a lower proportion of N remaining at any given time during the corn growing season. However, N release proceeded more rapidly than mass loss in both years. For example, it took 1959 GDD (75 d) for the 50:50 mixture in the no PPL treatment to lose half of its mass in 2012, while it took only 642 GDD (26 d) for this mixture to lose half of its N. The early N release in the 2012 and 2013 seasons resulted in a stable level of N remaining by approximately 1500 GDD (57–60 d) in 2012 and 1000 GDD (39–45 d) in 2013. Figures 6 and 7 show that subsurface banded PPL application did not alter N release patterns of the cover crops relative to no PPL. However, the broadcast treatment decreased the proportion of N remaining at any given time in litter bags with high cereal rye composition (>50%) throughout both seasons (Fig. 6 and 7, bottom left panels). Incorporating the residues and PPL appeared to reduce the proportion of N remaining in residues with >50% hairy vetch composition, but increased the proportion of N remaining in residues with mostly cereal rye (Fig. 6 and 7, bottom right panels).

Cumulative Proportional Mass Loss and Nitrogen Release

We defined cumulative proportional mass loss as the proportion of initial cover crop mass that was lost during the corn growing season. The quadratic equation provided an excellent fit to cumulative proportional mass loss as a function of cover crop

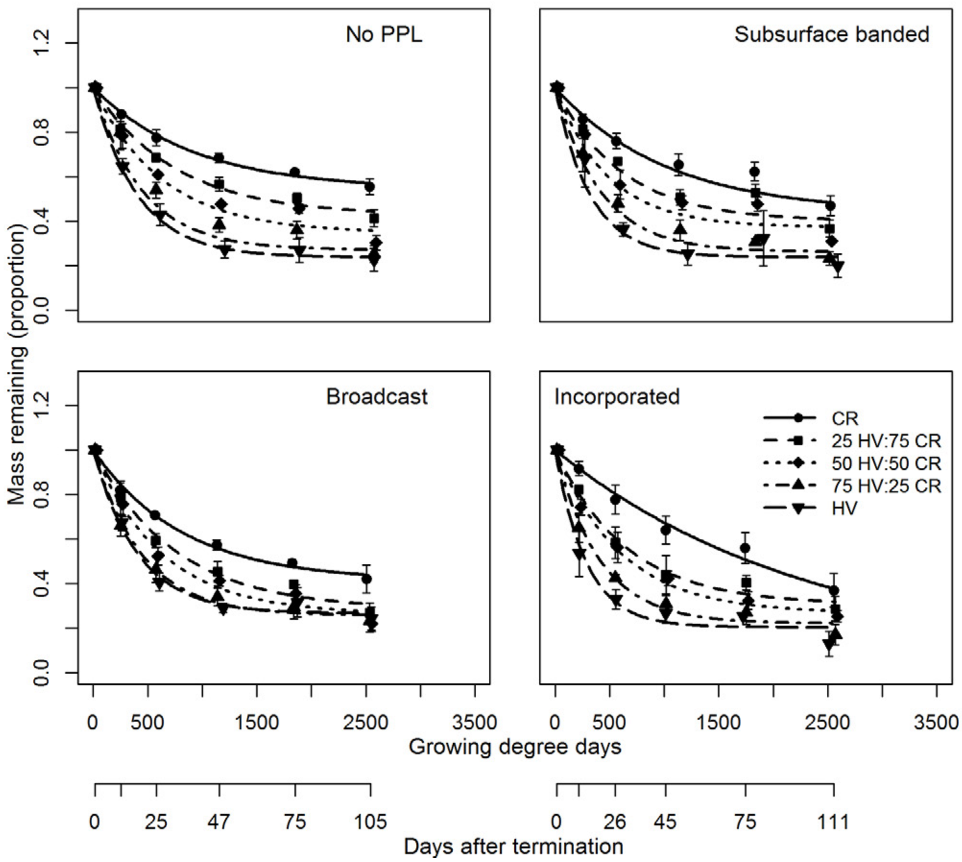

Fig. 5. Proportion of mass remaining in litter bags containing a range of hairy vetch (HV)/cereal rye (CR) biomass proportions and subjected to different pelletized poultry litter (PPL) management during the 2013 corn growing season. Each point represents the mean of three replicates of a particular cover crop biomass proportion and PPL treatment at a given time. Curves are exponential decay models fit to each cover crop biomass proportion within each PPL treatment. Error bars are ± 1 SD. The secondary *x* axis on the bottom left panel shows days after termination that litter bags were collected for the no-till PPL treatments, while the secondary *x* axis on the bottom right panel shows days after termination that litter bags were collected for the incorporated treatment. Noise was added to the *x* coordinates for points and their error bars to avoid excessive overlapping.

biomass proportion ($R^2 = 0.98$). For the no PPL treatment, the quadratic model predicted that cumulative proportional mass loss increased significantly from 0.42 to 0.76 as the proportion of hairy vetch biomass in the cover crop increased ($P < 0.05$, Fig. 8 top left panel, Table 5). Subsurface banded application of PPL did not affect any of the model terms relative to no PPL. The broadcast and incorporated treatments had significantly greater intercept estimates ($P < 0.05$), which correspond to the cumulative proportional mass loss of pure cereal rye residue+PPL for the broadcast treatment, and pure cereal rye residue for the incorporated treatment. The broadcast treatment also had a significantly smaller linear coefficient than the no PPL and subsurface banded treatments ($P < 0.05$), while the incorporated treatment had a linear coefficient intermediate between that of the broadcast and other no-till treatments. Figure 8 (top left panel) shows that the broadcast treatment resulted in a greater cumulative proportional mass loss than the no PPL and subsurface banded treatments for litter bags with a high cereal rye composition, but that the differences among no-till PPL treatments decreased as hairy vetch/cereal rye biomass proportion increased. The incorporated treatment increased cumulative proportional mass loss for all cover crop biomass proportions relative to no PPL and subsurface banded treatments, but also had a slightly more pronounced effect on residues with high cereal rye compositions. There was no effect of PPL treatment on the quadratic coefficients, so all PPL treatments were assigned a common estimate (Table 5). Cumulative proportional mass loss was greater in 2013 than 2012, with the year effect decreasing with increasing hairy vetch/cereal rye biomass proportion ($P < 0.05$).

Cumulative proportional N release increased with increasing hairy vetch/cereal rye biomass proportion, following a hyperbolic function to a maximum of 0.76 to 0.90, depending on the PPL treatment (shape parameter $P < 0.05$ for all PPL treatments, $R^2 = 0.96$, Fig. 8 top right panel, Table 5). Pelletized poultry litter management had significant effects on intercept estimates ($P < 0.05$), which correspond to the cumulative proportion of N released during the corn growing season from pure cereal rye, or pure cereal rye residue+PPL for the broadcast treatment. The incorporated treatment resulted in no N release from pure cereal rye, while the broadcast treatment resulted in 43% N release from the pure cereal rye residue+PPL. The intercept estimates for the no PPL and subsurface banded treatments were intermediate between these extremes. The shape parameter estimates were not statistically different among the PPL treatments and all were assigned a common estimate. The asymptote estimates for the no PPL and subsurface banded treatments were similar, while the broadcast treatment had a significantly lower asymptote estimate ($P < 0.05$) and the incorporated treatment had a significantly greater asymptote estimate ($P < 0.05$) relative to no PPL and

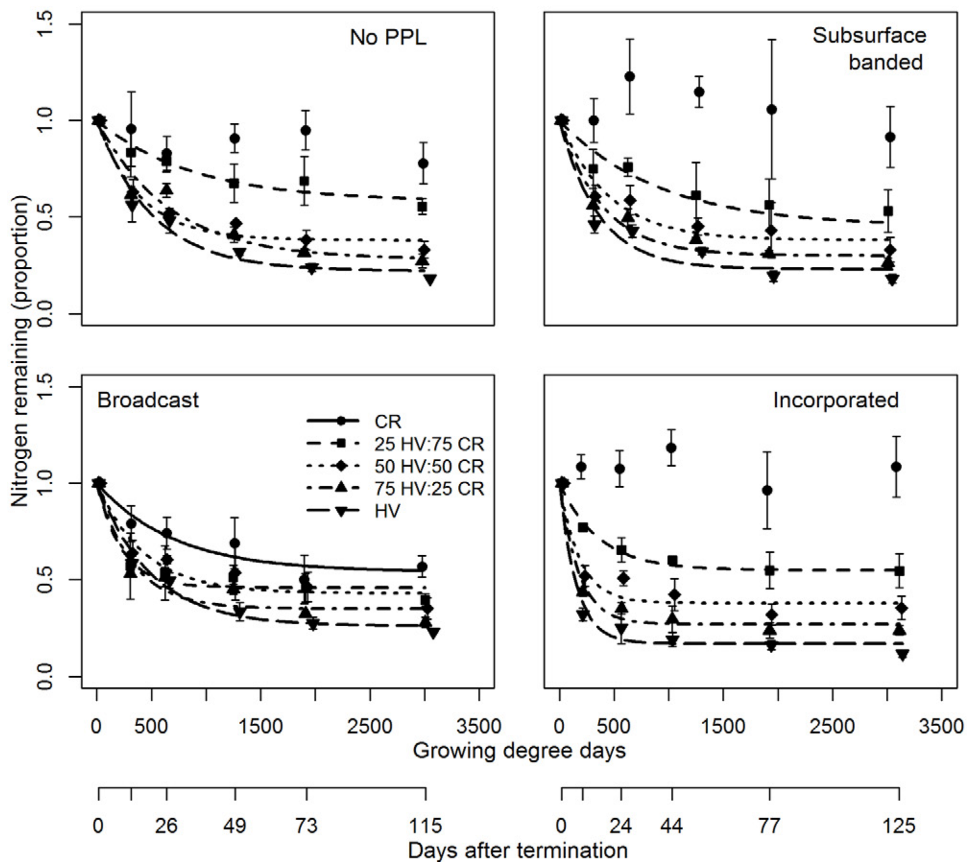

Fig. 6. Proportion of N remaining in litter bags containing a range of hairy vetch (HV):cereal rye (CR) biomass proportions and subjected to different pelletized poultry litter (PPL) management during the 2012 corn growing season. Each point represents the mean of three replicates of a particular cover crop biomass proportion and PPL treatment at a given time. Curves are exponential decay models fit to each cover crop biomass proportion within each PPL treatment. Error bars are ± 1 SD. The secondary *x* axis on the bottom left panel shows days after termination that litter bags were collected for the no-till PPL treatments, while the secondary *x* axis on the bottom right panel shows days after termination that litter bags were collected for the incorporated treatment. Noise was added to the *x* coordinates for points and their error bars to avoid excessive overlapping.

subsurface banded PPL. The cumulative proportional N release estimates were greater in 2013 than in 2012 ($P < 0.05$).

Mass Loss and Nitrogen Release Rates

Rates of mass loss increased linearly with increasing hairy vetch/cereal rye biomass proportion ($P < 0.05$ for all PPL treatments, $R^2 = 0.89$, Fig. 8 bottom left panel, Table 5). The intercepts, representing the mass decay constants for pure cereal rye, or pure cereal rye residue +PPL for the broadcast treatment, did not differ significantly among PPL treatments and all were assigned a common estimate. The slope of the incorporated treatment was significantly greater than for other PPL treatments ($P < 0.05$). There was also a significant PPL treatment × year interaction effect, where the difference between years was greater in the no-till PPL treatments than in the incorporated treatment ($P < 0.05$).

Trends in the N decay constant were not detected across cover crop biomass proportions, although the N decay constant was not estimated for pure cereal rye in the no PPL, subsurface banded, and incorporated treatments (Fig. 8 bottom right panel, Table 5). For all cover crops containing hairy vetch, N decay constants were significantly greater ($P < 0.05$) in the incorporated treatment than the other three PPL treatments, which were similar to each other. Nitrogen decay constants were greater in 2013 than in 2012 ($P < 0.05$).

DISCUSSION

Year Effects

Cover crop decomposition proceeded more completely and more rapidly in 2013 than in 2012. Other research has shown that the use of GDD as a timescale can reduce the effects of temperature differences on C and N mineralization patterns (Honeycutt et al., 1988). However, temperatures in both years of this study were similar to each other and the inter-annual decomposition differences were more likely due to moisture. The large moisture differences between 2012 and 2013 provide insight into the decomposition patterns of surface and buried cover crop residues in a relatively dry year vs. an average year (with a wet spring) for the mid-Atlantic United States.

The effect of year on cumulative proportional mass loss was greater for residues with greater cereal rye composition. One possible explanation for this interaction effect is that inter-annual differences in cereal rye N concentration, which were likely related to differences in growth stage at termination, and/or moisture conditions that affect soil N availability, had a greater effect on the mass loss of the high C/N ratio cereal rye residue than on the mass loss of the low C/N ratio hairy vetch

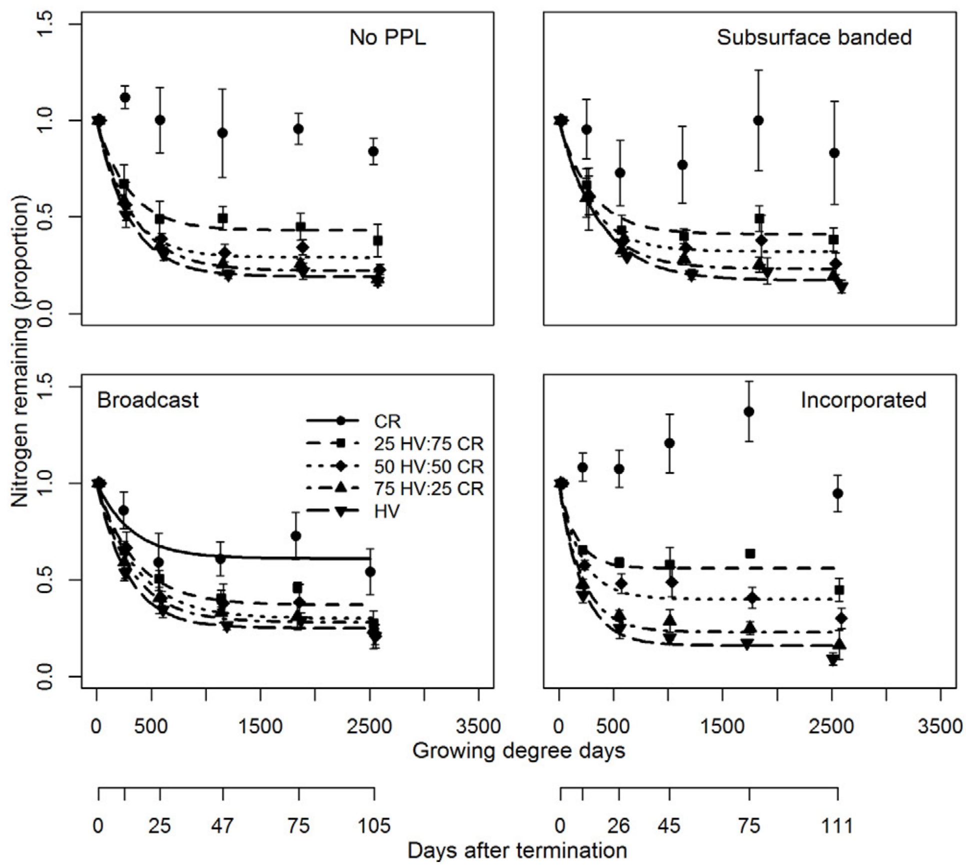

Fig. 7. Proportion of N remaining in litter bags containing a range of hairy vetch (HV)/cereal rye (CR) biomass proportions and subjected to different pelletized poultry litter (PPL) management during the 2013 corn growing season. Each point represents the mean of three replicates of a particular cover crop biomass proportion and PPL treatment at a given time. Curves are exponential decay models fit to each cover crop biomass proportion within each PPL treatment. Error bars are ± 1 SD. The secondary *x* axis on the bottom left panel shows days after termination that litter bags were collected for the no-till PPL treatments, while the secondary *x* axis on the bottom right panel shows days after termination that litter bags were collected for the incorporated treatment. Noise was added to the *x* coordinates for points and their error bars to avoid excessive overlapping.

residue. The effect of year on rates of mass loss was greater in the no-till treatments than in the incorporated treatment, as also noted by Wilson and Hargrove (1986). Burying the litter bags at ~20-cm depth exposed the residues to more constant moisture than placing them on the soil surface, which may have moderated the effects of low rainfall on the rate of mass loss in 2012.

Effects of Species Proportions, Poultry Litter, and Tillage on Cumulative Proportional Mass Loss and Nitrogen Release

We found that cumulative proportional mass loss and N release increased with increasing hairy vetch/cereal rye biomass proportion in both years. This trend supports the findings of Starovoytov et al. (2010), who reported that pure hairy vetch lost a greater proportion of initial mass by the end of the corn growing season than hairy vetch–small grain mixtures. On the other hand, Ranells and Wagger (1996) did not find clear trends in the cumulative proportional mass loss with hairy vetch/cereal rye biomass proportion, perhaps because their range of C/N ratios of residues was relatively narrow. The proportional mass loss after one growing season ranged from 0.60 to 0.90 for both studies (Ranells and Wagger, 1996; Starovoytov et al., 2010). These estimates are consistent with our estimates for hairy vetch and mixtures, but greater than our estimates for pure cereal rye. For proportional N release, Wagger (1989a) also found that hairy vetch released a greater proportion of its initial N than cereal rye during the subsequent growing season, estimating that the proportion of N released from hairy vetch ranged from 0.73 to 0.87, while the proportion of N released from cereal rye ranged from 0.13 to 0.47. Similarly, Stute and Posner (1995) estimated a proportional N release for hairy vetch of 0.80 during a corn growing season. These cumulative proportional N release estimates are similar to the ranges we observed for the monocultures. Consistent with our findings, Ranells and Wagger (1996) found that the cumulative proportional N release from a hairy vetch–cereal rye mixture was intermediate between that of the monocultures.

Subsurface banded application of PPL did not affect the decomposition patterns of cover crop residues, possibly because the PPL N was located too far below the soil surface to be used by the microbes that were decomposing surface residues. A study by Jingguo and Bakken (1997) found that a distance of only 3 to 6 mm between an N-rich legume residue "hotspot" and decomposing straw reduced microbial use of the legume N for decomposition of the straw. The fact that subsurface banded PPL application did not affect the cumulative proportional mass loss of cover crop residues suggests that this method of PPL application may effectively conserve surface residues, which can contribute to weed suppression and moisture conservation. The broadcast PPL treatment increased the cumulative proportional

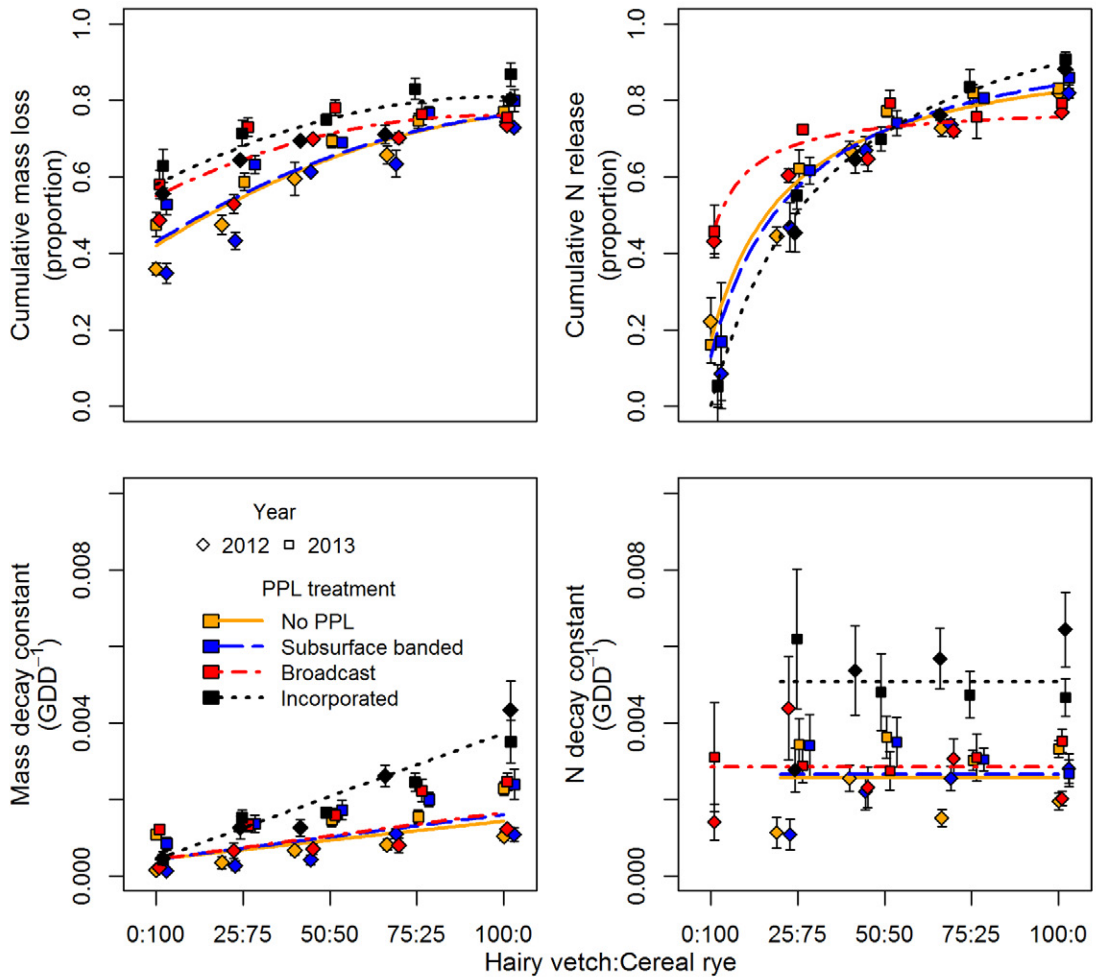

Fig. 8. Cumulative proportional mass loss and N release, and mass and N decay constants across hairy vetch/cereal rye biomass proportions. Units for mass and N decay constants are reciprocal growing degree days (GDD^{-1}). Error bars are ± 1 SE. Noise was added to the x coordinates for points and their error bars to avoid excessive overlapping.

mass loss and N release from the litter bags containing pure cereal rye residue, but decreased the cumulative proportional N release from the litter bags containing a high proportion of hairy vetch residue, relative to the same biomass proportions in the other no-till PPL treatments. It is important to recognize that because litter bags in the broadcast treatment contained PPL as well as residue, their mass loss and N release patterns represent the combined decomposition of both components. The litter bags containing pure cereal rye residue+PPL in the broadcast treatment probably lost more mass and released more N than litter bags containing pure cereal rye residue in the other no-till PPL treatments because of their lower initial C/N ratios.

Incorporation of residues and PPL with tillage increased the cumulative proportional mass loss of cover crop residues contained within litter bags relative to the no PPL and subsurface banded treatments, and, to a lesser extent, to the broadcast treatment. The cumulative proportional N release from pure cereal rye residue decreased with incorporation, while the cumulative proportional N release from pure hairy vetch residue increased relative to the no-till treatments. Burying the litter bags probably increased interaction of residues with soil microbes and provided a more constantly moist environment (Holland and Coleman, 1987), resulting in greater mass loss and N release of the pure hairy vetch and mixture residues. For the pure cereal rye residue in the incorporated treatment, soil N and PPL N appeared to have moved into the buried bags during the corn growing season, which may have increased C mineralization and mass loss relative to the no-till treatments, but resulted in essentially no net N release from the pure cereal rye litter bags over the course of the season.

Effects of Species Proportions, Poultry Litter, and Tillage on Mass Loss and Nitrogen Release Rates

Mass and N decay constants estimated for the pure hairy vetch residue in the no PPL and subsurface banded treatments fell within the range of estimates by Ruffo and Bollero (2003), who also used GDD as their decomposition timescale. On the other hand, our pure cereal rye mass decay constants fell below (2012) and above (2013) the range of their estimates. We found that rates of mass loss increased with hairy vetch/cereal rye biomass proportion, and the response was most pronounced in the incorporated treatment. Rates of N release from cover crops were also greater in the incorporated treatments than in the no-till treatments for all cover crops containing hairy vetch. These findings are consistent with Varco et al. (1993) and Wilson and Hargrove (1986), who found that legume residues lost mass and released N two to five times faster when buried than when on the soil surface.

Rates of N release were usually greater than rates of mass loss, except for pure cereal rye residue in the no PPL,

Table 5. Model parameter estimates for cumulative proportional mass loss and N release and mass and N decay constants as a function of hairy vetch/cereal rye biomass proportion for each pelletized poultry litter (PPL) treatment. Cumulative proportional mass loss and mass decay constants were modeled using polynomial equations; cumulative proportional N release was modeled using a rectangular hyperbolic function. Standard errors are shown in parentheses. All parameter estimates were significantly different than zero ($P < 0.05$), unless indicated with italicized font. Different lowercase letters are used to indicate significant differences between PPL treatments within the same variable and column ($P < 0.05$).

PPL treatment	Cumulative proportional mass loss		
	Intercept	Linear coefficient	Quadratic coefficient†
No PPL	0.42 (0.06)b	0.57 (0.06)a	–0.23 (0.04)
Subsurface banded	0.43 (0.06)b	0.56 (0.06)a	–0.23 (0.04)
Broadcast	0.55 (0.06)a	0.44 (0.06)b	–0.23 (0.04)
Incorporated	0.58 (0.06)a	0.46 (0.06)ab	–0.23 (0.04)
	Cumulative proportional N release		
	Intercept	Shape parameter†	Asymptote
No PPL	0.17 (0.03)b	3.53 (0.28)	0.80 (0.04)b
Subsurface banded	0.13 (0.03)b	3.53 (0.28)	0.89 (0.05)b
Broadcast	0.43 (0.03)a	3.53 (0.28)	0.36 (0.03)c
Incorporated	*0.01 (0.03)*c	3.53 (0.28)	1.20 (0.06)a
	Mass decay constant, GDD^{-1}		
	Intercept × 10^{-3}†	Linear coefficient × 10^{-3}	
No PPL	*0.43 (0.09)*	1.00 (0.14)b	
Subsurface banded	*0.43 (0.09)*	1.17 (0.15)b	
Broadcast	*0.43 (0.09)*	1.23 (0.15)b	
Incorporated	*0.43 (0.09)*	3.33 (0.19)a	
	N decay constant, GDD^{-1}‡		
	Intercept × 10^{-3}		
No PPL	2.57 (0.45)b		
Subsurface banded	2.66 (0.45)b		
Broadcast	2.85 (0.43)b		
Incorporated	5.08 (0.45)a		

† A common estimate was used for all PPL treatments because there was no significant effect of PPL treatment on this parameter.

‡ Nitrogen decay constant intercepts were estimated using the 0:100 hairy vetch/cereal rye biomass proportion in the broadcast treatment, and using the 25:75 hairy vetch/cereal rye biomass proportion for all other PPL treatments.

subsurface banded, and incorporated treatments. The rapid decline in litter bag N content may reflect the release of water-soluble N in hairy vetch [estimated to make up approximately 30% of tissue N concentration by Kuo and Sainju (1998)] as well as water-soluble N in PPL for the broadcast treatment. Portions of the soluble N pool may have been lost from the litter bags through leaching and not accompanied by substantial mass loss. Litter bags containing at least some hairy vetch residue released >50% of their cumulative proportional N release by the six-leaf growth stage (~700 GDD; 30 d) in 2012 and >75% by this stage in 2013. Our finding that the majority of N released from litter bags containing hairy vetch residue was released in the first 4 wk supports the body of literature on this subject (Wagger, 1989a; Varco et al., 1993; Stute and Posner, 1995; Ranells and Wagger, 1996). In contrast, the pure cereal rye in this study released N so slowly, or immobilized N, that it could not be modeled using exponential decay.

While rates of mass loss increased with hairy vetch/cereal rye biomass proportion, rates of N release did not display a trend in response to cover crop biomass proportion among the litter bags containing at least some hairy vetch. This result contradicts the findings from incubation studies, which report decreasing net N mineralization rates with increasing cereal rye biomass proportion in hairy vetch–cereal rye mixtures, likely because hairy vetch N is temporarily immobilized during the decomposition of cereal rye (Kuo and Sainju, 1998; Lawson et al., 2013). It appears that, in the present study, the N decay constants of the mixtures reflected the rates of N release from the hairy vetch component of the mixture without any interaction with the cereal rye. We speculate that the response of N mineralization constants to hairy vetch/cereal rye biomass proportion observed in lab incubations is due to the sustained physical proximity of hairy vetch N and cereal rye residues. In contrast, in the field, hairy vetch N can be released from litter bags before interaction with cereal rye, which is likely what occurred in the present study. Supporting this hypothesis, Fosu et al. (2007) found rapid N release from legumes using a litter bag approach, but observed initial N immobilization of the same legumes in a laboratory incubation.

Total Mass Remaining and Total Nitrogen Release

We presented results from this study as the proportion of initial mass and N remaining in the litter bags over GDD to model cover crop decomposition without the confounding differences in initial total residue mass and N content among the cover crop biomass proportions and PPL treatments. When estimating residue persistence and N contribution from cover crops, total mass remaining and total N release are more relevant than the proportional mass and N remaining or lost from the bags. Averaged across years and the no PPL and subsurface banded treatments, cover crop residue masses remaining at the end of the corn growing season in pure cereal rye, the 25:75, 50:50, 75:25 hairy vetch/cereal rye mixtures, and pure hairy vetch were: 4.74, 3.82, 2.75, 2.18, and 1.57 Mg ha^{-1}, respectively. Quantities of total N released by these same cover crop biomass proportions were: 8.5, 66, 139, 208, and 280 kg N ha^{-1}, respectively. These total N release estimates do not consider the additional N released by roots, which are estimated to contain 10% of the total hairy vetch N and 15% of the total cereal rye N (Kuo et al., 1997). On the other hand, these figures may slightly overestimate the N released from hairy vetch aboveground biomass for two reasons: (i) hairy vetch material used to fill the bags in this study was strictly non-decomposed material, with a greater N concentration than normally observed in full aboveground biomass samples of the species (Clark et al., 1997a; Sainju et al., 2005; Parr et al., 2011) and (ii) equivalent total biomass levels were targeted across all cover crop biomass proportions, resulting in a greater residue mass for pure hairy vetch in 2013 than would be typically observed for monoculture hairy vetch terminated at flowering (maximum biomass = ~6 Mg ha^{-1}; reviewed in Mirsky et al., 2012). When considering the quantities of N released by cover crop residues, it is also important to recognize that while cereal rye N was derived exclusively from the soil, a portion of hairy vetch N (approximately 80%; Poffenbarger et al., 2015) represented new N added to the cropping system through biological N_2 fixation.

Only a portion of N released from litter bags can be considered PAN because some of the N may be lost or immobilized. Rosecrance et al. (2000) found that the high N mineralization rate of hairy vetch resulted in three times and 10 times greater potential for N losses than a hairy vetch–cereal rye mixture and cereal rye monoculture, respectively in the absence of a crop. In that study, nearly half of the leaching and denitrification losses occurred within the first 30 d after cover crop termination, which is before the period of rapid N uptake by corn. Janzen and McGinn (1991) found that up to 14% of N in a lentil green manure may be volatilized when residue is left to decompose on the soil surface. Even though hairy vetch N may be susceptible to losses before uptake, Varco et al. (1993) observed that hairy vetch N is less susceptible to losses than fertilizer N, partly because a portion of N released from hairy vetch residue is immobilized during the breakdown of corresponding C additions from the hairy vetch. Using ^{15}N-labeled legume residues, several studies have reported that more legume N is recovered as soil organic N than as PAN within 1 to 2 yr after termination (Ladd et al., 1981; Janzen et al., 1990; Harris et al., 1994). Due to combined N losses and immobilization after residue N release, corn shoot N uptake from hairy vetch and hairy vetch–cereal rye mixtures has generally been only 15 to 30% of total cover crop N content (Wagger, 1989b; Decker et al., 1994; Clark et al., 1997a).

CONCLUSION

Our findings show that maximum residue persistence can be achieved using a pure cereal rye cover crop and no PPL or subsurface banded PPL, since pure cereal rye residue had the lowest cumulative proportional mass loss and the slowest rate of mass loss, and subsurface banded PPL application did not enhance the decomposition of surface residues. Pure hairy vetch residue released the most N, particularly when incorporated with PPL; however, incorporation also sped up the rate of N release, making it less synchronous with corn demand. Mixtures of hairy vetch and cereal rye provided intermediate cumulative proportional mass loss and N release and intermediate rates of mass loss, suggesting that they can provide both moderate residue persistence and N supply. Nitrogen release rates estimated in our study indicate that mixing cereal rye with hairy vetch does not delay the onset of N release from the cover crop residues.

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