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Cover Crop and Poultry Litter Management Influence Spatiotemporal Availability of Topsoil Nitrogen

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Green and animal manures provide plant-available N (PAN) in annual cropping systems and contribute to improved soil quality. Our objectives were to determine the effects of cover crop residue type and pelletized poultry litter (PPL) application method on: (i) the spatiotemporal distribution of topsoil mineral N (N_{min}), (ii) the average topsoil N_{min} at four developmental stages of corn (*Zea mays* L.), and (iii) corn N uptake. We collected soil and plant samples from a factorial experiment that included three cover crop residues: hairy vetch (*Vicia villosa* Roth), cereal rye (*Secale cereale* L.), and a hairy vetch/cereal rye mixture; and four PPL treatments: no PPL and 3.5 Mg PPL ha^{-1} either broadcast at planting, subsurface banded at the fifth-leaf stage, or broadcast and incorporated at planting. Most of the N_{min} in the broadcast treatment was concentrated near the soil surface, N_{min} associated with the subsurface band remained within 10 cm of the delivery location throughout the growing season, while N_{min} was distributed to a depth of 20 cm in the incorporated treatment. Average N_{min} to 30 cm was significantly greater in soil with hairy vetch residue than in soil with cereal rye residue at emergence and the fifth-leaf stage, while the cover crop mixture had average N_{min} levels intermediate between the monocultures or similar to cereal rye depending on the year. In both years, corn N uptake tended to be greatest with hairy vetch residue and broadcast or subsurface band PPL application, averaging 215 kg ha^{-1} across years in these treatments.

Abbreviations: BRD, broadcast pelletized poultry litter application; CONT, no pelletized poultry litter; INC, incorporated residues and pelletized poultry litter; N_{min}, mineral N; PAN, plant-available N; PPL, pelletized poultry litter; SSB, subsurface band pelletized poultry litter application.

Winter annual legume cover crops can release between 50 and 150 kg N ha^{-1} in the form of PAN during the following season (Ebelhar et al., 1984; Ranells and Wagger, 1996; Cook et al., 2010). While the amount of N released by winter annual legume cover crops is often not enough to fully meet corn demands in no-till systems (Utomo et al., 1990; Dou et al., 1994; Clark et al., 1997a), augmenting legume N with animal manure, ideally at a rate equal to crop P removal, may effectively fulfill corn N requirements during the season of application. Green and animal manures also increase soil potentially mineralizable N, reducing fertilizer N requirements in future seasons (Spargo et al., 2011). Unlike legumes, grass cover crops do not release substantial N during the subsequent growing season (Ranells and Wagger, 1996; Clark et al., 1997b), but they do produce high biomass and decompose slowly, providing effective weed control as surface mulches (Mischler et al., 2010; Reberg-Horton et al., 2011; Mirsky et al., 2012). A mixture of legume and grass cover crops can both release N and control weeds (Hayden et al., 2014).

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The distribution of soil N_{min} over space and time is one factor that controls the proportion of this pool available for plant uptake. For example, applying poultry litter in a band below the soil surface has been shown to reduce NH_3 volatilization by ~90% in no-till systems (Pote and Meisinger, 2014) and substantially reduce nutrient run-off losses, leading to greater corn yields than when poultry litter is surface applied (Pote et al., 2011; Adeli et al., 2012). Subsurface band application of N may also reduce N uptake by weeds (Di Tomaso, 1995) and prevent N immobilization in surface mulches (Mengel et al., 1982). On the other hand, subsurface band application of manure can increase denitrification due to the elevated moisture content and close proximity of available C and NO_3^-–N within the manure band (Comfort et al., 1988; Dosch and Gutser, 1996; Wulf et al., 2002). Timing of N availability is also important because a large pool of NO_3^-–N present in the soil before the period of rapid corn N uptake is vulnerable to losses through leaching or denitrification. The N release from legume residues is likely to be better synchronized with corn uptake when residues are left on the soil surface in a no-till system since incorporated residues exhibit rapid early-season N mineralization (Varco et al., 1993). Split-N applications, where a (usually small) portion of N fertilizer is applied pre-plant and the remainder is sidedressed when corn is at the fifth- to eighth-leaf stage, have been shown to increase crop N-uptake efficiency (i.e., the proportion of applied N taken up by the crop) compared with a single pre-plant N fertilizer application. This strategy may enhance uptake efficiency of manure N as well (Cassman et al., 2002; Dinnes et al., 2002).

Our goal was to evaluate combinations of cover crops and poultry litter application methods for a cover crop- and poultry litter-based no-till corn system with adequate and efficient N delivery. Our specific objectives were to determine the effects of cover crop residue type and PPL application method on: (i) the spatiotemporal distribution of topsoil N_{min}; (ii) the average topsoil N_{min} at four developmental stages of corn, and (iii) corn N uptake.

MATERIALS AND METHODS

Experimental Design and Site Description

A factorial experiment consisting of three different cover crops and four PPL application methods, organized as a split-block design with three blocks, was conducted at the Beltsville Agricultural Research Center (39.02° N lat., 76.94° W long.) in 2011–2012 and 2012–2013. The three cover crop treatments were: hairy vetch, cereal rye, and a mixture of hairy vetch and cereal rye planted in the fall of 2011 and 2012. The PPL treatments, which were laid out in strips perpendicular to cover crop treatments in the spring of 2012 and 2013, included a no PPL control (CONT), broadcast application at planting (BRD), subsurface band application at the fifth-leaf stage (SSB), and broadcast application with incorporation at planting (INC). Each specific combination of cover crop, PPL treatment, and block formed a plot measuring 3 m × 12 m in 2012 and 6 m × 12 m in 2013. The 2012–2013 experiment was performed in a field adjacent to the field used in 2011–2012, allowing both experiments to succeed the same crop in rotation. The soils in both fields were classified as fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts (Codorus series). Selected soil properties are provided in Table 1.

Table 1. Selected soil properties of study sites. Standard errors are shown in parentheses.

Soil properties, dry weight basis	2011–2012	2012–2013
USDA texture classification	Loam	Loam
No-till bulk density, g cm^{-3}	1.29 (0.03)	1.39 (0.03)
INC† bulk density, g cm^{-3}	1.21 (0.04)	1.32 (0.04)
Total C, g kg^{-1}	6.7 (0.6)	10.0 (1.7)
Total N, g kg^{-1}	0.4 (0.1)	0.7 (0.1)
pH, 1:1 soil/water	6.2 (0.2)	5.7 (0.1)
CEC, cmol kg^{-1}	5.9 (0.3)	7.4 (0.3)
Field capacity moisture, g g^{-1}‡	–	0.24

† INC refers to the incorporated treatment.

‡ Estimated using soil moisture data collected 2 d after a soaking rain (at maturity sampling in 2013).

Field Management

The seeding rates for hairy vetch, cereal rye, and the mixture were: 34 kg ha^{-1}, 168 kg ha^{-1}, and 20 kg ha^{-1} hairy vetch + 67 kg ha^{-1} cereal rye, respectively. We applied the three cover crop treatments in strips within each block using a grain drill. The two species within the mixture were planted in separate, sequential passes. Cover crops were terminated using a roller/crimper (I & J Manufacturing, Gap, PA) in no-till treatments (i.e., CONT, BRD, and SSB treatments) and by flail-mowing and disking in the INC treatment. At the time of cover crop termination in 2012, hairy vetch was in full flower and cereal rye was in the soft dough stage (85 on Zadoks scale); in 2013, hairy vetch was 50% flowering and cereal rye was in the milk stage (75 of Zadoks scale). Dates of cover crop planting and other field operations are shown in Table 2; additional details pertaining to cover crop planting are provided in Poffenbarger et al. (2015a).

Pelletized poultry litter (Perdue Agricycle, LLC Seaford, DE) was hand-applied just after planting in the BRD treatment and broadcast just before corn planting in the INC treatment using a Stoltzfus fertilizer spreader (W-Chain Sower spreader, Morgantown, PA). The INC treatment was power spaded (Imants 27sx, Reusel, Netherlands) to 20 cm and cultimulched after PPL application and just before planting. Round-up Ready corn (TA657–13VP, 111 d in 2012; TA522–22DP, 105 d in 2013 T.A. Seeds, Jersey Shore, PA) was planted at 84,000 seeds ha^{-1} with 76-cm row spacing the same day cover crops were rolled. All treatments received an estimated 10 kg PAN ha^{-1} as starter PPL (0.61 Mg PPL ha^{-1}) delivered at planting through the dry fertilizer boxes. In the SSB treatment, PPL was sidedressed at the fifth-leaf stage at the same rate as the BRD and INC treatments using a prototype subsurface band applicator, which delivered PPL approximately halfway between the corn rows (Fig. 1).

We applied PPL at a P-based rate of 3.6 Mg PPL ha^{-1} in 2012 (moisture content = 10.7% of fresh weight) and 3.4 Mg PPL ha^{-1} in 2013 (moisture content = 13.8% of fresh weight) to all PPL

Table 2. Dates of field operations and sampling events for each pelletized poultry litter treatment (CONT = no PPL control, BRD, Broadcast application; SSB, subsurface band application, INC, inorporated.

	2011–2012				2012–2013			
	CONT	BRD	SSB	INC	CONT	BRD	SSB	INC
Field operation					Field activities			
Cover crop planting	10 Oct.	10 Oct.	10 Oct.	10 Oct.	25 Sept.	25 Sept.	25 Sept.	25 Sept.
Cover crop termination	29 May	29 May	29 May	18 May	22 May	22 May	22 May	16 May
Corn planting	29 May	29 May	29 May	29 May	22 May	22 May	22 May	22 May
Poultry litter application	None	29 May	27 June	29 May	None	22 May	25 June	22 May
Weed control	1 June, 21 June	1 June, 21 June	1 June, 21 June	1 June, 21 June	31 May, 26 June	31 May, 26 June	31 May, 26 June	31 May, 26 June
Growth stage					Soil sampling			
Emergence	7, 8 June	7, 8 June	7, 8 June	7, 8 June	4, 5 June	4, 5 June	4, 5 June	4, 5 June
Fifth-leaf	28, 29 June	28, 29 June	28, 29 June	28, 29 June	26, 27 June	26, 27 June	26, 27 June	26, 27 June
Silking	31 July, 1 Aug.	31 July, 1 Aug.	31 July, 1 Aug.	31 July, 1 Aug.	23, 24 July	23, 24 July	23, 24 July	18 July
Maturity	1, 4 Oct.	1, 4 Oct.	1, 4 Oct.	1, 4 Oct.	10, 11 Sept.	10, 11 Sept.	10, 11 Sept.	10, 11 Sept.
Growth stage					Plant sampling			
Maturity	5 Oct.	5 Oct.	5 Oct.	5 Oct.	18 Sept.	18 Sept.	18 Sept.	18 Sept.

treatments except the CONT 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). Poultry litter pellets were assumed to have a similar proportion of mineralizable N as raw broiler poultry litter during a single growing season based on prior research (personal communication M. Cavigelli and J. McGrath, 2011). Pelletized poultry litter nutrient composition data are presented in Table 3.

Weed control for the corn was achieved using two applications (2.8 kg active ingredient ha^{-1}) of Round-up (glyphosate; Monsanto, St. Louis, MO) each season. The fields received 2.5 cm of irrigation water using a traveling gun system at each of three irrigation events in 2012, and 4 cm of water at each of three irrigation events in 2013 (Fig. 2). The fields were irrigated as part of a companion involving N_2O flux measurements that was conducted in the same field.

Soil and Plant Sampling

We collected aboveground biomass at cover crop termination by clipping all material within a 76 cm × 67 cm frame in four to six locations within each cover crop strip. The cover crop samples were sorted to separate species, weighed after oven drying at 60°C, ground to pass a 1-mm screen, and analyzed for total tissue C and N concentrations (Carlo Erba NC2500 Elemental Analyzer, Carlo Erba, Milan, Italy).

We collected soil samples at the following corn growth stages: emergence, fifth-leaf (post-subsurface band application), silking, and physiological maturity (sampling dates provided in Table 2). In all cover crop residues and PPL treatments except SSB, we took 2-cm diam. soil cores halfway between the corn rows (i.e., interrow center) and at a distance of 20 and 38 cm on both sides of the interrow center. Because the corn rows were 76 cm apart, the cores collected at 38 cm from the interrow center were located in the corn rows. The cores were split into four depth increments (0–5, 5–10, 10–20, 20–30 cm). In the plots receiving subsurface banded PPL, we took soil cores at 0, 5, 10, 25, and 38 cm from the band, which was placed approximately at the interrow center, and split at five depth increments (0–5, 5–10, 10–15, 15–20, 20–30 cm). In each plot, four parallel transects perpendicular to the corn rows were sampled in this way, with cores from the same depth and distance from the interrow center or band composited. The sampled area, measuring 30 cm deep × 38 cm wide (from interrow center to one corn row), in each combination of plot, growth stage, and year will be referred to as a soil face.

Immediately after sampling, we passed the fresh soil samples through a 6.4-mm sieve, took a fresh weight, and collected a ~10-g subsample for gravimetric moisture determination by drying at 105°C. The fresh weight and moisture content of each sample were used to calculate the sample dry weight, which was then divided by the sample volume to obtain bulk density. Each sample was spread in a thin layer for rapid air-drying and passed through a 2-mm sieve. We extracted N_{min} from a 2-g subsample of each air-dried soil sample by shaking for 1 h in 20 mL of 1 M KCl according to typical methods used by soil testing labs (Griffin et al., 2011). Although air-drying can affect concentra-

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

Table 3. Nutrient composition of pelletized poultry litter (PPL). Standard errors are shown in parentheses.

PPL properties, fresh weight basis	2012	2013
Moisture, g kg^{-1}	106.8 (1.1)	137.5 (2.8)
Total N, g kg^{-1}	31.5 (0.5)	33.6 (0.9)
NH_4^+–N, g kg^{-1}	6.6 (0.1)	8.2 (0.5)
Organic N, g kg^{-1}	25.0 (0.5)	25.4 (1.0)
Plant-available N, g kg^{-1}	19.0 (0.6) †	20.1 (0.5) †

† Estimated plant-available N (PAN) assuming 50% mineralization of organic N during the corn growing season and that 90% of PPL NH_4^+-N was plant-available.

tions of extracted NO_3^-–N and NH_4^+–N (Li et al., 2012), the drying step allowed us to store the samples before extraction. Extracts of the air-dried soils provide a relative measure of PAN for comparison among treatments. We analyzed filtered extracts colorimetrically for NO_3^-–N using cadmium reduction and reaction with sulfanilamide and N-1-napthylethylenediamine dihydrochloride and for NH_4^+–N by reaction with salicylate and dichloro-isocyanuric acid (2012: Technicon Autoanalyzer II, Technicon Instruments, Tarrytown, NY; 2013: Seal AQ2 Automated Discrete Analyzer, Mequon, WI).

At physiological maturity, all corn plants within a 3-m section in the center of each plot were cut at the base and weighed fresh. A six-plant subsample, including ears, was chopped and weighed before and after drying at 60°C, ground to pass a 1-mm sieve, homogenized, and analyzed for total C and N concentration by combustion analysis (LECO CHN 2000, LECO, St. Joseph, MI). The subsample moisture content was used to estimate the dry weight of the full 3-m section. The dry weight of the full 3-m section was then multiplied by the tissue N concentration of the subsample to estimate corn N uptake on an area basis.

Calculations and Statistics

Soil Moisture Content

Soil moisture content values for all sampling locations of each soil face were pooled into nine regions of equal area and then averaged to avoid biasing means toward the more densely sampled areas of the soil faces. We split the soil moisture data set by year and analyzed each year using repeated measures ANOVA with the lme function in R (Pinheiro et al., 2014). The model included the following factors as fixed effects: a three-way interaction of growth stage, cover crop residue type, and tillage treatment (no-till vs. INC), and plot location coordinates. We assigned location coordinates to each plot based on relative horizontal and vertical distances from a within-field reference location so that spatial variation throughout the field could be accounted for in statistical models. In addition to including growth stage as a fixed effect, it was also included as a random covariate, modeled with the CAR1 correlation structure, with plot as a grouping factor and random effect. This captured the temporal autocorrelation of the residuals. Tillage (no-till vs. INC) was included as a fixed factor instead of PPL treatment because Akaike's Information Criterion values were lower, and mean square error values were similar for models that included tillage as a factor instead of PPL treatment. We verified homogeneity of variance using a plot of residuals. Means were computed using the lsmeans function (Lenth, 2014), and multiple comparisons were made using a false discovery rate adjustment in the glht function (Hothorn et al., 2008).

Spatial Distribution of Soil Mineral Nitrogen

We modeled the effect of Euclidean distance from the N source on the natural log of N_{min} for each soil face. The N source was considered to be the soil surface for the control, BRD, and INC treatments, and the PPL band for the SSB treatment after sidedress application. We used a Gaussian random walk model for diffusion/dispersion (Cortis and Berkowitz, 2004):

$$y = a + \frac{x}{s\sqrt{2\pi}} e^{-d^2/2s^2} \qquad [1]$$

where y is the natural log of N_{min} at a given Euclidean distance d from the N source, x represents the height of the normal curve's peak, a is the asymptote of the normal curve's tail, and s is a shape coefficient controlling the width of the normal curve. The variable x reflects the N_{min} concentration in the N source, relative to further away from the N source, a reflects the N_{min} concentration far away from the N source, and s represents the spatial extent of the N source. We performed nonlinear model fitting

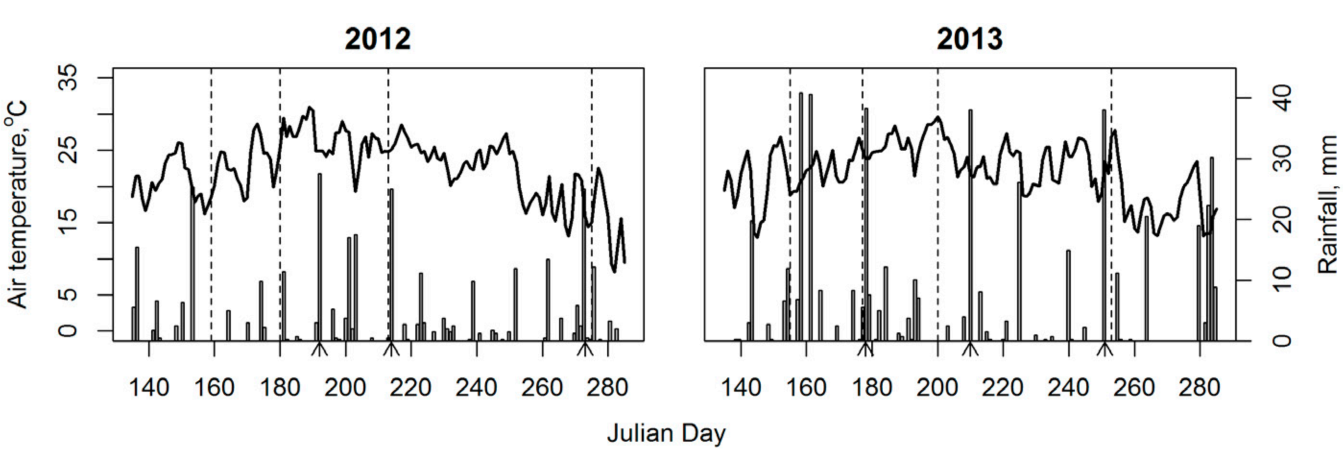

Fig. 2. Average daily air temperature (black lines) and daily total rainfall (gray bars) in 2012 and 2013 corn growing seasons at Beltsville, MD. Vertical dashed lines indicate soil sampling dates. Arrows on the x axis indicate dates of irrigation events.

separately for each soil face using the nls function in R (R Core Team, 2014).

Random walk model residuals were computed as the difference between predicted and observed values, and further analyzed for other possible spatial trends. For the SSB treatment, residuals were modeled as a function of distance from the soil surface using a second random walk fit to account for cover crop residue N_{min} as well as PPL band N_{min}. Inverse distance-weighted interpolation was then used on the residuals for all soil faces using gstat (Pebesma, 2004). Inverse distance weighting computes a weighted average:

$$\hat{Z}(s_0) = \frac{\sum_{i=1}^{N} w(s_i) Z(s_i)}{\sum_{i=1}^{N} w(s_i)} \quad [2]$$

$$w(s_i) = \left\| s_i - s_0 \right\|^{-p} \quad [3]$$

where $\hat{Z}$ is the weighted average for an arbitrary point, s_0, Z is a value at a known point, S_i, n is the total number of known points used in interpolation, and w is the weight. The symbol || indicates Euclidean distance, and p is the inverse distance weighting power. We selected a p value of 4 based on visual interpretation of the smoothness of prediction surfaces. Using the random walk models and inverse-distance weighting interpolation for each soil face, predictions were generated for all 1 cm × 1 cm cells of a 30 cm-deep × 38 cm-wide prediction grid. The random walk and inverse-distance weighting predictions for each cell of each grid were added together, and then these values were averaged across blocks, back-transformed, and plotted using the levelplot function in R (Sarkar, 2008).

Random walk model parameter estimates and standard errors presented in this paper were estimated using data from all three blocks of each cover crop residue type × PPL treatment × growth stage × year. The nlme function was used with block included as a random effect (Pinheiro et al., 2014). To quantitatively evaluate cover crop residue type and PPL treatment effects on the spatial distribution of N_{min}, we compared random walk model parameter estimates using unequal variance t tests (Ruxton, 2006). Degrees of freedom were conservatively estimated as the minimum nlme-reported degrees of freedom among the two treatments, minus one. A false discovery rate adjustment was performed on t test P values to account for multiple comparisons using the p.adjust function (R Core Team, 2014).

Average Soil Mineral Nitrogen Content and Corn Nitrogen Uptake

We averaged the spatial N_{min} predictions for each grid across cells, on the log-scale, to generate N_{min} averages for each face. The average N_{min} concentrations were converted to units of kg N ha^{-1} using the average bulk density of either the no-till or INC treatments within each year. The natural log of average soil N_{min} contents were analyzed using lme (Pinheiro et al., 2014), with the interaction of cover crop residue type and PPL treatment, as well as plot location coordinates, as fixed effects, block as a random effect, and plot location coordinates as spatial covariates in an exponential correlation structure (corExp). The natural logs of NO_3^-–N concentrations were averaged for each face as described for soil moisture content, and then back-transformed and converted to units of kg N ha^{-1}. The proportion of N_{min} as NO_3^-–N was computed for each observation, logit-transformed, and analyzed to determine the effects of proximity to PPL band (within band or away from band), cover crop residue type, and their interactions for just the SSB treatment. We analyzed corn N uptake data as described for average soil N_{min} content, except the analysis was performed using teh original scale ratehr than the natural log scale.

Sampling Scheme Comparison

Using the spatial N_{min} predictions for the SSB treatment, we compared different theoretical soil sampling schemes in terms of how closely they matched true N_{min} concentrations to 30 cm. We considered the true soil N_{min} concentration to be the average N_{min} of all cells for a given prediction grid. The sampling schemes consisted of different numbers of cores taken away from the band for each core taken within 5 cm of the band on the prediction grids. Sampling scheme estimates were made by averaging the N_{min} concentration for the cells within 5 cm horizontally of the PPL band to a 30-cm depth, with N_{min} concentrations for 2 cm wide × 30 cm deep groups of cells selected randomly from at least 10 cm horizontal distance from the PPL band. Supplementary Fig. 1 shows the effect of soil sampling schemes on the accuracy of N_{min} estimates.

RESULTS AND DISCUSSION

Weather Conditions

Daily mean temperatures and precipitation during the 2012 and 2013 growing seasons are presented in Fig. 2. Average monthly temperatures were approximately 5% greater than 30-yr average monthly temperatures for Beltsville, MD in both years. While 2012 was a relatively dry year (76% of average rainfall), rainfall during the 2013 corn growing season was close to the 30-yr average (98% of average). The month of June was particularly wet in 2013 (Fig. 2). Between corn emergence and the corn fifth-leaf stage, 114 mm of precipitation fell in 2013, relative to only 20 mm over this time period in 2012.

Cover Crop Biomass, Nitrogen Content, and Carbon/Nitrogen Ratios

Cover crops were highly productive both years (Table 4), with cereal rye producing nearly twice as much biomass as hairy vetch. In 2012, the mixture produced intermediate biomass relative to the monocultures, while in 2013 the mixture was more productive than either monoculture. The mixtures and hairy vetch monocultures contained two to three times as much N as the cereal rye monocultures. The C/N ratios of hairy vetch and cereal rye were below and above the mineralization/immobili-

Table 4. Biomass, N content, and C/N ratios of cover crop residues. Standard errors are shown in parentheses.

	2012			2013		
Residue type	Biomass	N content	C/N ratio	Biomass	N content	C/N ratio
	Mg ha^{-1}	kg ha^{-1}		Mg ha^{-1}	kg ha^{-1}	
Cereal rye	10.5 (0.8)	56 (6)	93 (5)	10.4 (0.3)	61 (3)	80 (2)
Mixture	8.3 (0.5)	154 (12)	27 (2)	12.4 (0.9)	163 (14)	37 (2)
Hairy vetch	5.8 (0.1)	171 (9)	17 (1)	5.0 (0.2)	145 (9)	16 (1)

zation threshold of ~25 (Clark et al., 1997a; Kuo et al., 1997), respectively, in both years. The C/N ratios of the mixtures were close to (2012) or above (2013) this threshold.

Soil Moisture Content

Greater rainfall and irrigation volumes in the spring and summer of 2013 led to greater soil moisture content in 2013 than in 2012 (Table 5). Soil moisture content differed among corn growth stages within each year ($P < 0.05$), with greater soil moisture at corn emergence and maturity than at the fifth-leaf and silking growth stages. Because the effect of tillage on moisture content was qualitatively similar for all cover crop residues, we presented moisture content for the no-till and INC treatments averaged across cover crop residue types. The INC treatment had significantly lower soil moisture than the no-till treatments for most growth stages in both years ($P < 0.05$).

Spatial Distribution of Soil Mineral Nitrogen

We did not include N_{min} concentrations of samples collected at the location of starter PPL delivery (0- to 5-cm depth in corn row) at emergence in the spatial analysis to simplify modeling the distribution of N_{min}. Also, given that immediately after subsurface band application, the N_{min} concentration of the PPL band was not expected to differ among cover crop residue types, we assigned the maximum N_{min} concentration among the PPL band samples to all cover crop residues within each block and year. For some soil faces, no spatial trends in N_{min} were detected and a mean concentration was estimated for Parameter a of Eq. [1]. We did not fit random walk equations to the INC treatment because the homogenization of soil N_{min} with tillage eliminated a distinct source in most cases. For the soil faces that could be fit with the random walk equation, the model explained 56 to 96% of the variation among sampled locations and blocks (mean R^2 = 0.80). Figure 3 provides an example of the random walk model fit to data collected in the SSB treatment at the fifth-leaf growth stage in 2012.

Corn Emergence

At corn emergence in both years, most combinations of residue types and no-till PPL treatments exhibited a trend of decreasing N_{min} from the soil surface to depth, with greatest N_{min} concentrations within the surface 10 cm (Fig. 4). The higher N_{min} concentrations in the surface ~10 cm at corn emergence likely reflect the surface placement of decomposing residues in the no-till PPL treatments, as well as PPL for the BRD treatment. One important exception to this spatial trend was the cereal rye residue with no broadcast PPL. Mineral N concentrations were low at all soil face locations under the unamended cereal rye residue (<5 mg kg^{-1}), likely due to a combination of: N_{min} depletion during cereal rye growth, N_{min} immobilization during cereal rye decomposition, and low quantities of N_{min} released from the cereal rye residue. In other studies, the presence of a grass cover crop surface residue has been shown to either not affect (Huntington et al., 1985) or decrease N_{min} during the corn growing season relative to bare soil (Rosecrance et al., 2000; Sarrantonio, 2003; Wells et al., 2013). The N_{min} concentration at the soil surface and the depth that the N_{min} extended tended to be greater with greater hairy vetch composition in the residue. Broadcast PPL amendment also increased these two attributes, particularly in the cereal rye residue. In some cases, estimates for x and s (Eq. [1]) reflected these cover crop residue and PPL treatment effects, but not always because x and s also varied with Parameter a. Incorporating the cover crop residues and PPL increased N_{min} concentrations in the tilled layer (0- to 20-cm depth) compared with at the 20- to 30-cm depth increment for all three cover crop residues in both years. Visual inspection of the prediction grids indicates that the N_{min} concentrations within the tilled layer (top 20 cm) were greater for the hairy vetch and mixture residues than for the cereal rye residue in 2012, and greater for the hairy vetch than the mixture and cereal rye residues in 2013 (Fig. 4).

Corn Fifth-Leaf Stage

At the fifth-leaf stage in 2012, soil N_{min} concentrations tended to be greater than at emergence, yet the depth trends observed at emergence remained evident (Fig. 5). This finding is consistent with several studies conducted on no-till corn systems, which reported an increase in N_{min} between emergence and the fifth-leaf growth stage (Ebelhar et al., 1984; Huntington et al., 1985; Cook et al., 2010). However, between emergence and the fifth-leaf

Table 5. Gravimetric soil moisture content at each sampling event during the 2012 and 2013 corn growing seasons, averaged across cover crop residue types and no-till pelletized poultry litter treatments. Different lowercase letters indicate significant differences among growth stages within the same tillage treatment and year ($P < 0.05$). Different uppercase letters indicate significant differences ($P < 0.05$) between the no-till and incorporated (INC) treatments within the same growth stage and year. Standard errors are shown in parentheses.

	2012		2013	
Growth stage	No-till treatments	INC	No-till treatments	INC
Emergence	0.180 (0.002) aA	0.168 (0.004) bB	0.245 (0.002) aA	0.220 (0.004) aB
Fifth-leaf	0.162 (0.002) bA	0.129 (0.004) cB	0.243 (0.002) aA	0.208 (0.004) bB
Silking	0.158 (0.002) bA	0.136 (0.004) cB	0.185 (0.002) bA	0.192 (0.004) cA
Maturity	0.182 (0.002) aA	0.182 (0.004) aA	0.243 (0.002) aA	0.220 (0.004) aB

growth stage in 2013, N_{min} concentrations decreased for the hairy vetch residue (all PPL treatments), while remaining relatively constant for the mixture and cereal rye residues (except near the PPL band in the SSB treatment). At the fifth-leaf stage in 2013, spatial predictions revealed a trend of greater N_{min} at the soil surface than at the depth for the cereal rye and cover crop mixture residues in all PPL treatments, while this depth trend was not observed under the hairy vetch residue (Fig. 5). We hypothesize that the 2013 findings, which were contradictory to the 2012 results, reflect the wet conditions between collection of the emergence and the fifth-leaf samples (Fig. 2), which caused N_{min} (specifically, NO_3^-–N) to move out of the 0- to 30-cm layer of soil for the hairy vetch treatments. The wetter conditions in 2013 may have also encouraged the release of soluble C and N from hairy vetch and/or broadcast PPL and limited O_2 diffusion in the soil, processes which would facilitate denitrification losses. Other authors have reported maximum denitrification rates of 6 mg N kg^{-1} d^{-1} for surface-applied hairy vetch residue (Aulakh et al., 1991).

Within the SSB treatment, the spatial predictions showed a region of high soil N_{min} concentrations (320–640 mg kg^{-1}) at the location of PPL delivery in both years. Mineral N concentrations decreased rapidly with distance from the center of the band, and the band's zone of influence (Parameter *s* of Eq. [1]) extended to a radius of only ~3 to 5 cm. Elongated regions of elevated N_{min} concentrations were observed below the subsurface bands, although concentrations in this region did not exceed 20 mg kg^{-1}.

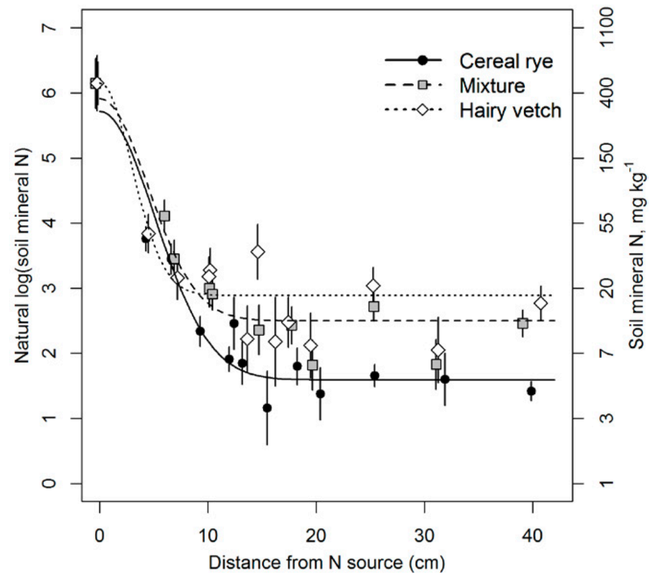

Fig. 3. Natural log of soil mineral N concentration as a function of Euclidean distance from pelletized poultry litter band at the fifth-leaf growth stage in 2012. The curves are random walk models fit to each cover crop residue type. Vertical lines are ± one standard error. To aid in visual interpretation, noise was added to means and standard error bars in the x direction and values were pooled for distances between 25 and 27 cm, and 38 and 42 cm from the band.

Corn Silking Stage

At silking in both years, N_{min} was generally below 10 mg kg^{-1} and only slightly elevated at the soil surface (0–10 cm) vs. at

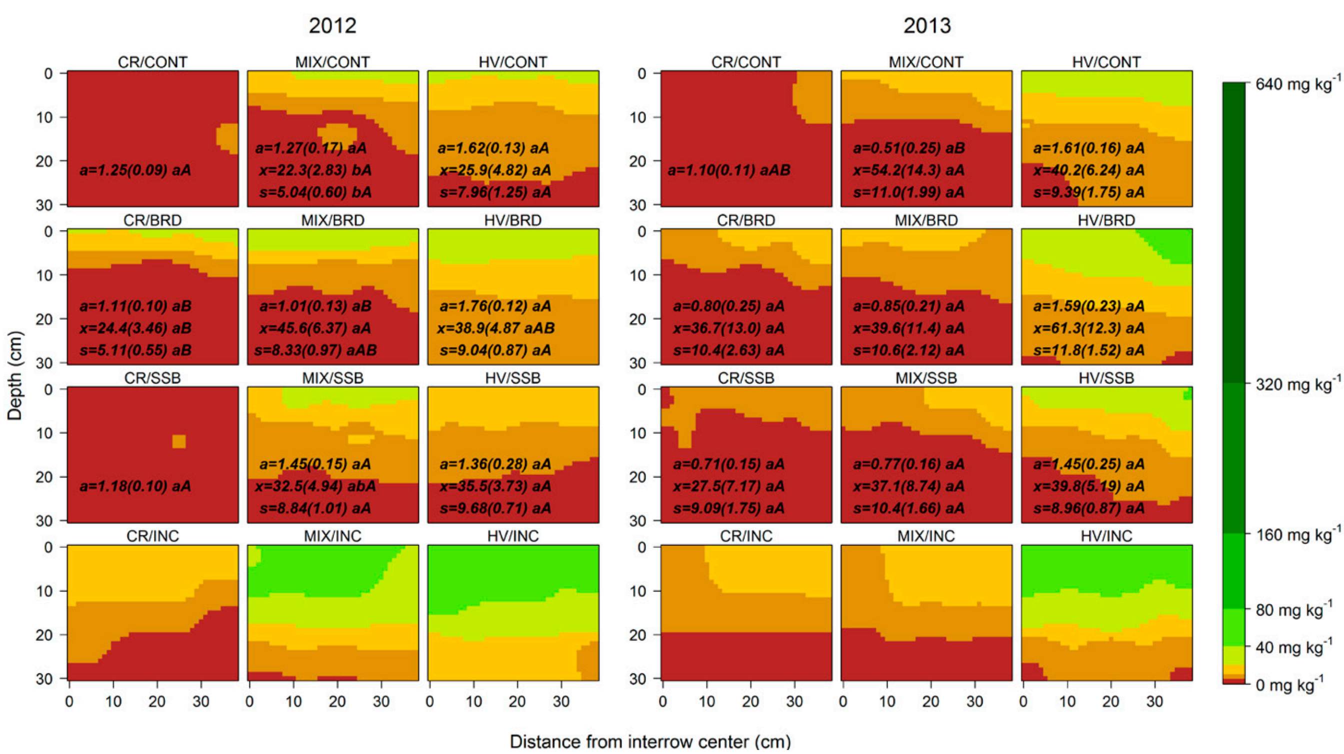

Fig. 4. Spatial distribution of soil mineral N concentration at corn emergence in 2012 and 2013 for three cover crop residues (CR = cereal rye, MIX = mixture, HV = hairy vetch) and four pelletized poultry litter (PPL) treatments (CONT = no PPL control, BRD = broadcast application, SSB = subsurface band application, INC = incorporated). Random walk models were fit as a function of distance from the soil surface for the CONT, BRD, and SSB treatments. Random walk model parameter estimates (see Eq. [1]) and standard errors (shown in parentheses) are on the natural log scale. Different lowercase letters indicate that estimates for that parameter are significantly different (*P* < 0.05) among PPL treatments within the same cover crop residue and year. Different uppercase letters indicate that estimates for that parameter are significantly different (*P* < 0.05) among different residues within the same PPL treatment and year.

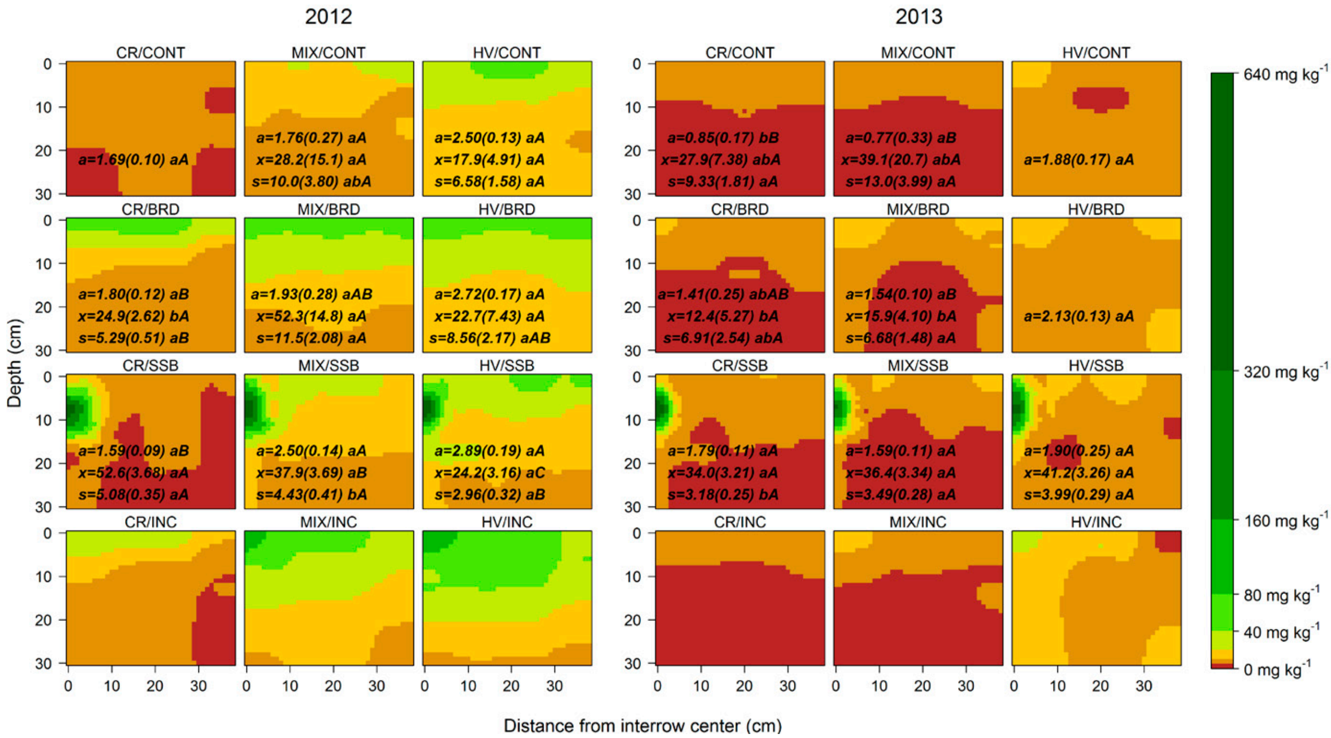

Fig. 5. Spatial distribution of soil mineral N concentration at the corn fifth-leaf stage in 2012 and 2013 for three cover crop residues (CR = cereal rye, MIX = mixture, HV = hairy vetch) and four pelletized poultry litter (PPL) treatments (CONT = no PPL control, BRD = broadcast application, SSB = subsurface band application, INC = incorporated). Random walk models were fit as a function of distance from the soil surface for the CONT and BRD treatments, and as a function of distance from the PPL band for the SSB treatment. Random walk model parameter estimates (see Eq. [1]) and standard errors (shown in parentheses) are on the natural log scale. Different lowercase letters indicate that estimates for that parameter are significantly different ($P < 0.05$) among PPL treatments within the same cover crop residue and year. Different uppercase letters indicate that estimates for that parameter are significantly different ($P < 0.05$) among different residues within the same PPL treatment and year.

depth (Fig. 6), likely because corn N demand was high at this growth stage. The only exceptions were in the PPL band both years and in the mixture and hairy vetch INC treatments in 2012. Within the SSB treatment, soil N_{min} remained elevated (up to 160 mg kg^{-1}) in the center of the PPL band and in the 5-cm radius surrounding the band (40–80 mg kg^{-1}). In 2012, elevated N_{min} concentrations of 5 to 10 mg kg^{-1} extending halfway to the corn row in the hairy vetch treatment, and 10 cm laterally in the mixture, provided evidence of some minor N_{min} movement away from the band. Although, the NH_4^+–N within the band had been largely converted to the mobile NO_3^-–N form by silking (Supplementary Fig. 2), the low soil moisture in 2012 probably limited substantial N_{min} movement away from the band. In 2013, the spatial predictions showed no evidence of N_{min} movement away from the band, probably because the N_{min} within the band remained mainly in the less mobile NH_4^+–N form (Supplementary Fig. 2). The wet soil conditions in 2013, combined with high microbial respiration within the band, would have decreased O_2 availability and thereby inhibited nitrification and/or promoted denitrification (Bateman and Baggs, 2005). In the 2012 mixture and hairy vetch INC treatments, N_{min} remained elevated (up to 40 mg kg^{-1} in mixture and 80 mg kg^{-1} in hairy vetch) at the 0 to 20 cm compared with the 20- to 30-cm depth increment.

Corn Physiological Maturity

At corn maturity in both years, the spatial predictions showed elevated N_{min} concentrations at the soil surface relative to below 15 cm for all cover crop residue types and PPL treatments, except for the cereal rye residue with no PPL and mixture residue with broadcast PPL in 2012 (Fig. 7). The slight increase in N_{min} concentrations at the soil surface between silking and maturity in 2013 was probably due to increased net mineralization relative to corn uptake during maturation (Fig. 6 and 7). Mineral N concentrations of up to 160 mg kg^{-1} were estimated in the PPL band in 2012, and 20 to 40 mg kg^{-1} in the PPL band in 2013. Mineral N concentrations >20 mg kg^{-1} were isolated to <5 cm surrounding the PPL delivery site in the SSB treatment. In 2012, regions of N_{min} concentrations between 5 and 20 mg kg^{-1} in the mixture INC treatment, and between 10 and 80 mg kg^{-1} in the hairy vetch INC treatment were observed extending from approximately 5- to 30-cm depth across the soil face except in the corn row. The high concentrations of N_{min} remaining at corn maturity posed a risk for NO_3^-–N leaching losses.

Average Soil Mineral Nitrogen Content

The hairy vetch cover crop provided greater average N_{min} than cereal rye during the early part of both corn growing seasons ($P < 0.05$; Fig. 8 and 9). Just before the phase of rapid corn N uptake (fifth-leaf) in 2012, average N_{min} content for the surface 30 cm was 68 kg ha^{-1} under hairy vetch and 20 kg ha^{-1} under

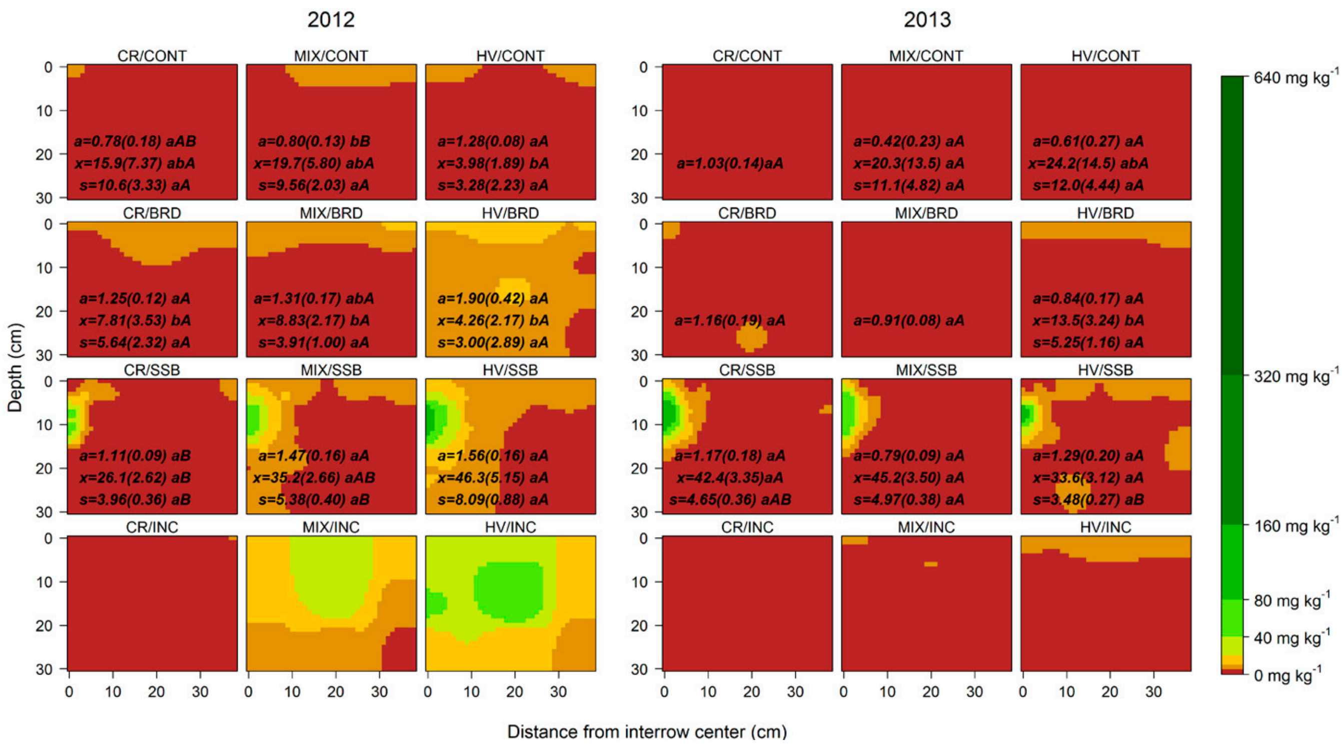

Fig. 6. Spatial distribution of soil mineral N concentration at the corn silking stage in 2012 and 2013 for three cover crop residues (CR = cereal rye, MIX = mixture, HV = hairy vetch) and four pelletized poultry litter (PPL) treatments (CONT = no PPL control, BRD = broadcast application, SSB = subsurface band application, INC = incorporated). Random walk models were fit as a function of distance from the soil surface for the CONT and BRD treatments, and as a function of distance from the PPL band for the SSB treatment. Random walk model parameter estimates (see Eq. [1]) and standard errors (shown in parentheses) are on the natural log scale. Different lowercase letters indicate that estimates for that parameter are significantly different ($P < 0.05$) among PPL treatments within the same cover crop residue and year. Different uppercase letters indicate that estimates for that parameter are significantly different ($P < 0.05$) among different residues within the same PPL treatment and year.

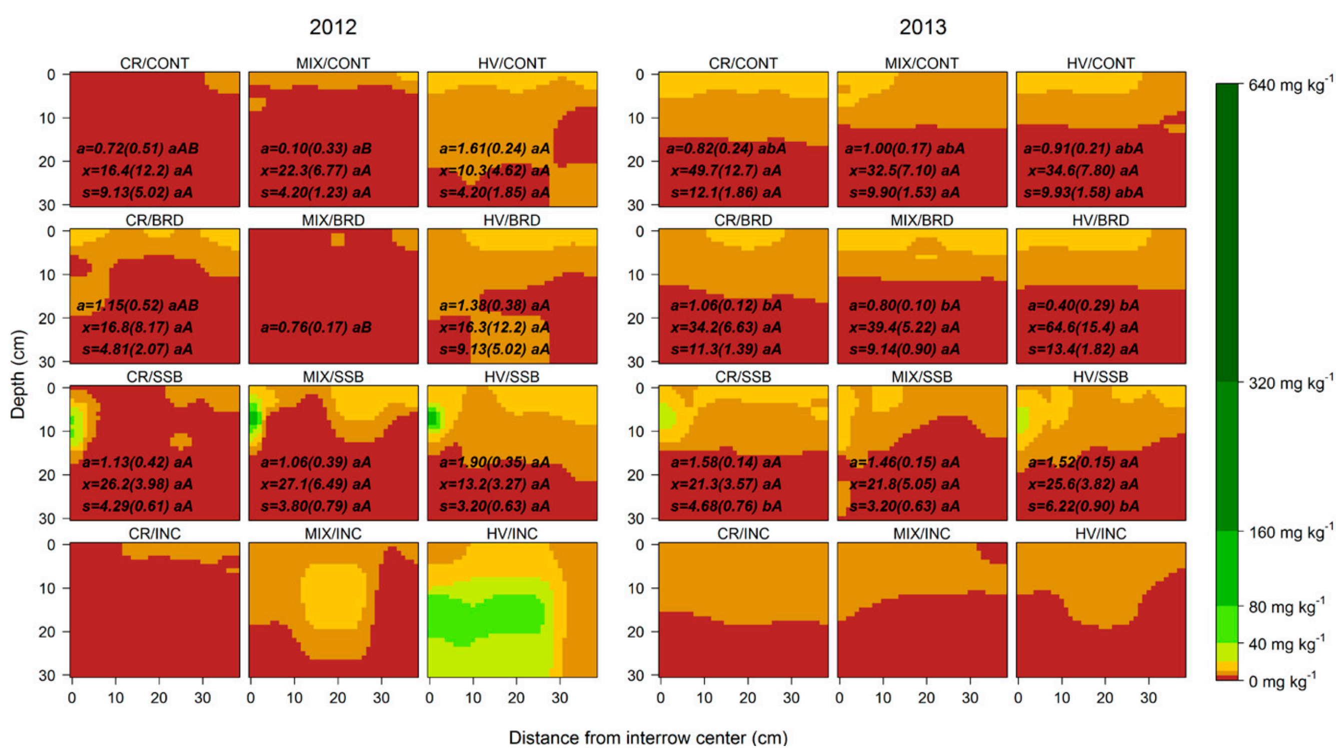

Fig. 7. Spatial distribution of soil mineral N concentration at corn maturity in 2012 and 2013 for three cover crop residues (CR = cereal rye, MIX = mixture, HV = hairy vetch) and four pelletized poultry litter (PPL) treatments (CONT = no PPL control, BRD = broadcast application, SSB = subsurface band application, INC = incorporated). Random walk models were fit as a function of distance from the soil surface for the CONT and BRD treatments, and as a function of distance from the PPL band for the SSB treatment. Random walk model parameter estimates (see Eq. [1]) and standard errors (shown in parentheses) are on the natural log scale. Different lowercase letters indicate that estimates for that parameter are significantly different ($P < 0.05$) among PPL treatments within the same cover crop residue and year. Different uppercase letters indicate that estimates for that parameter are significantly different ($P < 0.05$) among different residues within the same PPL treatment and year.

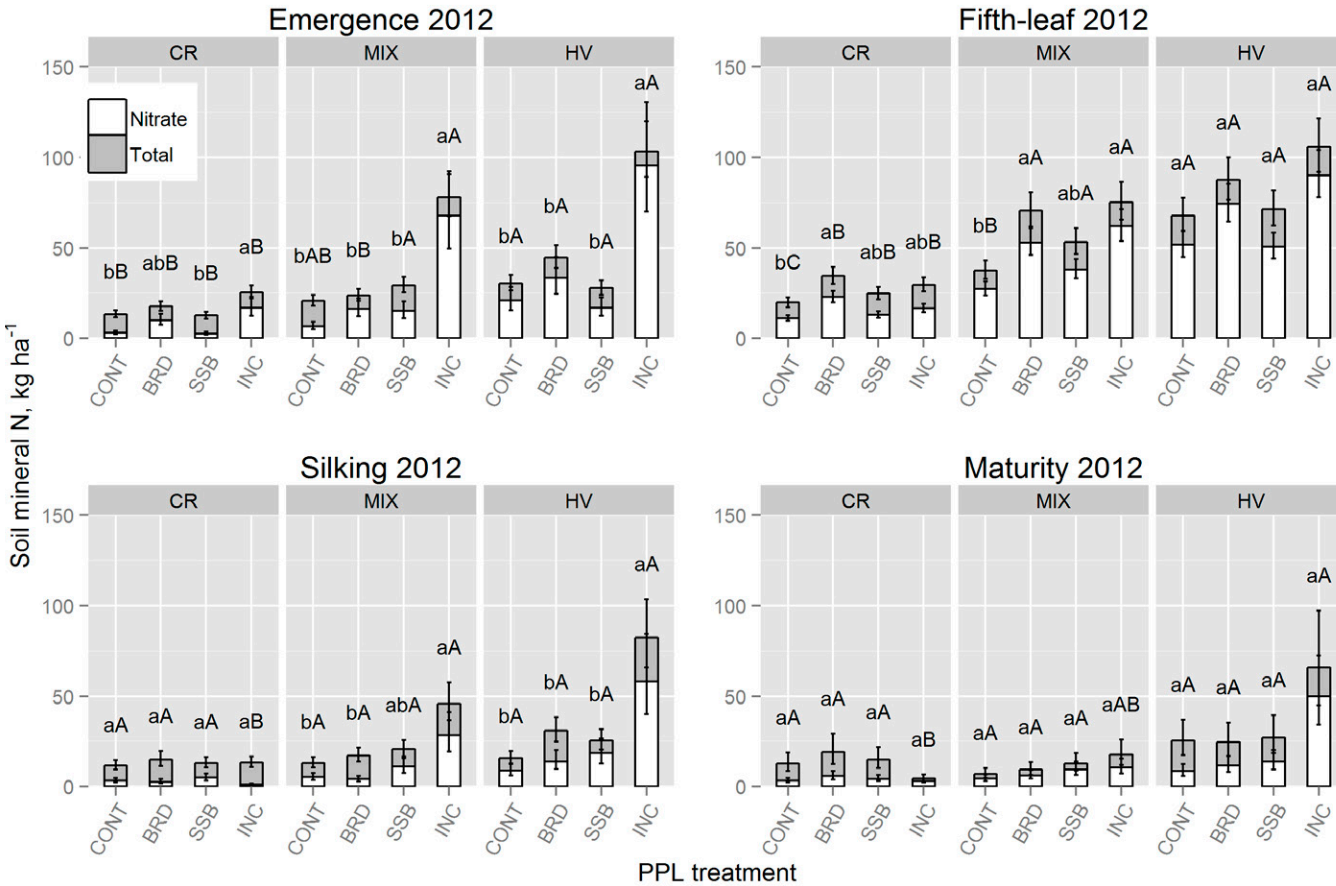

Fig. 8. Average soil mineral N (N_{min}) content to the 30-cm depth by growth stage, cover crop residue type (CR = cereal rye, MIX = mixture, HV = hairy vetch), and pelletized poultry litter (PPL) treatment (CONT = no PPL control, BRD = broadcast application, SSB = subsurface band application, INC = incorporated) in 2012. We computed average total N_{min} as the mean of N_{min} spatial predictions. Average NO_3^-–N estimates were calculated using the mean of measured concentrations. Different lowercase letters indicate significant differences (*P* < 0.05) in average total N_{min} among PPL treatments within the same cover crop residue and growth stage. Different uppercase letters indicate significant differences (*P* < 0.05) in average total N_{min} among different residues within the same PPL treatment and growth stage. Error bars represent 67% confidence intervals.

cereal rye when no PPL was applied. At the fifth-leaf growth stage in 2013, these values were 27 and 16 kg ha^{-1}, respectively. Other researchers found N_{min} levels of 40 to 100 kg ha^{-1} to 20 or 30 cm under hairy vetch residue (Huntington et al., 1985; Cook et al., 2010) and 25 kg ha^{-1} to 20 cm under cereal rye residue (Huntington et al., 1985) at this growth stage. The average N_{min} content of the cover crop mixture at the fifth-leaf stage was intermediate between the N_{min} of the monocultures in 2012 (38 kg ha^{-1}) and more similar to the N_{min} under cereal rye (17 kg ha^{-1}) in 2013. This year effect on average N_{min} under the mixtures was consistent with the greater C/N ratio of the mixture in 2013 relative to 2012 (Table 4).

There were few statistical differences among the no-till PPL treatments within each cover crop residue, but average N_{min} tended to be greater in the BRD than CONT and SSB treatments in the early stages of corn growth (Fig. 8 and 9). The trend toward elevated N_{min} in the BRD treatment relative to the other no-till PPL treatments indicates that the PPL N applied on the soil surface at the time of corn planting was mineralized and entered the soil rather than volatilized or immobilized in the surface residues. On average, N_{min} in the surface 30 cm at corn emergence was 2.4 times as great in the INC treatment as the CONT and SSB treatments and 1.9 times as great as the BRD treatment, with the greatest effect of the INC treatment observed in the hairy vetch residue. While both the INC and BRD treatments had received PPL before this sampling date, the greater average N_{min} content at emergence in the INC treatment than in the BRD treatment was probably a result of the more rapid N release from residues and PPL after incorporation. Other studies have reported approximately 50% more N released from incorporated legume residues than surface-applied residues around 4 wk after cover crop termination (Wilson and Hargrove, 1986; Varco et al., 1993; Poffenbarger et al., 2015b). In the relatively dry 2012 season, the trend of greater average N_{min} in the INC treatment persisted throughout the season for the mixture and hairy vetch residues (Fig. 8), while in the wetter 2013 season, PPL treatment affected N_{min} only at corn emergence (Fig. 9).

Proportion of Soil Mineral Nitrogen as NO_3^-–N

For most treatment and growth stage combinations, NO_3^-–N made up approximately 50% or more of the average total N_{min}. The proportion of NO_3^-–N tended to be lower in treatments with relatively low N_{min} levels (Fig. 8 and 9). Immediately after subsurface band PPL application in both

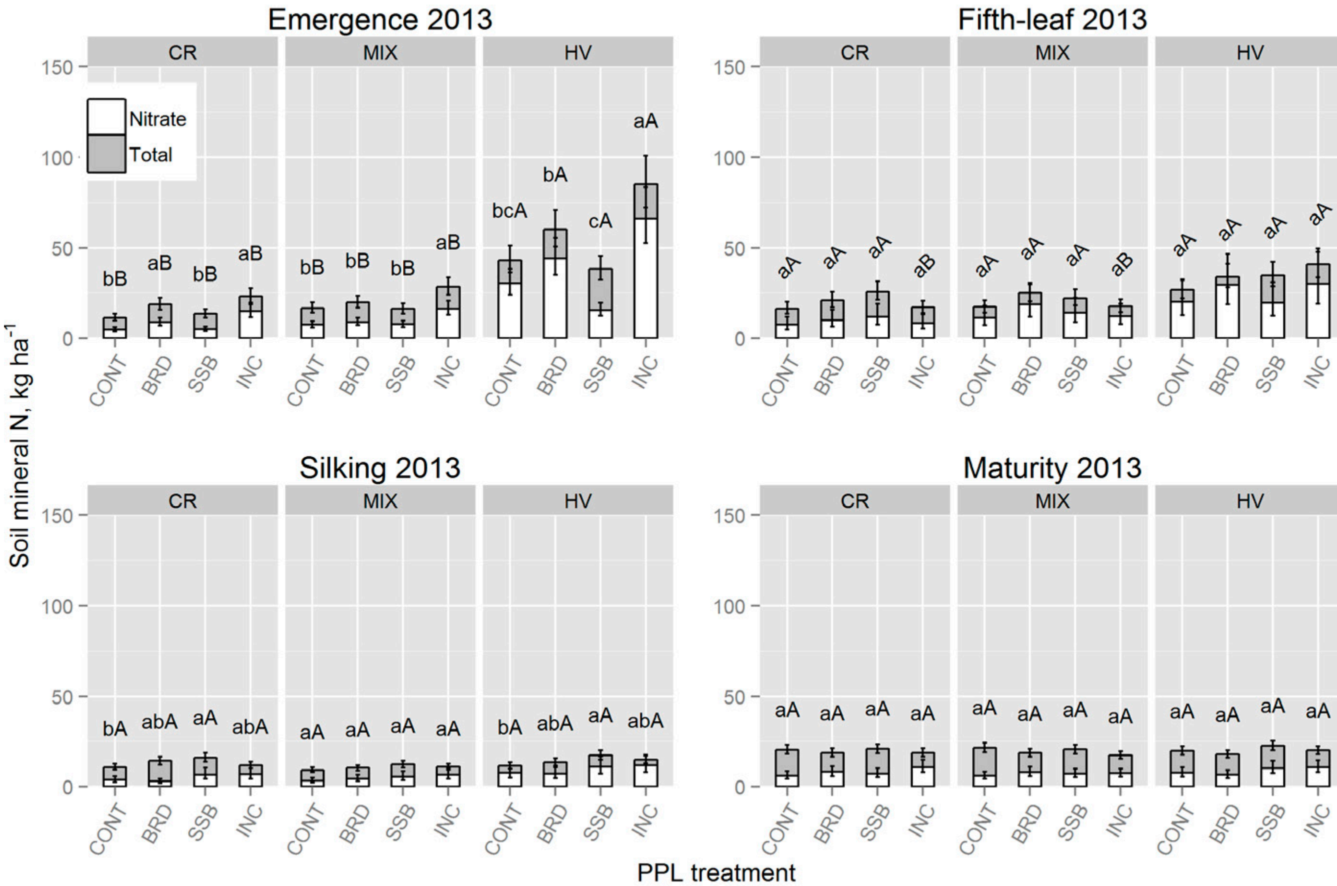

Fig. 9. Average soil mineral N (N_{min}) content to a 30-cm depth by growth stage, cover crop residue type (CR = cereal rye, MIX = mixture, HV = hairy vetch), and pelletized poultry litter (PPL) treatment (CONT = no PPL control, BRD = broadcast application, SSB = subsurface band application, INC = incorporated) in 2013. We computed average total N_{min} as the mean of N_{min} spatial predictions. Average NO_3^-–N estimates were calculated using the mean of measured concentrations. Different lowercase letters indicate significant differences (*P* < 0.05) in average total N_{min} among PPL treatments within the same cover crop residue and growth stage. Different uppercase letters indicate significant differences (*P* < 0.05) in average total N_{min} among different residues within the same PPL treatment and growth stage. Error bars represent 67% confidence intervals.

years, NH_4^+–N made up >75% of N_{min} within the band, while NO_3^-–N made up the majority of N_{min} outside of the band (Supplementary Fig. 2). In 2012, N_{min} within the band had become mostly NO_3^-–N by silking, while in 2013 N_{min} within the band remained mostly NH_4^+–N throughout the season.

Corn Nitrogen Uptake

Corn N uptake ranged from 97 to 252 kg ha^{-1} in 2012 and from 43 to 196 kg ha^{-1} in 2013 (Table 6). The lower corn N uptake in 2013 is consistent with the average topsoil N_{min} results suggesting early-season N losses in the latter year. Hairy vetch residue provided significantly greater N to corn than cereal rye for all PPL treatments in both years (*P* < 0.05). Averaged across years, corn took up 70, 102, and 160 kg N ha^{-1} in cereal rye, mixture, and hairy vetch residues with no PPL amendment. Significantly greater corn N uptake or grain yields with hairy vetch residue than with cereal rye residue have been previously reported in the literature, particularly when no supplemental N was applied (Wagger, 1989; Clark et al., 1997b; Vaughan and Evanylo, 1998, 2007). Corn N uptake in the 2012 mixture was similar to, or greater than, corn N uptake in the hairy vetch residue, depending on the PPL treatment. However, corn N uptake in the 2013 mixture was significantly less than in the hairy vetch residue (*P* < 0.05), and generally similar to corn N uptake in cereal rye. Although cover crop mixtures are appealing in that they can merge multiple services (e.g., weed suppression and N supply), the composition and properties of cover crop mixtures can vary greatly among growing seasons, soil properties, and levels of residual N (Clark et al., 2007; Brennan et al., 2011; Poffenbarger et al., 2015a), which can complicate decisions about N input rates for the following crop.

We measured significantly greater corn N uptake in one or more of the PPL-amended treatments than in the CONT treatment for all cover crop residue types (*P* < 0.05), suggesting that none of the three residue types provided enough N to fully meet corn N requirements. The PPL treatments added approximately 50 kg PAN ha^{-1}, averaged over cover crop residue types and the BRD, SSB, and INC treatments, in both years (Table 6). We observed that corn N uptake differences among cover crop residues persisted even with the application of PPL, suggesting that 3.5 Mg PPL ha^{-1} was insufficient to meet corn N requirements in the cereal rye residue in both years and also in the mixture residue in 2013. The amount of PAN provided by hairy vetch residue and PPL in both years and that provided by the

Table 6. Corn N uptake at physiological maturity for three cover crop residues and four pelletized poultry litter (PPL) application methods (CONT = no PPL control, BRD = broadcast application, SSB = subsurface band application, INC = incorporated) in 2012 and 2013. Different lowercase letters indicate significant differences ($P < 0.05$) among PPL treatments within the same cover crop residue. Different uppercase letters indicate significant differences ($P < 0.05$) among different residues within the same PPL treatment. Standard errors are shown in parentheses.

	Corn N uptake, kg ha^{-1}		
PPL	Cereal rye	Mixture	Hairy vetch
		2012	
CONT	97 (18) bB	136 (17) bAB	190 (17) bA
BRD	97 (31) abB	232 (17) aA	252 (17) aA
SSB	162 (18) aB	216 (17) aAB	224 (17) abA
INC	115 (17) abC	242 (18) aA	183 (18) bB
		2013	
CONT	43 (31) bB	68 (31) bB	130 (31) cA
BRD	92 (31) aB	125 (31) aB	196 (31) aA
SSB	101 (31) aC	139 (31) aB	183 (31) abA
INC	86 (31) aB	76 (31) bB	158 (31) bA

mixture residue and PPL in 2012 was likely adequate to achieve average grain yields for irrigated corn in the state (state irrigated corn grain yield averages were 12.30 and 11.80 Mg ha^{-1} in 2012 and 2013, respectively; USDA-National Agricultural Statistics Service, 2015). Our observed corn responses to PPL amendment are consistent with results of other published studies (Wagger, 1989; Utomo et al., 1990; Clark et al., 1997a; Clark et al., 2007), which reported optimal N fertilizer rates of 0 to 100 kg ha^{-1} following late-terminated hairy vetch, and greater rates of 100 to 300 kg ha^{-1} following late-terminated hairy vetch–cereal rye mixtures and cereal rye monocultures.

Corn N uptake was generally similar between the BRD and SSB treatments. Other studies, conducted using non-pelletized poultry litter, have shown greater corn N uptake with subsurface band application than broadcast application (Pote et al., 2011; Adeli et al., 2012). However, Adeli et al. (2012) found no difference in corn N uptake between broadcast and subsurface band application when PPL was used, suggesting that PPL is less susceptible than non-pelletized poultry litter to N losses when surface-applied.

In 2012, the hairy vetch INC treatment resulted in lower corn N uptake than the hairy vetch BRD treatment ($P < 0.05$). Given that ample soil N_{min} was present throughout the season in the hairy vetch INC treatment (Fig. 8), we attribute the reduced corn N uptake to the low soil moisture in this treatment (Table 5). Averaged across cover crop residue types, the INC treatment resulted in significantly lower corn N uptake than the BRD and SSB treatments in 2013 ($P < 0.05$; Table 6). This was likely due to rapid N mineralization from the cover crop residues and/or PPL after incorporation (Varco et al., 1993; Dou et al., 1994; Poffenbarger et al., 2015b), which generated a pool of soil N_{min} that was partially lost between corn emergence and the fifth-leaf stage (Fig. 9).

Study Implications

The goal of this study was to develop a cover crop- and poultry litter-based no-till corn system with adequate and efficient N delivery. The combination of hairy vetch residue and PPL, broadcast or subsurface banded at a P-based rate, provided adequate N for corn without causing excessive N_{min} in the fall. However, our 2013 soil N_{min} results suggest that the rapid availability of hairy vetch N could pose a risk for early-season N_{min} losses in a wet spring. We found that cereal rye and the hairy vetch–cereal rye mixture generated a smaller N_{min} pool than hairy vetch before the corn fifth-leaf stage, reducing the risk for early-season N losses. Our N uptake results showed that corn growing in the cereal rye residue required a PPL application rate higher than the P-based rate that we applied. On the other hand, the P-based rate appeared to deliver sufficient N to corn growing in the hairy vetch–cereal rye mixture in 2012. That said, because soil N_{min} and corn N uptake results differed considerably for the mixture residue between the 2 yr, decisions regarding PPL application rate should be made with some knowledge of mixture composition and/or C/N ratio, properties that can help predict N release from the mixtures (Poffenbarger et al., 2015b).

Our results showed a clear advantage of broadcast and subsurface band PPL application methods over incorporation, due to the better soil moisture conservation in a relatively dry year (2012) and lower risk of early-season N_{min} losses in a wet spring (2013). According to other studies, subsurface banded PPL also offers the benefit of reduced NH_3 volatilization (Pote and Meisinger, 2014) and P losses (Pote et al., 2011), but the disadvantage of greater denitrification losses relative to surface application (Comfort et al., 1988; Dosch and Gutser, 1996; Wulf et al., 2002).

By monitoring the spatial distribution of topsoil N_{min} after subsurface band PPL application, we discovered that corn plants took up N_{min} from the PPL band before substantial movement of N_{min} away from the band, causing PPL N_{min} to remain localized around the point of delivery at least through the end of the corn growing season. This finding implies that careful soil sampling methods must be employed throughout a corn growing season to avoid over- or underestimating the N_{min} contribution of this highly concentrated patch. We found that a sample comprising four to six cores (30 cm deep) away from the band for every one 30 cm-deep core in the band (within 5 cm of center) would provide the most accurate estimate of N_{min} at all growth stages (Figure S1). Based on the spatial distribution of several soil nutrients in soil receiving subsurface banded poultry litter, Tewolde et al. (2013) recommended that 15-cm deep soil cores be taken every 5 cm between bands for every one core in the band, equating to approximately 14 cores away from the band per core in the band for a 76-cm row spacing. Adjusting for differences in sampling depth, this recommendation represents a similar proportion of soil taken within the band vs. away from the band as our sampling scheme.

CONCLUSION

Cover crop residue type and PPL application method affected the spatiotemporal distribution of topsoil N_{min}, and ultimately the amount of N available to corn. Hairy vetch residue resulted in relatively high N_{min} concentrations extending deeper into the soil than the cover crop mixture and cereal rye residue treatments, particularly early in the corn growing season. Most of the N_{min} in the BRD treatment was concentrated near the soil surface, N_{min} associated with the PPL band remained within 10 cm of the delivery location throughout the growing season, while N_{min} was distributed to a depth of 20 cm in the INC treatment. The hairy vetch residue provided significantly greater average soil N_{min} to 30 cm than the cereal rye residue at emergence and the fifth-leaf stage, while the cover crop mixture resulted in average N_{min} levels either intermediate to the monocultures or similar to cereal rye, depending on the year. None of the three residue types provided enough N to fully meet corn N requirements without PPL N, as indicated by the greater corn N uptake measured in one or more of the PPL-amended treatments than in the CONT treatment for all cover crop residue types. Incorporating cover crop residues and PPL with tillage exacerbated dry soil conditions in 2012 and led to excess N_{min} from the hairy vetch residue after corn harvest. In the relatively wet spring, the rapid N mineralization of hairy vetch residue in the INC treatment led to early-season losses of N_{min}. Therefore, the no-till treatments provided more efficient delivery of cover crop and PPL N. For each cover crop residue type, the broadcast and subsurface band application methods provided a similar amount of PAN.

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