ABSTRACT

Title: NITROGEN DYNAMICS IN COVER CROP-BASED NO-TILL CORN

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Legume/grass cover crop mixtures and sidedress subsurface band manure application are two approaches to improving nitrogen (N) use efficiency in a cover crop-based no-till corn (*Zea mays* L.) system. The objectives of this study were to: 1) quantify cover crop biomass and N content in response to different hairy vetch (*Vicia villosa* Roth)/cereal rye (*Secale cereale* L.) sown proportions, 2) evaluate the effects of cover crop species proportions and pelletized poultry litter (PPL) application method on residue decomposition, and 3) model the spatio-temporal dynamics of soil inorganic N as influenced by different cover crop residues and subsurface band-applied PPL. Results suggest that cover crop mixtures can accumulate as much biomass as a cereal rye monoculture and as much N as a hairy vetch monoculture, and have decomposition patterns intermediate between those of monocultures. Subsurface band PPL application provided a localized N source that did not influence decomposition of surface mulches.

NITROGEN DYNAMICS IN COVER CROP-BASED NO-TILL CORN

by

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Contents

List of tables

List of figures

Chapter 1 Introduction

Background and problem definition

No-till cropping and organic agriculture represent two of the most successful strategies to maintain agricultural profitability while improving long-term soil health. Organic grain production enhances soil quality relative to conventional production through the use of plant- and manure-based fertility sources and by diversified crop rotations, which build soil organic matter and boost soil biological activity (Dick 1992, Teasdale et al. 2007). The disproportionate growth of organic dairy and poultry industries relative to organic grain production in recent years (Dmitri and Oberholtzer 2009) has resulted in a high demand and price premiums for organic grain (USDA-ERS 2011). No-till cropping reduces soil erosion, improves soil physical structure, conserves water, and increases soil organic matter in previously tilled croplands (Blevins et al. 1983, Chan and Mead 1988, Pimental et al. 1995, Franzluebbers and Arshad 1997, Six et al. 2002, Spargo et al. 2008). These conservation benefits, along with fuel cost savings and reduced field operations (Kern and Johnson 1993), have led to increasing farmer adoption of no-till cropping, with an estimated 30% of corn (*Zea mays* L.) cropland in no-till production in 2009 (Horowitz et al. 2010). While the two systems offer complementary soil health and economic benefits, they have been largely incompatible: organic production relies on primary tillage for weed control, while no-till production relies on conventional herbicides. A cover crop-based rotational no-till system, in which a rolled cover crop provides weed control, offers the potential to combine the soil-building features of organic practices with the soil-conserving features of no-till. By reducing the number of tillage operations and the volume of herbicides required for weed control, this system may provide a strategy for organic farmers to expand their production and for conventional farmers to manage herbicide-resistant weed populations in no-till fields. In fact, both groups have identified the development of cover crop-based rotational no-till as a critical research need (Sooby et al. 2007, Price et al. 2011).

A cover crop-based rotational no-till soybean (*Glycine max* (L.) Merr.) system, in which soybeans are no-till planted into a mat of cover crop residue flattened by a roller/crimper, has been successfully implemented in field trials in the eastern and central U.S. (Davis 2010, Mischler et al. 2010a, Bernstein et al. 2011, Smith et al. 2011, Mirsky et al. 2013). In this system, the winter-hardy grass cover crop, cereal rye (*Secale cereale* L.), is rolled in late spring, forming a thick, highly-persistent mulch. The mulch suppresses weeds both physically and biogeochemically, by stimulating nitrogen (N) immobilization in the soil profile due to their high carbon (C) inputs (Wells et al. 2013). The large-seeded legume cash crop emerges through the mulch and is unaffected by N depletion in the soil profile as it acquires N through symbiotic N fixation. The system is termed “rotational no-till” because tillage is not performed during the soybean phase of the crop rotation, but is recommended prior to cover crop planting in the fall to control perennial weeds. A cover crop-based rotational no-till system has been developed for corn, using the winter annual legume cover crop, hairy vetch (*Vicia villosa* Roth), which releases N and provides physical weed suppression after termination in late spring. However, inability to consistently control weeds and provide adequate N fertility has limited the success of this system (Mischler et al. 2010b).

One approach to addressing weed control challenges associated with the cover crop-based rotational no-till corn system is to use a legume/grass cover crop mixture.

Growing cereal rye with hairy vetch may increase overall biomass of the cover crop (Clark et al. 1997a, Sainju et al. 2005, Brainard et al. 2012), and increase mulch persistence by slowing decomposition of residues (Ranells and Wagger 1996, Ruffo and Bollero 2003). However, growing a grass with a legume can reduce the N release rate and total available N from the residue (Kuo and Sainju 1998, Rosecrance et al. 2000). The recently-developed subsurface band applicator for dry manure provides one strategy to efficiently deliver supplemental N required to meet corn N demands. Localized manure placement has been shown to improve N use efficiency in no-till corn (Pote et al. 2011, Adeli et al. 2012).

Justification

The many potential benefits associated with legume/grass cover crop mixtures relative to monocultures, including greater biomass production and N accumulation, increased legume biological N fixation and better-timed residue decomposition, has spurred adoption of these and other types of cover crop mixtures among conservation-minded producers. In a recent survey of farmers who use cover crops in the North Central U.S., 63% have used two-species and multi-species mixtures on their farms (SARE-CTIC 2013). However, a recent meta-analysis of cover crop effects on subsequent corn yields found that while legume/grass mixtures had an overall positive effect on yields relative to bare soil and grass cover crops, the outcomes varied greatly because cover crop management practices have not been established to optimize cover crop mixtures for desired services and establishment costs (Miguez and Bollero 2005). Although the benefits of legume/grass mixtures have been well-documented, further research is needed to determine how seeding rates, planting and termination dates, soil properties, and weather conditions affect the biomass, species proportions, N content and N fixation of mixtures. Furthermore, because N contributions and weed suppression from cover crops remain difficult to predict among diverse temperature and moisture conditions, research is needed to quantify how properties of the cover crop mixture and manure management affect decomposition of a rolled mulch.

Animal manures are an important nutrient source in cropping systems, although they tend to oversupply phosphorus (P) when applied as the sole N source (Preusch et al. 2001, Toth et al. 2006). Excessive manure P application may be avoided by applying manure at a P-based rate in conjunction with a legume N source. The most common manure delivery method in no-till systems is surface application prior to corn planting, which can lead to high rates of N loss through NH_3 volatilization (Keller and Mengel 1986, Sharpe et al. 2004). A prototype subsurface band poultry litter applicator has been shown to reduce NH_3 volatilization losses by ~90% (Pote and Meisinger 2014) and increase corn yields relative to broadcast application (Pote et al. 2011, Adeli et al. 2012) with minimal disturbance to surface residues. Subsurface manure application may also reduce the effect of supplemental N on decomposition rates of the surface mulches (Mengel et al. 1982) and reduce weed growth (DiTomaso 1995), but may increase denitrification losses due to the close proximity of available C and NO_3^--N, the substrates required for denitrification (reviewed in Dell et al. 2011 and Maguire et al. 2011). Applying manure at the corn fifth-leaf growth stage rather than at planting is expected to improve N use efficiency by reducing opportunities for N loss prior to corn uptake (Cassman et al. 2002, Dinnes et al. 2004). While previous research suggests that manure placement and timing of application have an important impact on agronomic outcomes, little work has been performed to measure and model the spatiotemporal distribution of inorganic N as affected by dry manure placement, especially in integrated cover crop-manure systems.

Research approach

A replicated field experiment was initiated at the Beltsville Agricultural Research Center in fall 2011 and repeated in fall 2012. The experiment included a factorial of six hairy vetch (*Vicia villosa* Roth)/cereal rye (*Secale cereale* L.) sown proportions (four different mixtures and two monocultures) and four pelletized poultry litter (PPL) applications (no PPL, sidedress subsurface banded PPL at P-based rate, pre-plant broadcast PPL at P-based rate, and pre-plant broadcast-incorporated PPL at P-based rate as a tillage check) in a no-till corn system. Within this larger experiment, three specific studies were conducted. The first study characterized cover crop biomass, species biomass proportions, N content and hairy vetch N fixation at the time of termination across hairy vetch/cereal rye sown proportions on four site-years. In the second study, residues of each species were mixed at specific proportions and placed in litter bags, which were installed on two site-years and collected over time to determine mass and N loss of residues as affected by cover crop proportions, PPL application (0 vs. 67 kg plant-available N ha^{-1}), PPL placement (broadcast vs. subsurface band) and tillage (incorporated vs. no-till). Soil moisture and temperature conditions during decomposition were continuously monitored using soil sensors. In the third experiment, soil cores were collected at specific corn interrow locations and depths and at several corn growth stages during two corn growing seasons. The samples were analyzed for soil inorganic N to determine the spatiotemporal distribution of soil inorganic N as affected by cover crop species proportions (monocultures and one mixture), and sidedress subsurface band PPL application relative to no PPL, pre-plant broadcast PPL and pre-plant broadcast-incorporated PPL. Soil temperature, moisture and electrical conductivity measurements were also collected continuously at specific soil profile locations to monitor conditions within and around the PPL band.

Objectives and hypotheses

1) Evaluate total aboveground cover crop biomass and species proportions in response to different hairy vetch/cereal rye sown proportions
    a. Hypothesis 1: Biomass proportions of each species in mixture will change as the seeding rate of one species increases and the seeding rate of the other species declines, and the total biomass will increase with increasing seeding rate of the more productive monoculture.
2) Characterize N content and biological N fixation across a gradient of hairy vetch/cereal rye biomass proportions
    a. Hypothesis 1: Monoculture cereal rye will have the lowest N content. Cover crop N content will increase as hairy vetch biomass proportion in cover crop increases, reach maximum N content in mixture, and decrease slightly in monoculture hairy vetch.
    b. Hypothesis 2: The proportion of biologically fixed N in hairy vetch will decrease linearly as the proportion of hairy vetch biomass in mixture increases.
3) Evaluate the potential for transfer of biologically fixed N from hairy vetch to cereal rye grown in mixture

    a. Hypothesis: The proportion of biologically-fixed N in cereal rye will increase as the proportion of hairy vetch biomass in mixture increases.

4) Test whether and at what sown proportions the biomass and N accumulation of hairy vetch/cereal rye mixtures exceed the average biomass and N accumulation of monocultures ("overyielding")
    a. Hypothesis: the biomass and N accumulation of mixtures will exceed the average biomass and N content of monocultures for some sown proportions.
5) Determine the effects of hairy vetch/cereal rye biomass proportions and PPL application treatment (no PPL vs. subsurface band vs. broadcast vs. incorporated) on the proportion of mass and N loss during the subsequent corn growing season and on the rates of mass and N loss
    a. Hypothesis 1: The proportions and rates of mass and N loss will increase linearly as hairy vetch proportion in the cover crop residue increases.
    b. Hypothesis 2: Subsurface band PPL application will not affect the proportion and rates of mass and N loss relative to no PPL application.
    c. Hypothesis 3: Broadcast application of PPL will increase the proportion and rates of mass and N loss relative to the no PPL treatment for cover crop mixtures containing >50% cereal rye biomass.
    d. Hypothesis 4: Tillage will increase the proportion and rates of mass and N loss for residues relative to the no PPL treatment regardless of cover crop composition.
6) Model the spatial distribution of soil inorganic N at five important developmental

stages of corn as affected by cover crop residue type (hairy vetch vs. mixture vs. cereal rye) and PPL application treatment (no PPL vs. broadcast vs. subsurface band vs. incorporated)

  a. Hypothesis 1: Soil inorganic N concentration will be greatest at the soil surface and decrease with increasing distance from the soil surface in the no PPL treatment under surface cover crop residues containing hairy vetch. There will be no spatial pattern to soil inorganic N concentration under pure cereal rye residue with no PPL.
  b. Hypothesis 2: Soil inorganic N concentration will be greatest at the soil surface and decrease with increasing distance from the soil surface in the broadcast PPL treatment.
  c. Hypothesis 3: Soil inorganic N concentration will be greatest at the PPL band and decrease with increasing distance away from the band. Soil inorganic N will also be elevated at the soil surface under cover crop residues containing hairy vetch in the subsurface band PPL treatment.
  d. Hypothesis 4: Soil inorganic N concentration will be uniform throughout the plow layer in the incorporated PPL treatment.
  e. Hypothesis 5: The peak (soil profile region of elevated inorganic N) and background soil inorganic N concentrations will be greatest at fifth-leaf stage and decline over the corn growing season in all PPL and cover crop treatments.

7) Estimate and compare soil inorganic N in soil profiles as affected by growth stage, cover crop residue type (hairy vetch vs. mixture vs. cereal rye) and PPL

application treatment (no PPL vs. broadcast vs. subsurface band vs. incorporated)

a. Hypothesis 1: Soil inorganic N will be greatest at the fifth-leaf growth stage, moderate at emergence and silking, and lowest at the milk and blacklayer growth stages.
b. Hypothesis 2: Cover crop residue composition will have a significant effect on soil inorganic N throughout the corn growing season, following this order: hairy vetch > mixture > cereal rye.
c. Hypothesis 3: Pelletized poultry litter application treatment will have a significant effect on soil inorganic N throughout the corn growing season, following this order: incorporated > subsurface band > broadcast > no PPL.

Chapter 2 Literature review

Cover crop-based rotational no-till

The cover crop-based rotational no-till system relies on fall-planted cover crops that are rolled the following spring to control weeds during the subsequent crop growing season. Generally, legumes, such as the winter-hardy annual legume hairy vetch (*Vicia villosa* Roth), are grown prior to corn (*Zea mays* L.) because they release nitrogen (N) during decomposition. In contrast, grasses, such as cereal rye (*Secale cereale* L.), often precede N-fixing soybeans (*Glycine max* (L.) Merr.) because the grasses produce a large amount of carbon (C)-rich biomass and decompose slowly for optimal weed suppression (reviewed in Mirsky et al. 2012). Prior to planting the cash crop, the cover crop is terminated at a specific reproductive growth stage (after anthesis for grasses, Mirsky et al. 2009; after flowering for hairy vetch, Mischler et al. 2010b) using a roller/crimper implement. The roller/crimper consists of a hollow steel cylinder 30-60 cm in diameter with blades along the outside of the cylinder designed to crush and crimp the cover crop, forming a dense, unidirectional mulch (Ashford and Reeves 2003).

Research has shown that the mulch formed after cover crop termination by rolling/crimping may suppress weeds through several mechanisms: by physically blocking emergence (Teasdale and Mohler 2000), by reducing light transmittance (Teasdale and Mohler 1993), by releasing allelopathic chemicals (Creamer et al. 1996) and/or by immobilizing N in the case of high C/N ratio grass mulches (Wells et al. 2013). However, the ability of a cover crop to form an effective weed-suppressive mulch depends upon its biomass production: Mohler and Teasdale (1993) found that cover crop residue must be present at greater than 8 Mg ha^{-1} to achieve 75% inhibition of weed emergence. Due to the great importance of high cover crop biomass in achieving consistent weed control, several researchers have investigated management practices to optimize cover crop productivity. Mirsky et al. (2011) found that biomass of cereal rye and hairy vetch/cereal rye mixtures could be increased by 2 Mg ha^{-1} by planting in late August relative to mid-October or by delaying termination by 10 days in the spring, resulting in greater weed suppression by the cover crop mulch. Research has also been directed toward manipulating seeding rate and fertility to achieve biomass levels sufficient for weed control. For example, Ryan et al. (2011) evaluated the effects of poultry litter applied at three rates and three seeding rates on cereal rye biomass and subsequent weed suppression. Their results suggest that N fertility may have a greater effect than seeding rate on resulting cereal rye biomass, but that the early ground cover achieved with a high seeding rate may be necessary for optimum weed control.

Cover crop-based rotational no-till corn production: system performance

Several studies have been conducted to evaluate the performance of cover crop-based rotational no-till corn. Delate et al. (2011) evaluated weed management, yields and economic performance of soybean, corn and irrigated tomato (*Lycopersicon esculentum* Mill.) in cover crop-based rotational no-till and standard tillage organic production in Iowa. A rolled hairy vetch/cereal rye mixture provided inferior weed control relative to the standard tillage treatment. Among the three crops, corn suffered the greatest weed competition. Corn yields and returns were consistently lower in the no-till system than the standard tillage system, likely due to a combination of low rainfall, weed competition, vetch regrowth and N deficiency. Similarly, in Kentucky, Suarez (2010) found that corn no-till planted into rolled hairy vetch produced lower and more variable yields than corn planted into tillage-incorporated hairy vetch.

In the mid-Atlantic U.S., research has been performed to tease apart the factors that influence corn performance in the cover crop-based rotational no-till system. In a Pennsylvania study testing this system, corn performance was limited by incomplete weed control, hairy vetch regrowth, poor crop establishment and N limitation (Mischler et al. 2010b). However, the authors found that delaying cover crop termination from late May to late June increased hairy vetch biomass and reduced weed biomass during the corn growing season. Delayed termination dates also resulted in greater corn yields as a result of more effective termination, lower weed pressure and reduced cutworm damage. Teasdale et al. (2012) also found that corn yields in a hairy vetch-based organic no-till system were greatest when the planting date was delayed until mid-June, due to reduced weed competition. The use of high-residue cultivation in the cover crop-based rotational no-till corn system resulted in comparable yields to corn planted into disk-killed hairy vetch.

Hairy vetch/cereal rye mixtures

Hairy vetch/cereal rye mixtures have been proposed as one approach to improve weed suppression and N supply in the cover crop-based rotational no-till corn system (Mirsky et al. 2012, Teasdale et al. 2012). Past research has uncovered many of the agricultural benefits and ecological mechanisms associated with legume/grass mixtures. Legumes and grasses derive N from different pools (legumes from atmospheric N_2; grasses from soil), a feature that allows both N scavenging and atmospheric N fixation to occur simultaneously in legume/grass cover crop mixtures (Clark et al. 1997a). Furthermore, legumes grown in mixture with a grass often derive a greater proportion of their N from biological N fixation than in monoculture, and in some cases, this fixed N may be transferred to the companion grass (Ta and Faris 1987, Mallarino et al. 1990a, Frey and Schuepp 1992, Izaurralde et al. 1992, Jensen 1996, Paynel and Cliquet 2003, Brainard et al. 2012, Schipanski and Drinkwater 2012). In fact, the N concentration of grasses in mixtures with legumes have been shown to increase as the proportion of legume in mixture increases (Tosti et al. 2010, Hayden et al. 2014), indicating that the grass is able to acquire greater soil inorganic N when grown in mixture with a N-fixing legume than when grown with other grasses. Grasses and legumes differ in their architecture: the upright nature of grasses provides a trellis onto which a viney legume can climb to access greater light. The complementary ways in which grasses and legumes acquire resources can lead to greater biomass production and N accumulation of mixtures relative to monocultures.

A review was performed on nine published hairy vetch/cereal rye cover crop mixture studies conducted in the southeast, mid-Atlantic, mid-West and Pacific Northwest U.S. The review, which included data from the present study, summarized findings from 81 mixtures grown on 29 site-years between 1988 and 2013 (data from each study, averaged across site-years are presented in Table 2.1). Seeding rates ranged from 7 to 45 kg ha^{-1} for hairy vetch in mixture and 34 to 134 kg ha^{-1} for cereal rye in mixture (Table 2.1). In planting the mixtures, the majority of authors reduced the seeding rate of hairy vetch by less than half relative to its monoculture seeding rate and halved the seeding rate of cereal rye relative to its monoculture seeding rate. Cover crops were planted between early September and early November, and terminated between early April and late May. Among all site-years and treatments of the studies reviewed, biomass of mixtures ranged from 1.7 to 15.5 Mg ha^{-1} (mean = 6.3, standard error = 0.24), and N content ranged from 40 to 310 kg N ha^{-1} (mean = 122, standard error = 6.06). Seventy-eight percent of the mixtures produced greater biomass than both monocultures and 68% accumulated greater N than both monocultures. Statistical significance of mixture vs. monoculture biomass differences was not considered in calculating these percentages. A Relative Yield of Mixture index (Table 2.1) was calculated for the mixtures in which the seeding rates for each species were proportionally increased or decreased relative to their monoculture seeding rates following a replacement series design. A Relative Yield of Mixture value greater than one indicates that the mixture performed better than the weighted (by sown proportion) average of monocultures, a phenomenon termed "overyielding". Of these replacement series mixtures, 100% demonstrated biomass overyielding and 77% demonstrated N overyielding; 47% produced greater biomass in mixture than both monocultures, and 20% accumulated greater N than both monocultures.

Across all site-years and treatments of studies reviewed, several trends were observed among the reported variables. First, mixture biomass, N content and C/N ratio increased with increasingly delayed termination dates ($P<0.05$, Figure 2.1). Hairy vetch seeding rate in mixture was positively correlated with mixture N content ($P<0.10$), and cereal rye seeding rate in mixture was positively correlated with mixture biomass ($P<0.05$, Figure 2.2). Mixture C/N ratios were also positively and negatively correlated with cereal rye and hairy vetch seeding rates, respectively ($P<0.05$, data not shown). Study location appeared to be an important factor affecting biomass production and N content, with warmer climates producing mixtures with greater biomass and N content than colder climates (GA > NC = MD > IL = WA = MI). Planting date did not seem to affect mixture performance within this review. Other work has shown that a single day in the spring is more important than a single day in the fall in terms of cover crop biomass production, and this review may not have provided a wide enough range of planting dates to capture this effect (Mirsky et al. 2011). Only a relatively small subset of studies included data on the proportion of each species in mixture, and this variable did not show a relationship with other variables. However, Hayden et al. (2014) found that seeding rates were an excellent predictor of legume/grass proportions in mixture. Other studies have reported that timing of management plays an important role in mixture composition (Clark et al. 1994, Lawson et al. 2012). Soil inorganic N concentration is also known to be an important controlling factor on the proportion of legume biomass in mixture, since legumes tend to be more competitive when soil N levels are low (Clark et al. 1994). Weather may also influence mixture composition: studies suggest that hairy vetch is less competitive with cereal rye in colder conditions (also with later planting date and earlier termination date) because hairy vetch is less cold-tolerant than cereal rye (Ruffo and Bollero 2003, Lawson et al. 2012).

Cover crop residue quality and decomposition

Cover crop mixtures offer the potential to control weeds and supply N in a subsequent corn growing season, but the persistence and N release of the cover crop mulch depend on the residue quality. Grass cover crops tend to have a higher C/N ratio than legume cover crops (21 to 51 for cereal rye; 8 to 14 for hairy vetch; Clark et al. 1997a, Wagger 1989b, Kuo and Jellum 2002, Parr et al. 2011), and greater fraction of water-soluble C (Kuo et al. 1997b, Kuo and Sainju 1998), which contribute to the slow decomposition and low N release of grasses. In fact, residues with C/N ratios greater than 25 can reduce soil plant-available N because microbes utilize soil N during decomposition, making less available for a N demanding crop such as corn (Clark et al. 1997a, Kuo et al. 1997a). By immobilizing N and decomposing slowly, such high C/N residues contribute to physical and biogeochemical suppression of weeds. On the other hand, the low C/N ratio of legumes and high water-soluble N fraction (Kuo et al. 1997a, Kuo and Sainju 1998) allow them to decompose quickly, releasing a large proportion of N rapidly but providing little residue persistence for weed suppression. Cover crop residues with moderately high C/N ratios (10-30) associated with legume/grass mixtures have resulted in reduced emergence and biomass of weeds compared to pure legume residue (Teasdale and Abdul-Baki 1998) and greater N contribution compared to pure grass residue (Clark et al. 1997a). Residue C constituents such as lignin and polyphenol also drive decomposition dynamics, albeit mostly at later stages of decomposition (Herman et al. 1977, Berg and Staaf 1980, Melillo et al. 1989, Palm and Sanchez 1991). Although hairy vetch has been reported to have a higher lignin content than cereal rye, its low C/N ratio facilitates faster decomposition during the first corn growing season (Wagger 1989b, Lawson et al. 2012).

In controlled laboratory incubation studies, researchers have found that decreasing residue C/N ratios by manipulating the proportion of hairy vetch and cereal rye in cover crop residues leads to increasing N mineralization rates and increasing size of potentially mineralizable N pools (Kuo and Sainju 1998, Rosecrance et al. 2000, Lawson et al. 2012). Similar trends of increasing rates of mass and N loss (estimated using exponential decay constants) and increasing quantity of N losses with decreasing C/N ratios have been observed, although not consistently, in field studies using hairy vetch and cereal rye surface residues (N loss: Wagger 1989b, N decay constant and N loss: Ranells and Wagger 1996, mass decay constant: Starovoytov et al. 2010, mass and N decay constants: Ruffo and Bollero 2003). Across these four studies, (with residue C/N ratios ranging from 8 to 44), mass and N decay constants ranged from 0.005 to 0.06 day^{-1} and averaged 0.02 day^{-1} for mass and 0.03 day^{-1} for N. Averaged across the four studies, the residues lost 81% of their mass (range: 64-89) and 73% of their N (range: 13-94). The effect of C/N ratio on rates and quantities of loss could not be detected when estimates were pooled across studies. Thus, while C/N plays a role in decomposition, other factors must be considered to accurately estimate cover crop decay. Research has shown that incorporating residues increases the rate of decomposition 2-5x relative to surface placement (Wilson and Hargrove 1986, Holland and Coleman 1987, Varco et al. 1993). Some data suggest that decomposition occurs faster when less residue is added to a soil (Broadbent and Bartholemew 1945), while other studies have found no effect of loading rate (Jenkinson 1977, Honeycutt et al. 1993).

The large variability in decay constants observed among site-years suggests that temperature and moisture conditions have a strong effect on decomposition patterns. Several authors have modeled decomposition over temperature- and moisture-adjusted timescales to generate parameter estimates that are more consistent among site-years and between laboratory and field studies. For example, Honeycutt et al. (1988) and Ruffo and Bollero (2003) used heat units, computed by summing mean daily soil or air temperatures above 0° C, to adjust decomposition models for the effect of temperature. Heat units appear to adequately predict N mineralization over a soil potential range of -0.03 to -0.01

MPa (Doel et al. 1990). Stroo et al. (1989) proposed “decomposition days”, a timescale specifically designed for decomposition of surface residues, which involves calculating temperature and moisture factors and summing the most limiting factor for each day. This approach has been used in soil erosion models (Schomberg and Steiner 1997). In 2004, Quemada proposed “adjusted growing degree days”, calculated by dividing daily mean temperature by the difference between daily maximum and minimum temperatures to capture the interaction of moisture and temperature on decomposition of surface mulches. Rather than using adjusted timescales, Andren and Paustian (1987) used the interaction of Q_{10} temperature relationships and a log-linear function of soil water potential to modify rate constants for buried residues. One important note is that most field studies conducted to quantify residue decomposition have used a litter bag approach, where mesh bags filled with a constant mass of residue are retrieved over time. However, some authors have suggested that temperature and moisture conditions within the mesh bag may differ from outside the bag and that the mesh may exclude some organisms from participating in decomposition (reviewed in Cotrufo et al. 2010).

Effects of cover crops on soil inorganic N and corn N uptake

Field soil inorganic N (NO_3^--N + $NH4^+$-N) measurements taken after termination of legume/grass mixtures complement data related to cover crop N release provided by laboratory incubations and field litter loss studies. The release of N by decomposing hairy vetch residues has led to increased soil inorganic N concentrations relative to bare soil in several studies. In the presence of a corn crop, peak soil inorganic N concentrations have typically been reached 3-4 weeks after termination of surface or incorporated hairy vetch residues (Elbehar et al. 1984, Huntington et al. 1985, Kuo et al. 1997a, Cook et al. 2010), prior to the period of rapid N uptake by corn. Huntington et al. (1985) found that peak soil inorganic N under hairy vetch surface residues exceeded bare soil by 15 kg N ha^{-1} to 20 cm, while Elbehar et al. (1984) reported that peak soil inorganic N concentrations were ~25 kg N ha^{-1} greater to 7.5 cm under hairy vetch than under corn residue. Soil inorganic N reached 50-100 kg ha^{-1} to 30 cm in a study with hairy vetch surface residues by Cook et al. (2010). Incorporated hairy vetch residues provided 20 to 100 kg N ha^{-1} more N to 30 cm than no cover crop pre-sidedress in corn, with 10-20 kg N ha^{-1} from hairy vetch roots only (Kuo et al. 1997a, Kuo and Jellum 2002). Soil inorganic N concentrations under hairy vetch surface residues may be 2-4x greater near the soil surface than at depth prior to corn uptake (Sarrantonio 2003, Cook et al. 2010), and up to 2x greater near the surface than at depth when residues are incorporated (Varco et al. 1993, Kuo et al. 1997a). The presence of grass cover crop surface residues has been shown to either not affect (Huntington et al. 1985) or decrease soil inorganic N during the corn growing season relative to bare soil (Rosecrance et al. 2000, Sarrantonio 2003). Hairy vetch/cereal rye mixture surface residues have had either no effect (Rosecrance et al. 2000) or a slight positive effect on soil inorganic N concentrations (Sarrantonio 2003). Incorporated hairy vetch/cereal rye mixture residues either decreased soil inorganic N by 20 kg N ha^{-1} relative to no cover crop or increased soil inorganic N up to 26 kg N ha^{-1} to 30 cm relative to no cover crop (Kuo and Jellum 2002). In general, soil inorganic N concentrations tend to be higher when cover crop residues are incorporated than surface-applied (Varco et al. 1993).

Hairy vetch has been shown to be less aggressive at scavenging soil N than cereal rye (Shipley et al. 1992), and this can lead to elevated soil inorganic N levels under cover crops containing hairy vetch relative to cereal rye prior to cover crop termination in the spring (Ranells and Wagger 1997). After termination, approximately 65% of hairy vetch N is released from surface residues within the first 30 days (Wagger 1989b, Varco et al. 1993, Ranells and Wagger 1996). Rosecrance et al. (2000) found that the high N mineralization rate of hairy vetch resulted in 3x and 10x greater potential for N losses through leaching and denitrification than hairy vetch/cereal rye mixture and cereal rye monoculture, respectively in the absence of a crop. Nearly half of the losses occurred within the first 30 days after cover crop termination, which is prior to the period of rapid N uptake by corn. Even though hairy vetch N may be susceptible to losses prior to uptake, Varco et al. (1993) observed that hairy vetch N is probably less susceptible to losses than fertilizer N, partly because a greater proportion of N released from hairy vetch residues was immobilized.

The N contributions of a hairy vetch cover crop typically result in increased corn N uptake and grain yield relative to bare soil, while N immobilization due to a cereal rye cover crop can lead to lower corn N uptake and grain yields relative to bare soil. In a review of five studies that tested corn response to cover crop management in conventional no-till systems, corn N uptake totals relative to bare soil checks were greatest after monoculture hairy vetch, intermediate after hairy vetch/cereal rye mixtures, and lowest after monoculture cereal rye with no other N amendments. Averaged across all 20 site-years of the five studies, relative N uptake estimates for corn following hairy vetch, mixture and cereal rye with no other N amendments were 39, 23 and -16 kg N ha^{-1}, respectively (means from each study are presented in Table 2.2). The corn relative N uptake estimates corresponded to 26% and 22% of average hairy vetch and mixture N contents, respectively. Thus, although a hairy vetch residue may release ~80% of its N during a corn growing season, much of this N is not taken up by the corn crop. Corn relative grain yields followed a similar trend as N uptake results, with a 37% and 25% yield boost following hairy vetch and hairy vetch/cereal rye mixture, respectively and 16% yield decrease following cereal rye with no other N amendments. With all site-years pooled, there was a positive correlation between cover crop N content and corn relative N uptake and relative grain yield (Figure 2.3). In an organic system, Parr et al. (2011) found that hairy vetch and hairy vetch/cereal rye mixtures did not consistently improve corn yields relative to a bare soil check because weed growth, hairy vetch regrowth, and water stress negatively impacted the hairy vetch cover crop treatments. Results from a meta-analysis on corn yield response to winter cover crops support the findings of my review (Miguez and Bollero 2005). In a review of 37 peer-reviewed manuscripts on legume, legume/grass mixture, and grass cover crops, legumes increased corn yields by 37%, mixtures increased yields by 17% and grasses decreased yields, but not significantly, relative to no-cover controls without N fertilizer. The positive effect of legume cover crops on yield decreased as N fertilizer rate increased, while the positive effect of mixture and grass cover crops increased with increasing N fertilizer rate. Region was an important factor explaining corn response to cover crops: cover crops improved corn yields in the northeast and southeast by 15%, on average, whereas only marginal yield benefits from cover crops were observed in the north Central and northwest U.S.

Manure application timing and placement

The spatial and temporal distributions of N inputs are important factors controlling N losses and crop response to N. Manure injection may reduce NH_3 volatilization by 40 -

nearly100% relative to broadcast application (reviewed in Maguire et al. 2011) and prevent applied N from becoming immobilized in surface mulches (Mengel et al. 1982). Because most annual weeds are small-seeded and emerge from the soil surface, while corn is large-seeded and emerges from ~4 cm depth, delivering N below the soil surface gives corn preferential access to N over most weeds (DiTomaso 1995, Mohler 1996). On the other hand, manure injection has been shown to increase denitrification losses by 2-4x (albeit <2% of total manure N) relative to surface application due to the close proximity of available C and NO_3^--N, the substrates required for denitrification (Dosch and Gutser 1996, Wulf et al. 2002, Rodhe et al. 2006). Manure injection has the potential to increase N leaching losses relative to surface application, especially at high manure application rates (Weslien et al. 1998, Ball-Coelho et al. 2006, Ball-Coelho et al. 2007). High concentrations of NH_3-N, NO_2^--N and Na^+, along with elevated pH and moisture levels in manure bands can limit root penetration into the band (Sawyer et al. 1990). However, overall, corn N recovery (Ball-Coelho et al. 2006) and yields have been greater (Klausner and Guest 1981, Sutton et al. 1982, Schmitt et al. 1995, Ball-Coelho et al. 2005), and plant-available N has been more reliably predicted (Russelle et al. 2008), for injected manure relative to surface-applied manure. Split applications of N fertilizer, where a portion of N fertilizer is applied pre-plant and the remaining is applied at sidedress, have also proven to be more efficient than single pre-plant applications in corn production (Cassman et al. 2002, Dinnes et al. 2004) because they reduce the risk of N losses before the period of rapid corn N uptake. To my knowledge, there is not yet evidence to prove that sidedress manure application results in greater N use efficiency relative to pre-plant application.

Several technologies exist to inject liquid manure into soil with minimum surface disturbance (reviewed in Maguire et al., 2011). These liquid manure injection implements cannot be used for poultry litter due to the bulky, solid nature of the material. The recent development of a dry manure (<30% moisture) subsurface banding implement will allow localized placement of poultry litter as an alternative to broadcast application in no-till systems. The implement combines conveyance mechanisms for dry manure with no-till planter implements, and relies on gravity rather than pressure to guide litter into the furrow. The system is able to apply manure more accurately and at lower rates than a broadcast spreader without disturbing surface residues, but application speed is roughly half that of broadcast application. Recent work testing the subsurface band poultry litter applicator suggests that the new implement is capable of achieving the nutrient efficiency gains observed for injection of other manures. Subsurface band application of poultry litter has resulted in 90% reduction in NH_3 volatilization relative to broadcast application in no-till corn (Pote and Mesinger 2014), 55% reduction in P losses relative to broadcast application in perennial pastures (Pote et al. 2011), and 16-36 % increase in corn yields relative to broadcast application (Adeli et al. 2012, Pote et al. 2011).

While the spatial and temporal distributions of soil inorganic N are known to influence efficiency of N use, few studies have been performed to measure and model the movement of inorganic N in cropping system surface soil profiles. McCormick et al. (1983) and Comfort et al. (1988) used a grid placed on exposed soil faces to sample soil at various distances from a liquid manure band in uncropped fields. Sawyer et al. (1990) used a similar approach, coupled with systematic core sampling in a corn field. The studies reported high concentrations of NH_4^+-N (up to ~800 mg NH_4^+-N kg^{-1} soil) immediately after manure application, with elevated concentrations extending ~12 cm laterally on either side and 5-10 cm downward (McCormick et al. 1983, Comfort et al. 1988, Sawyer et al. 1990). Over time and beginning on the outer fringes of the band, NH_4^+-N was replaced with high concentrations of NO_3^--N (up to ~800 mg NO_3^--N kg^{-1} soil). Complete nitrification occurred within 3-7 weeks after application (McCormick et al. 1983, Comfort et al. 1988, Sawyer et al. 1990). Elevated concentrations of NO_3^--N were observed in the band 90+ days after application, but NO_3^--N had also moved outward and downward from the band, making it more susceptible to losses, at least without uptake by plants (Comfort et al. 1988). High soil moisture (up to 3x background levels), pH of up to 8.2, and elevated electrical conductivity (up to 8x background levels) measured in the manure band had the potential to limit root growth in the band for up to 6 weeks after application (Comfort et al. 1988, Sawyer et al. 1990). Furthermore, accumulation of 35 mg NO_2^--N kg^{-1} has been observed as NH_4^+-N concentrations, pH and electrical conductivity decline, perhaps causing a second phase of root toxicity (Sawyer et al. 1990). Accumulation of NO_2^--N can accumulate if high soil pH and aqueous NH_3 inhibit *Nictrobacter* activity but do not inhibit *Nitrosomonas* activity (Court et al. 1964). Although moisture conditions within the manure bands are generally greater than background soil, all studies have shown accumulation of NO_3^--N when no nitrification-inhibitor was used. The high moisture levels coupled with high soluble C (up to 4x greater than background levels, Comfort et al. 1988) and NO_3^--N concentrations provide optimal conditions for denitrification to occur.

Knowledge of soil inorganic N movement over time and space is important when attempting to collect a soil sample that can accurately represent plant-available N. Based on the spatial distribution of several soil nutrients in soil receving subsurface band-applied poultry litter, Tewolde et al. (2013) concluded that random sampling would not be appropriate to obtain representative soil samples. To accurately represent mean soil nutrient levels, they suggested that soil cores be taken every 5 cm between poultry litter bands. Systematic sampling methods have been used to obtain inorganic N samples in fields with concentrated N fertility (Schmitt et al. 1995, Zebarth et al. 1999, Adeli et al. 2012). A “soil slice” sample, capturing all soil between poultry litter bands has also been proposed (Tewolde et al. 2013). Starr et al. (1992) compared soil NO_3^--N means from samples collected using different size cores to soil NO_3^--N means from a “soil slice”. They then employed resampling techniques to determine the minimum number of soil cores required for each core size to accurately estimate the true soil inorganic N concentration. While even the smallest core size could be used to estimate NO_3^--N values, they found that fewer cores were needed when large core sizes were taken. This study was not performed on a field that received a localized fertility application, but their approach could be extended to this application.

Conclusion

A cover crop-based rotational no-till system is currently being developed to provide ecologically-based weed control and N delivery, among other cover crop services, to the subsequent cash crop. Several challenges have been identified that limit the success of the hairy vetch-corn system, including insufficient weed suppression, hairy vetch regrowth, unreliable corn establishment, and inadequate N supply. Hairy vetch/cereal rye mixtures have been proposed as an alternative to hairy vetch to improve system performance. This review confirmed the potential for greater biomass and N content of hairy vetch/cereal rye cover crop mixtures relative to monocultures, and identified factors that influence the biomass, N content and residue quality of a cover crop mixture. These factors include seeding rate, termination date, and site-specific conditions such as soil N and weather. Many studies have been conducted to quantify the decomposition of cover crop residues in the field, and suggest that while residue quality and tillage regime are important factors affecting decomposition, reliable predictions require models that account for temperature and moisture as well. Across many site-years, the capacity of hairy vetch and hairy vetch/cereal rye mixtures to supply N has had a positive effect on corn grain yields, while cereal rye had either no effect or a negative effect on yields.

A second proposed tactic to improve N supply and N use efficiency of the cover crop-based rotational no-till corn system is subsurface band application of poultry litter. Past work on manure and N fertilizer placement and timing suggests that the spatio-temporal distribution of inorganic N plays an important role controlling N loss and immobilization. Subsurface manure application is known to improve N use efficiency, yet little work has been done to measure and model soil inorganic N movement associated with a poultry litter band over time. Studying liquid manure bands, researchers have measured high concentrations of NH_4^+-N immediately after manure injection, accompanied by elevated soil moisture, electrical conductivity, pH and soluble C. This NH_4^+-N is replaced by NO_3^+-N after several weeks while soil moisture, EC and pH decline. Nitrate-N may then be taken up by plants, be denitrified, or move throughout the soil profile. The spatial distribution of soil properties in fields with subsurface band-applied *poultry litter* has not been fully investigated. Several approaches to sampling fields with concentrated fertility sources have been proposed, but a greater understanding of spatio-temporal soil inorganic N distribution is required to establish reliable sampling protocols.

Table 2.1 A summary of hairy vetch/cereal rye cover crop mixture management practices, and biomass and nitrogen (N) content results from peer-reviewed studies and a Beltsville, MD study conducted 2011-2013. The review includes articles that reported data on monocultures of both species and mixture(s). Individual site-years for which monoculture and mixture data were not collected were excluded. Means across all site-years for each factor level within each study are presented. Factors that were tested within particular studies are indicated with italicized text. Mixture biomass or N contents that exceed monoculture values are bolded. Standard errors representing variability between site-years within each study are presented in parentheses.

Author	Locationδ	Planting time‡	Termination‡	Mixture seed, kg ha^{-1}†	Mono seed, kg ha-^{1}†	Mono vetch biomass, Mg ha^{-1}	Mono rye biomass, Mg ha^{-1}	Mixture biomass, Mg ha^{-1}	Mono vetch N, Mg ha^{-1}	Mono rye N, Mg ha^{-1}	Mixture N, Mg ha^{-1}	RYM biomass§	RYM N	C/N
Clark et al. 94	M	m S	*e/m A*	*14/47*	28/94	1.2(0.5)	3.5(0.6)	3.3(0.7)	55(17.0)	71(8.5)	**80(5.5)**	1.6(0.2)	1.3(0.0)	19.6(3.2)
Clark et al. 94	M	m S	*e/m A*	*14/94*	28/94	1.2(0.5)	3.5(0.6)	**3.9(0.8)**	55(17.0)	71(8.5)	**90(0.5)**			21.2(4.8)
Clark et al. 94	M	m S	*e/m A*	*21/47*	28/94	1.2(0.5)	3.5(0.6)	3.4(0.6)	55(17.0)	71(8.5)	**89(0.2)**			18.5(3.8)
Clark et al. 94	M	m S	*e/m A*	*21/94*	28/94	1.2(0.5)	3.5(0.6)	**3.9(0.7)**	55(17.0)	71(8.5)	**96(2.0)**			19.4(3.1)
Clark et al. 94	M	m S	*e/m A*	*28/47*	28/94	1.2(0.5)	3.5(0.6)	3.5(0.7)	55(17.0)	71(8.5)	**92(4.0)**			17.9(2.8)
Clark et al. 94	M	m S	*e/m A*	*28/94*	28/94	1.2(0.5)	3.5(0.6)	**4.0(0.6)**	55(17.0)	71(8.5)	107(2.5)			17.8(2.7)
Clark et al. 94	M	m S	*e/m M*	*14/47*	28/94	5.0(0.2)	6.7(0.4)	**6.9(0.3)**	159(2.0)	74(16.0)	151(11.0)	1.1(0.1)	1.3(0.0)	22.2(1.4)
Clark et al. 94	M	m S	*e/m M*	*14/94*	28/94	5.0(0.2)	6.7(0.4)	**7.9(0.5)**	159(2.0)	74(16.0)	151(14.5)			24.9(4.1)
Clark et al. 94	M	m S	*e/m M*	*21/47*	28/94	5.0(0.2)	6.7(0.4)	**7.9(0.4)**	159(2.0)	74(16.0)	**174(6.0)**			22.5(1.0)
Clark et al. 94	M	m S	*e/m M*	*21/94*	28/94	5.0(0.2)	6.7(0.4)	**8.5(0.6)**	159(2.0)	74(16.0)	**195(24.0)**			24.9(4.6)
Clark et al. 94	M	m S	*e/m M*	*28/47*	28/94	5.0(0.2)	6.7(0.4)	**8.0(0.4)**	159(2.0)	74(16.0)	**168(10.0)**			23.6(3.4)
Clark et al. 94	M	m S	*e/m M*	*28/94*	28/94	5.0(0.2)	6.7(0.4)	**8.7(0.6)**	159(2.0)	74(16.0)	**183(2.5)**			22.6(0.5)
Ranells, Wagger 96	N	m O	m A	22/56	34/112	3.8(0.9)	3.6(2.1)	**4.2(1.2)**	154(28.5)	41(23.5)	141(59.0)			17.5(3.5)
Clark et al. 97a	M	m S-e O	*e A*	28/47	28/94	2.8(0.3)	2.0(0.4)	**3.4(0.2)**	108(13.7)	30(3.8)	**109(5.5)**			12.3(0.9)
Clark et al. 97a	M	m S-e O	*l A*	28/47	28/94	3.3(0.1)	3.2(0.4)	**5.1(0.3)**	128(4.6)	38(5.6)	**145(7.3)**			14.5(1.2)
Teasdale, Abdul-Baki 98	M	m S	l M	45/45	45/45	5.3(1.5)	5.7(1.6)	**7.3(2.0)**	177(59.0)	55(14.0)	**181(56.5)**			19.0(1.0)

Kuo, Jellum 02	W	l S	l A	20/71	28/101	1.8(0.2)	1.5(0.3)	**2.1(0.1)**	58(6.1)	21(4.3)	48(4.1)			16.5(1.6)
Ruffo, Bollero 03	I	e O	e M	23/67	34/134	1.4(0.2)	3.7(0.4)	3.6(0.4)	40(3.2)	50(6.1)	**63(6.4)**			24.3(1.7)
Sainju et al. 05	W	O-N	A	19/40	28/80	4.2(0.9)	4.1(1.1)	**6.6(0.8)**	136(30.0)	42(13.3)	**193(65.3)**			17.6(7.2)
Parr et al. 11	N	O	*A*	28/56	28/118	5.0(0.6)	7.2(1.6)	5.9(1.4)	148(17.7)	41(4.6)	136(33.2)			20.5(1.4)
Parr et al. 11	N	O	*M*	28/56	28/118	4.4(0.8)	5.5(3.1)	**6.4(1.4)**	116(32.3)	29(16.5)	**139(38.9)**			18.5(0.9)
Hayden et al. 14	MI	e S	e M	*14/63*	42/94	4.3(1.3)	3.7(0.4)	**4.9(0.6)**	140(40.0)	40(0.0)	98(2.5)	1.3(0.1)	1.4(0.2)	
Hayden et al. 14	MI	e S	e M	*21/47*	42/94	4.3(1.3)	3.7(0.4)	4.3(0.8)	140(40.0)	40(0.0)	95(15.0)	1.1(0.0)	1.1(0.1)	
Hayden et al. 14	MI	e S	e M	*28/31*	42/94	4.3(1.3)	3.7(0.4)	**5.2(0.8)**	140(40.0)	40(0.0)	125(15.0)	1.3(0.1)	1.2(0.2)	
Hayden et al. 14	MI	e S	e M	*35/16*	42/94	4.3(1.3)	3.7(0.4)	**5.0(1.0)**	140(40.0)	40(0.0)	130(20.0)	1.2(0.1)	1.1(0.1)	
Hayden et al. 14	MI	e S	e M	*7/78*	42/94	4.3(1.3)	3.7(0.4)	4.3(0.8)	140(40.0)	40(0.0)	70(5.0)	1.1(0.0)	1.2(0.1)	
This study	M	m S-e O	m/l M	*14/101*	34/168	6.3(0.3)	11.2(0.6)	11.1(1.5)	181(15.8)	65(9.9)	127(12.0)	1.4(0.1)	1.1(0.1)	42.6(4.3)
This study	M	m S-e O	m/l M	*20/67*	34/168	6.3(0.3)	11.2(0.6)	11.0(1.1)	181(15.8)	65(9.9)	140(11.2)	1.2(0.1)	1.1(0.2)	39.6(5.9)
This study	M	m S-e O	m/l M	*27/34*	34/168	6.3(0.3)	11.2(0.6)	10.0(0.8)	181(15.8)	65(9.9)	157(12.5)	1.2(0.0)	1.0(0.1)	29.3(2.1)
This study	M	m S-e O	m/l M	*7/134*	34/168	6.3(0.3)	11.2(0.6)	**11.6(1.1)**	181(15.8)	65(9.9)	127(10.8)	1.5(0.0)	1.5(0.1)	45.4(4.8)

δ M = MD, N = NC, W = WA, I = IL, MI = MI

‡ e = early, m = mid, l = late, S = September, O = October, N = November, A = April, M = May

†Hairy vetch seeding rate/cereal rye seeding rate

§ $RYM = \frac{Y_m}{(P_v Y_{vv} + P_r Y_{rr})}$

where Y_m is the biomass or N content of the cover crop mixture, P_v and P_r are the seeding rate proportions of the full monoculture seeding rates for hairy vetch and cereal rye, respectively, Y_{vv} and Y_{rr} arrre the monoculture biomass or N contents of hairy vetch and cereal rye, respectively.

Table 2.2 A summary of cover crop nitrogen content (CC N), and corn N uptake and grain yield response to cover crop monocultures and mixtures relative to bare soil controls from peer-reviewed studies. Relative corn N uptake and relative grain yields were calculated across all site-years of each study using only treatments that did not receive additional N fertility. Standard errors representing variability between site-years within each study are presented in parentheses.

	--------------- Cereal rye ---------------			--- Hairy vetch/cereal rye mixture ---			---------------- Hairy vetch ----------------			---- Bare, no N check ----	
Study	CC N, kg ha^{-1}	Corn N, kg ha^{-1}	Corn yield, Mg ha^{-1}	CC N, kg ha^{-1}	Corn N, kg ha^{-1}	Corn yield, Mg ha^{-1}	CC N, kg ha^{-1}	Corn N, kg ha^{-1}	Corn yield, Mg ha^{-1}	Corn N, kg ha^{-1}	Corn yield, Mg ha^{-1}
Elbehar et al. 1984	36.0(na)		+0.2(na)				209.0(na)		+2.6(na)		3.8(na)
Wagger 1989a,b†	82.7(11.9)	-25.8(6.2)	-1.3(0.4)				151.8(17.2)	+40.3(12.3)	+2.5(0.2)		5.7(1.3)
Clark et al. 1994	72.3(2.7)		-0.8(0.1)	131.1(8.8)		+1.1(0.1)	107.0(11.1)		+2.6(0.2)		5.2(0.8)
Decker et al. 1994							151.7(24.2)	+28.3(11.9)	+1.2(0.4)	137.7(10.9)	6.6(0.4)
Clark et al. 1997a,b	34.1(3.5)	-9.1(3.7)	-1.1(0.4)	126.9(8.0)	+23.4(4.7)	+1.4(0.6)	117.8(7.7)	+46.25(9.1)	+2.3(0.7)	83.4(8.2)	4.7(0.4)

†In Wagger (1989a), N uptake by corn was reported relative to bare control.

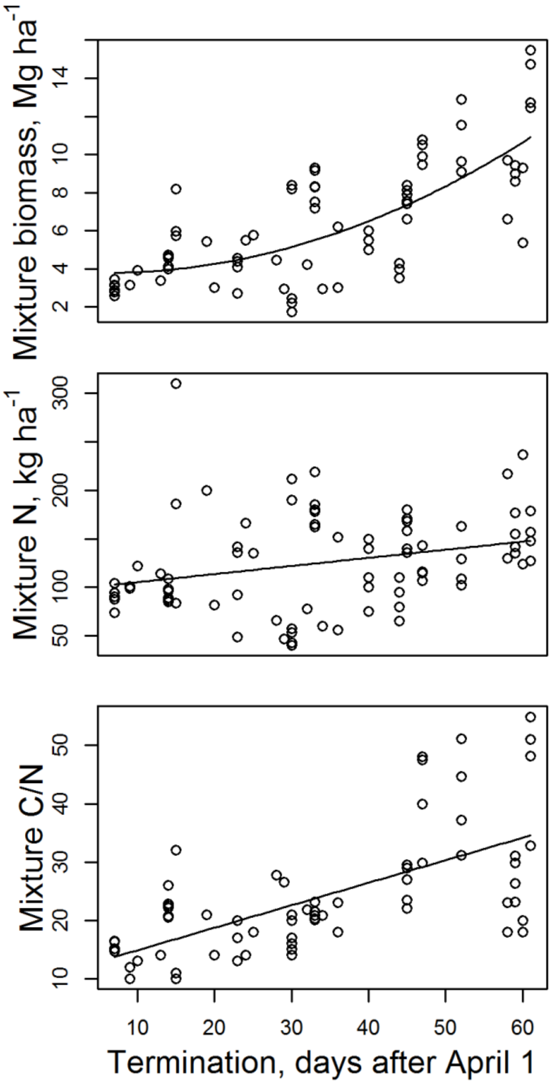

Figure 2.1 The relationships between cover crop mixture termination date and cover crop mixture biomass (top), nitrogen (N) content (middle) and C/N ratio (bottom). Data were compiled from nine peer-reviewed journal articles and a Beltsville, MD study that was conducted from 2011-2013. $\boldsymbol{Mixture\ biomass = 3.88 + 0.029x + 0.0024x^2}$. $\boldsymbol{Mixture\ N\ content = 96.9 + 0.84x}$. $\boldsymbol{Mixture\ C/N = 11.0 + 0.39x}$. Correlation coefficients were 0.73, 0.28 and 0.78, for the three relationships, respectively.

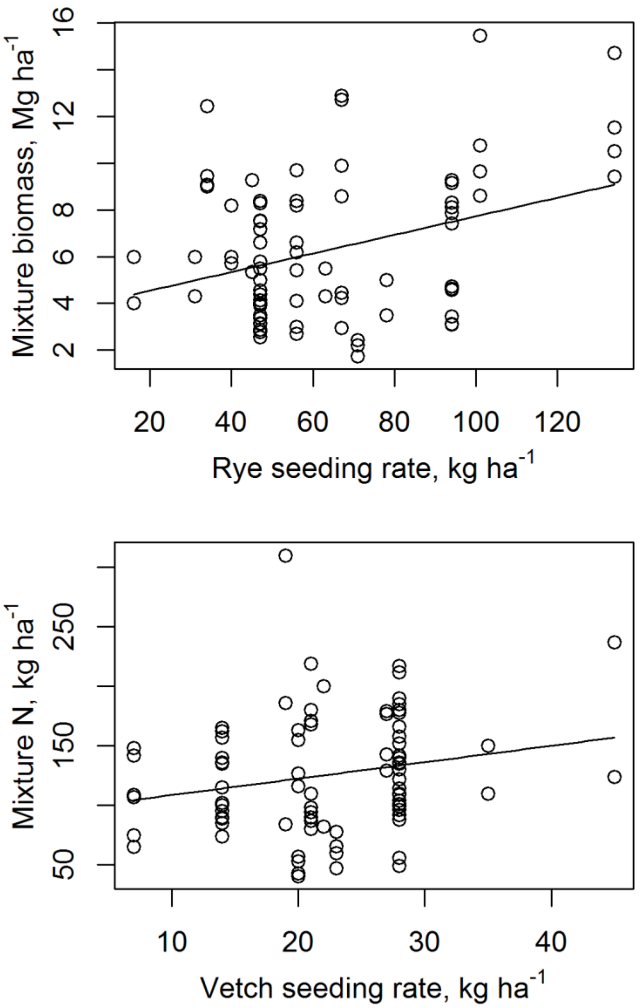

Figure 2.2 Top: The relationship between cereal rye seeding rate in mixture and mixture biomass production; bottom: the relationship between hairy vetch seeding rate in mixture and mixture nitrogen (N) content. Data were compiled from nine peer-reviewed journal articles and a Beltsville, MD study that was conducted from 2011-2013. $\boldsymbol{Mixture\ biomass = 3.75 + 0.04x}$. $\boldsymbol{Mixture\ N\ content = 94.8 + 1.38x}$. Correlation coefficients were 0.34 and 0.21 for the two relationships, respectively.

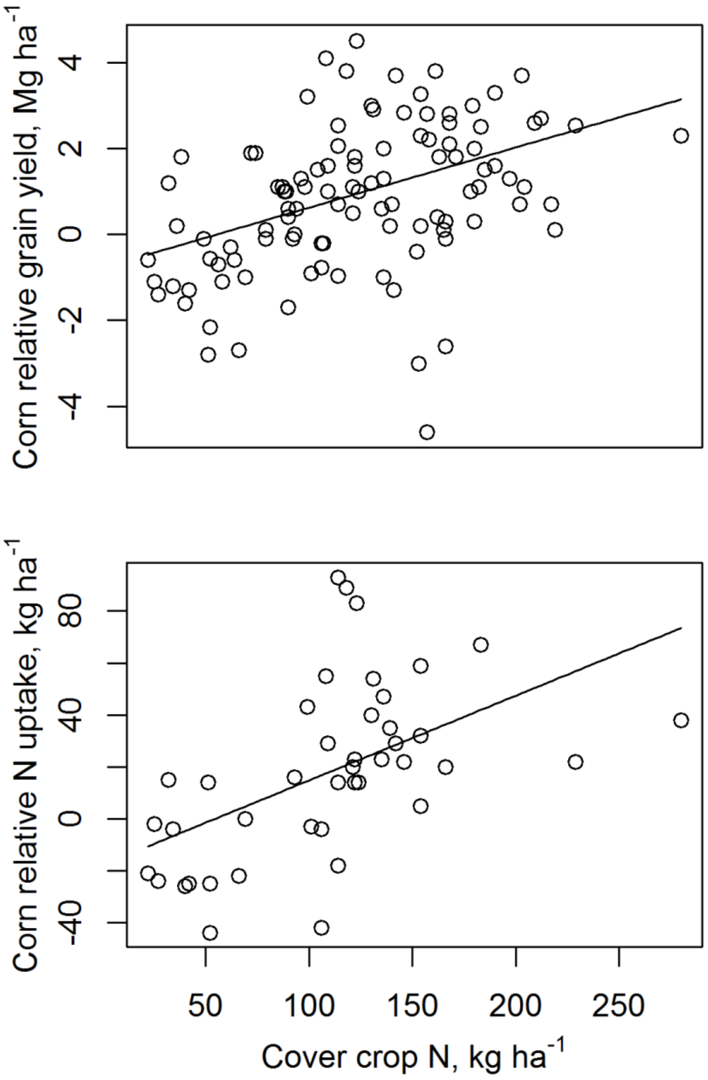

Figure 2.3 The relationships between cover crop nitrogen (N) content and corn grain yield relative to bare soil, no N fertility control (top) and corn N uptake relative to bare soil, no N fertility control (bottom). Data were compiled from five published studies conducted in conventional no-till systems using hairy vetch, cereal rye or hairy vetch/cereal rye mixture cover crops. $\boldsymbol{Corn\ relative\ grain\ yield\ =\ -0.78\ +\ 0.014x}$. $\boldsymbol{Corn\ relative\ N\ uptake\ =\ -17.8\ +\ 0.33x}$. Correlation coefficients were 0.43 and 0.67 for the two relationships, respectively.

Chapter 3 Biomass, nitrogen content and biological nitrogen fixation of hairy vetch/cereal rye cover crop mixtures as influenced by species proportions

Abstract

Legume/grass cover crop mixtures may deliver the benefits of each component species and out-perform monocultures in terms of biomass and N accumulation. However, the proportions of each species in mixture may influence cover crop performance and the suitability of a cover crop mixture for specific functions. The objectives of this study were to: 1) evaluate total aboveground cover crop biomass and species proportions at different legume/grass sown proportions using the winter-annual legume, hairy vetch (*Vicia villosa* Roth) and the winter cereal, cereal rye (*Secale cereale* L.), 2) characterize nitrogen (N) content and biological N fixation across a gradient of hairy vetch/cereal rye biomass proportions, 3) evaluate the potential for transfer of biologically fixed N from hairy vetch to cereal rye in mixture, and 4) test whether and at what sown proportions hairy vetch/cereal rye mixtures are more productive than monocultures as measured by biomass and N content. A gradient of six hairy vetch/cereal rye sown proportions ranging from 100% hairy vetch to 100% cereal rye was drilled in fall 2011 and 2012 at two sites in Beltsville, MD. The following spring, the cover crops were sampled, separated by species, dried, and analyzed for N content and biological N fixation using the ^{15}N natural abundance method. Aboveground dry matter ranged from approximately 5 Mg ha^{-1} in the least productive hairy vetch monoculture to 15 Mg ha^{-1} in the most productive mixture. Biomass levels were similar among the cereal rye monoculture and hairy vetch/cereal rye mixtures, but declined with the hairy vetch monoculture. In three of the four site-years, cereal rye was the dominant component of mixtures. Nitrogen content increased from approximately 63 to 180 kg ha^{-1} as hairy vetch biomass in the mixture increased, and was estimated to plateau when hairy vetch reached 50% of the cover crop biomass in three of the four site-years. Biologically fixed N made up approximately 85% of hairy vetch N content when grown in mixture, and 16-80% of hairy vetch N content when grown in monoculture. Transfer of fixed N from hairy vetch to cereal rye was not detected. Competition indices (Land Equivalent Ratio and Relative Crowding Coefficient) indicated that hairy vetch/cereal rye mixtures performed at least as well, and often better than the average of monocultures in terms of biomass production and N acquisition.

Introduction

Cover cropping provides several important services in agroecosystems, including erosion control, biological diversity, weed suppression, nutrient retention and supply, and soil carbon (C) sequestration (Meisinger et al. 1991, Pimentel et al. 1992, Decker et al. 1994, Pimentel et al. 1995, Teasdale 1996, Kuo et al. 1997b). However, individual cover crop species vary in their capacity to achieve these functions. Small grain cover crops such as cereal rye (*Secale cereale* L.), grow rapidly and produce substantial biomass, making them excellent at scavenging nitrogen (N) (Meisinger et al. 1991, Shipley et al. 1992), preventing erosion, and building soil organic matter (Sainju et al. 2002, Snapp et al. 2005). Cereal rye also provides reliable weed suppression both as a living cover crop and as a thick surface mulch in no-till systems (Burgos and Talbert 1996, Kruidhof et al. 2008, Mischler et al. 2010a, Smith et al. 2011). However, cereal rye residues do not release substantial N upon decomposition, and can cause N immobilization in the subsequent cash crop season (Ranells and Wagger 1996, Clark et al. 1997a, Kuo and

Sainju 1998). In contrast, winter annual legume cover crops, such as hairy vetch (*Vicia villosa* Roth), fix atmospheric N and release N upon decomposition, reducing the amount of N fertilizer required for the succeeding crop (Stute and Posner 1995, Ranells and Wagger 1997, Lawson et al. 2012). However, hairy vetch grows slowly in the fall and decomposes rapidly after termination, making it less effective than cereal rye at soil conservation and weed suppression (Teasdale 1993, Burgos and Talbert 1996, Hayden et al. 2014). The rapid N release from hairy vetch residues may lead to early-season N leaching losses prior to crop uptake (Rosecrance et al. 2000, Sarrantonio 2003). Furthermore, legume cover crops such as hairy vetch can cost up to 10x as much to establish as grasses due to their greater seed cost and generally weak emergence (Snapp et al. 2005). A hairy vetch/cereal rye cover crop mixture may provide the N scavenging, N provisioning, and weed suppression services lent by the component species, while modulating their negative attributes. For example, hairy vetch/cereal rye cover crop mixtures have been shown to accumulate more N than cereal rye monocultures (Clark et al. 1997a, Parr et al. 2011, Hayden et al. 2014) and achieve greater biomass production (Clark et al. 1994, Ruffo and Bollero 2003, Hayden et al. 2012) and weed suppression than hairy vetch monocultures (Burgos and Talbert 1996, Hayden et al. 2014). The intermediate C/N ratios of hairy vetch/cereal rye mixtures contribute to a moderate N release and decomposition rate relative to monocultures (Ranells and Wagger 1996, Kuo and Sainju 1998, Rosecrance et al. 2000).

Component crops within mixtures often differ in their patterns of resource use, leading to reduced competition, more efficient resource exploitation and greater overall productivity when grown together (Francis 1989). Legumes grown in mixture with a grass often derive a greater proportion of their N from biological N fixation than in monoculture (Mallarino et al. 1990b, Izaurralde et al. 1992, Brainard et al. 2012), allowing grasses to acquire greater soil N in mixture than in monoculture (Tosti et al. 2010, Hayden et al. 2014). Fixed N may even be transferred from the legume to the companion grass in mixtures (Frey and Schuepp 1992, Jensen 1996, Paynel and Cliquet 2003). Grasses and legumes also differ in their architecture: the upright nature of grasses provides a trellis onto which a viney legume can climb to access greater light. The complementary ways in which grasses and legumes acquire resources can lead to greater biomass production and N accumulation of hairy vetch/cereal rye mixtures relative to monocultures (Clark et al. 1997a, Teasdale and Abdul-Baki 1998, Sainju et al. 2005). Accordingly, some studies have found that weed suppression by hairy vetch/cereal rye mixtures is equally effective as cereal rye monocultures (Burgos and Talbert 1996, Teasdale and Abdul-Baki 1998, Hayden et al. 2012), and that hairy vetch/cereal rye mixtures can release equivalent N as hairy vetch monocultures (Ranells and Wagger 1996, Clark et al. 1997a, Sainju et al. 2005).

Research suggests that a cover crop mixture's biomass, N content, N release, and impact on subsequent cash crop yields are influenced by the component species' biomass proportions in mixture (Clark et al. 1994, Kuo and Sainju 1998, Lawson et al. 2012, Hayden et al. 2014). However, few studies have evaluated legume/grass mixture properties across a range of sown proportions, particularly in the context of cover crop services (Clark et al. 1994, Akemo et al. 2000, Karpenstein-Machan and Stuelpnagel 2000, Dhima et al. 2007, Tosti et al. 2010, Hayden et al. 2014). This limited body of work is not sufficient to establish management regimes for hairy vetch/cereal rye mixtures given the interactive effects of other factors on mixture properties. These other factors include timing of management (Clark et al. 1994, Lawson et al. 2012), weather conditions (Ruffo and Bollero 2003, Lawson et al. 2012), and soil N availability (Clark et al. 1994).

The objectives of this study were to: 1) evaluate total cover crop biomass and species proportions in cover crop mixtures in response to different sown proportions of hairy vetch and cereal rye, 2) characterize N content and biological N fixation across a gradient of hairy vetch/cereal rye biomass proportions, 3) evaluate the potential for transfer of biologically fixed N from hairy vetch to cereal rye grown in mixture, and 4) test whether and at what sown proportions biomass and N accumulation of hairy vetch/cereal rye mixtures exceed the average biomass and N accumulation of monocultures ("overyielding"). We hypothesize that: 1) biomass proportions of each species in mixture will change as the seeding rate of one species increases and the seeding rate of the other species declines, and the total biomass will increase with increasing seeding rate of the more productive monoculture, 2) cover crop N content will increase as hairy vetch proportion in biomass increases, reach maximum N content in mixture, and decrease slightly in hairy vetch monoculture, 3) the proportion of biologically fixed N in hairy vetch will decrease linearly as the proportion of hairy vetch in mixture increases, 4) the proportion of biologically-fixed N in cereal rye will increase as the proportion of hairy vetch biomass in mixture increases, and 5) the biomass and N accumulation of mixtures will exceed the average biomass and N content of monocultures for some sown proportions.

Methods

Experimental methods

A field experiment was initiated at the Beltsville Agricultural Research Center in the fall of 2011 and replicated in the fall of 2012. The experiment included six hairy vetch/cereal rye sown proportions (four different mixtures and two monocultures) planted in a randomized complete block design at each of two farms: North Farm, which has been managed organically since 2000 and certified by the Maryland Department of Agriculture according to National Organic Program requirements since 2003 (39.03 N, 76.93 W) and South Farm, which is under conventional agricultural management (39.02 N, 76.94 W). Both farms have four fields that are maintained in a corn (*Zea mays* L.) - soybean (*Glycine max* (L.) Merr.) - wheat (*Triticum aestivum* L.) rotation with a cover crop fallow year that precedes either the corn or soybean phase in the rotation. This experiment was embedded just prior to the corn phase of the crop rotation. A soybean cover crop was planted following wheat to reduce spatial heterogeneity of soil inorganic N and provide some residual N for the subsequent cover crops. Soils on North Farm are classified as fine-loamy, mixed, active, mesic Fluvaquentic Endoaquepts (Hatboro series) and soils on South Farm are classified as fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts (Codorus series). Three replicates were planted on each site-year. The site-years in this paper are labeled as “North Farm” (“NF”) or “South Farm” (“SF”) followed by the year in which the cover crops were sampled (2012 or 2013).

The soybean cover crop was incorporated by disking in late summer each year prior to cover crop establishment. The soybeans were expected to accumulate ~200 kg N ha^{-1} prior to termination, except on North Farm in 2013 where soybeans were highly productive and accumulated approximately 350 kg N ha^{-1}. The fields were fertilized with 56 kg potassium (K) ha^{-1} as K_2SO_4, cultivated and cultimulched to prepare a cover crop seedbed. Seeding rates of each species were varied in a proportional replacement series design (Conolly et al. 1986), with hairy vetch/cereal rye sown proportions of: 0/1, 0.2/0.8, 0.4/0.6, 0.6/0.4, 0.8/0.2, 1/0. The monoculture hairy vetch and cereal rye seeding rates were 34 kg ha^{-1} and 168 kg ha^{-1}, respectively and the mixture sown proportions represent proportions of each species' monoculture seeding rate. The monoculture seeding rates were selected to produce optimum biomass of each species based on preliminary research. The use of monoculture densities that produce optimal biomass of each species is recommended to minimize the effect of changes in total density on mixture performance (Trenbath 1976, Rejamnek et al. 1989). The two cover crop species were independently drilled on 19 cm row spacing to ensure precise seeding rates across all experimental units. Hairy vetch seed was inoculated with *Rhizobia* prior to drilling covers. The cover crops were planted on October 7, 2011 and September 17, 2012 on North Farm and on October 10, 2011 and September 25, 2012 on South Farm.

Soil samples were collected after cover crop establishment in the fall (November 21, 2011 and October 12, 2012) in each rep to a depth of 30 cm for soil inorganic N analysis and routine soil testing. The soil samples were air-dried and passed through a 2 mm sieve. Inorganic N (NO_3^--N + NH_4^+-N) in two-gram soil subsamples was extracted with 20 mL of 1M KCl by shaking for one hour. Filtered extracts were analyzed colorimetrically for NO_3^--N using cadmium reduction and reaction with sulfanilamide and N-1-napthylethylenediamine dihydrochloride and for $NH4^+$-N by reaction with salicylate and dichloro-isocyanuric acid (Seal AQ2 Automated Discrete Analyzer, Mequon, WI). Soil samples were analyzed for pH, cation exchange capacity, and Mehlich 3-extractable nutrient concentrations at A&L Eastern Labs (Richmod, VA).

Cover crops were terminated on May 17, 2012 and May 31, 2013 on North Farm and on May 29, 2012 and May 22, 2013 on South Farm using a roller/crimper. The roller/crimper consists of a hollow steel cylinder 30-60 cm in diameter with blades along the outside of the cylinder designed to crush and crimp the cover crop, forming a dense, unidirectional mulch (Ashford and Reeves 2003). Effective termination by the roller/crimper requires that cereal rye be at anthesis or a later growth stage (Mirsky et al. 2009) and that hairy vetch be flowering or developing pods (Mischler et al. 2010b). In three of the four site-years, hairy vetch was in full flower and cereal rye was in the soft dough stage, except on South Farm in 2013 when hairy vetch was 50% flowering and cereal rye was in the milk stage. Aboveground biomass was collected by clipping all material within a 76 cm x 67 cm frame immediately after termination in four to six locations within each plot (North Farm 2012: n = 88, South Farm 2012: n = 99, North Farm 2013: n = 61, South Farm 2013: n = 101). The location of each biomass sample was recorded as relative distance coordinates to evaluate potential spatial effects on cover crop biomass and N content. The biomass samples were separated by species, oven dried (60°C), weighed dry and ground to pass a 1.0-mm screen.

Tissue C and N concentrations, and isotope ratios of naturally-occurring ^{15}N in the species comprising each sown proportion were determined by isotope ratio mass spectrometry at the Cornell University Stable Isotope Lab (Thermo Delta V interfaced to Temperature Conversion Elemental Analyzer, Thermo Scientific, Waltham, MA). The ^{15}N abundance of a given sample ($\delta^{15}N$) was calculated as:

$$\delta^{15}\mathrm{N}(‰) = \frac{(\text{sample atom}\%\ {}^{15}N - 0.3663)}{0.3663} x\ 1000$$

where 0.3663 is the standard atmospheric %^{15}N.

Subsamples of the ground plant material and soil samples collected from the surface 5 cm of the fields were ashed for 4 hours at 550° C to determine the ash fractions of biomass samples and contaminating soil. The fraction by weight of hairy vetch or cereal rye biomass, $F_{biomass}$, was calculated as:

$$F_{biomass} = (A_{soil} - A_{sample})/(A_{soil} - A_{plant})$$

where A_{soil} is the ash fraction of contaminating soil, $A_{sample}$is the ash fraction of the contaminated biomass sample, and A_{plant} is the ash fraction of uncontaminated hairy vetch or cereal rye biomass, which was estimated using clean biomass samples. Biomass weights were adjusted as:

$$M_{adj} = F_{biomass} M_{sample}$$

where M_{sample} is the contaminated sample dry weight. Finally, N concentrations and ^{15}N abundances were adjusted as:

$$N_{adj} = \frac{N_{sample} - N_{soil}(1 - F_{biomass})}{F_{biomass}}$$

where $N_{sample}$and N_{soil} are the N concentrations or ^{15}N abundances of the biomass sample and soil, respectively.

Statistical analysis

Cover crop biomass in response to sown proportions was modeled using plant interaction models developed by de Wit (1960).

$$y_v = \frac{y_{vv} P_v k_v}{(P_v k_v) + P_r}$$

$$y_r = \frac{y_{rr} P_r k_r}{(P_r k_r) + P_v}$$

$$y_{total} = y_v + y_r$$

where y_v is the hairy vetch biomass, y_{vv} is the hairy vetch monoculture biomass, P_v is the proportion of the monoculture hairy vetch seeding rate, k_v is the Relative Crowding Coefficient (RCC) of hairy vetch with respect to cereal rye, P_r is the proportion of the monoculture cereal rye seeding rate, y_r is the cereal rye biomass, y_{rr} is the cereal rye monoculture biomass, and k_r is the RCC of cereal rye with respect to hairy vetch. Although de Wit's original models were used to compute the RCC for each proportion separately in competition studies, it can also be estimated by fitting this model for y as a function of P across all values of P to generate biomass predictions across a range of densities (Hall 1974). The RCC is a measure of an individual species' aggressiveness: the greater the RCC value, the better a species has done in mixture (Williams and McCarthy 2001). An RCC value greater than one indicates that the species performed better when grown with the opposing species than when grown with itself. The product of two species' RCCs provides a measure of overyielding: values greater than one indicate that mixture biomass exceeded the sown proportion-weighted average of monoculture biomass (Hall 1974). The term "overyielding" does not imply that the mixture produced greater absolute biomass than both monocultures (this phenomenon is termed "transgressive overyielding"). Relative Crowding Coefficients have been shown to vary in response to monoculture densities, so interpretation of this index is limited to the monoculture seeding rates used in this study (Connolly 1986, Snaydon 1991).

Model fitting was performed for each site-year independently using the nlme function in R, with rep included as a random effect (R Development Core Team 2014). We used mean monoculture biomass values to parameterize y_{vv} and y_{rr} as constants in the model. In addition to the de Wit analysis, total cover crop biomass at each sown proportion was compared to monoculture biomass using a linear mixed model (R function lme) with rep as a random effect. Means were calculated using lsmeans and contrasts were performed using glht in R package multcomp (R Development Core Team 2014). Cover crop biomass residuals (for both de Wit models and linear mixed models) were analyzed for spatial correlation by constructing semivariograms using the vgm function in R (R Development Core Team 2014). Visual inspection of semivariograms indicated that spatial correlation was present for one or both species in some of the site-years. Therefore, an exponential correlation structure, using corExp with x and y coordinates as spatial covariates, was included in models when it decreased the Akaike Information Criterion (AIC) by at least two. In non-linear (nlme) models that included spatial correlation, rep was assigned as a fixed effect rather than random effect to achieve model convergence.

Relative Crowding Coefficients were bootstrapped (bootstrap replications =1000) and bootstrap samples were plotted on frequency histograms to confirm that they were normally distributed. The RCCs and RCC products were evaluated to see whether their 90% and 95% confidence intervals overlapped with one. The confint function in R was used to determine confidence intervals of RCCs. The confidence intervals of the RCC products were calculated for each site-year as:

$$CI = |k_v k_r| \pm 1.96\sqrt{var_{prd}}$$

with the variance of the product of the RCCs (variance of $k_v \ x \ k_r$) for each site-year calculated using a first-order Taylor expansion (Goodman 1962):

$$var_{prd} = {k_v}^2 var(k_r) + {k_r}^2 var(k_v) + var(k_v) var(k_r)$$

The RCCs and RCC products were declared significantly different when the 90% or 95% confidence interval did not overlap with one.

The N content of each cover crop species for each sample was computed as the product of the species tissue N concentration and biomass. Total N content for each sample was computed as the sum of each species' N content. The de Wit model did not accurately predict the effect of sown proportion on cover crop N content. Instead, linear or quadratic equations were used to model hairy vetch and cereal rye N content and total aboveground N content of cover crops as a function of hairy vetch biomass proportion. The hairy vetch biomass proportion was calculated as the proportion of hairy vetch biomass out of the total biomass collected in each sample at the time of cover crop termination. Regression was performed only over the range of hairy vetch biomass proportions that were observed in the field to avoid making predictions in regions of no data. The lme function in R was used for model fitting, with rep included as a random effect and monoculture N contents included as constants (R Development Core Team 2014). Semivariograms on the residuals indicated that spatial correlation was present for some of the N variables in some site-years, so an exponential correlation structure, using corExp with x and y coordinates as spatial covariates, was included in models when it improved the AIC value by at least two.

The proportion of aboveground N derived from the atmosphere (pNdfa) was calculated using the following equation (Shearer and Kohl 1986).

$$pNdfa = (\delta^{15}N_{ref} - \delta^{15}N_{leg})/(\delta^{15}N_{ref} - \mathrm{B})$$

where $\delta^{15}N_{ref}$ is the average δ^{15}N value of monoculture cereal rye samples and non-legume weeds collected at the time of cover crop termination each year in non-cover-cropped areas in each field (representing δ^{15}N of soil), $\delta^{15}N_{leg}$ is the δ^{15}N for hairy vetch, and B is the δ^{15}N of legume shoots that are fully dependent upon N_2 fixation, approximated as -0.84 based on an average value for hairy vetch reported in Unkovich et al. (2008). Fixed N transferred from hairy vetch to cereal rye was estimated using the same equation, substituting δ^{15}N of cereal rye for $\delta^{15}N_{leg}$ as in Moyer-Henry et al. (2006). This approach assumes that no fractionation of ^{15}N occurs during interspecific transfer. Total fixed N was calculated as the product of the pNdfa and total N content for a given biomass sample. Hairy vetch and cereal rye pNdfa, and hairy vetch total fixed N were analyzed using the same approach as hairy vetch N content. Most site-years did not demonstrate significant relationships between pNdfa and hairy vetch biomass proportion among mixtures. Therefore, means of pNdfa for hairy vetch and cereal rye grown in mixture (all mixture sown proportions pooled) and monoculture were calculated for each site-year using a linear mixed model with rep as a random effect (function lme). Means were calculated using lsmeans and contrasts were performed using glht in R package multcomp (R Development Core Team 2014). One replicate of the South Farm 2013 site-year was dropped from the analysis of pNdfa and total fixed N due to probable manure contamination of cover crop samples. Samples that had significant soil contamination (>8% for cereal rye and >12% for hairy vetch) were also excluded from the analysis. The total C content of cover crops was calculated in the same manner as total N content. The C/N ratio was computed for each sample, data were log-transformed and related to hairy vetch biomass proportion using the same approach as used for cover crop N.

Land Equivalent Ratio (LER) was used to evaluate mixture advantage in terms of biomass production and N content.

$$LER_v = \frac{y_{vr}}{y_{vv}}$$

$$LER_r = \frac{y_{rv}}{y_{rr}}$$

$$LER_m = LER_v + LER_r$$

where LER_v and LER_r are partial LERs of hairy vetch and cereal rye, respectively LER_m is the mixture LER, y_{vv} and y_{rr} are the monoculture biomass or N contents of hairy vetch and cereal rye, respectively, y_{vr} is the biomass or N content of hairy vetch in mixture with cereal rye, and y_{rv} is the biomass or N content of cereal rye in mixture with hairy vetch. Partial LERs that exceed the species' sown proportion in mixture indicate that the species performed better in mixture than expected based on monoculture biomass or N yields (Willey 1979). Mixture LERs greater than one indicate overyielding. The mixture LER complements the RCC product by providing estimates of mixture advantage at individual sown proportions and for N content as well as biomass. Land Equivalent Ratios were calculated for each sown proportion and analyzed by site-year using the lme function in R (R Development Core Team 2014). Rep was included as a random effect, and exponential spatial correlation was added when it improved the model fit. Means were calculated using lsmeans and contrasts were performed using glht in R package multcomp to determine whether mean mixture LERs were significantly different than one (R Development Core Team 2014).

Results

Soil properties and weather conditions

Soil properties were generally adequate for cover crop growth (Table 3.1). Among the soil nutrients analyzed, K was the only nutrient that was not rated as optimum for crop growth, and the sub-optimal sufficiency levels were only observed on North Farm. Inorganic N (NO_3^--N + NH_4^+-N) concentrations were similar in both fields within each year, and particularly high in fall 2012 (concentrations corresponded to 168 kg N ha^{-1} on North Farm and 144 kg N ha^{-1} on South Farm). Lower inorganic N concentrations in fall 2011 may have been a result of later soil sampling in 2011 relative to 2012, which allowed time for inorganic N to be taken up by cover crops or leached from the Ap horizon. Soil pH was approximately 6 across all site-years, which is within the preferred range of hairy vetch and cereal rye.

Both 2011-2012 and 2012-2013 cover crop growing seasons were relatively mild, with growing degree day totals for most months similar to or greater than 30-year averages (Table 3.2). The months of November and March were warmer than average in the first season, but cooler than average in the second season. Rainfall was close to average in fall 2011, but below average in spring 2012 and for most months during the 2012-2013 cover crop growing season.

Total aboveground biomass and species biomass proportions

Hairy vetch biomass in monoculture ranged from 4.98 to 7.08 Mg ha^{-1} and averaged 5.94 Mg ha^{-1} (mean of four site-year averages; Table 3.3, Figure 3.1). The monoculture biomass yields of cereal rye were 1.7-2x the monoculture hairy vetch biomass yields within each site-year, ranging from 10.30 to 12.78 Mg ha^{-1} and averaging 10.96 Mg ha^{-1}

(mean of four site-year averages). North Farm 2013 had the highest fall soil inorganic N concentrations and produced 1.4x the total cover crop biomass averaged across sown proportions of the other three site-years (North Farm 2012: 9.56, South Farm 2012: 8.72, North Farm 2013: 13.01, South Farm 2013: 9.99 Mg ha^{-1}). Weed biomass in the cover crops was negligible in all site-years (site-year averages were all < 12 kg ha^{-1}, Appendix 1).

The de Wit model provided an excellent fit to the aboveground biomass of each species across sown proportions (Table 3.3, Figure 3.1; all R^2 values > 0.70). As expected, hairy vetch biomass increased as the seeding rate of hairy vetch increased, and cereal rye biomass decreased as the seeding rate of cereal rye decreased. Mixture performance was similar in North Farm 2012 and South Farm 2013, where cereal rye was the more aggressive species (average RCC for both site-years was 4.8), and hairy vetch productivity tended to be slightly, but not significantly suppressed (average RCC for both site-years was 0.85). Equivalent biomass of cover crop species was achieved at 0.8/0.2 to 0.9/0.1 hairy vetch/cereal rye sown proportions. The RCC products in these two site-years were significantly greater than one (P<0.05), providing evidence that mixtures performed better than would be expected from monoculture biomass yields of each species. The models did not predict that total yields of mixtures extended above the cereal rye monoculture yields, but that replacing cereal rye plants with a species that produces less biomass (hairy vetch) did not result in a reduction in total biomass across mixtures. Largely consistent with the de Wit model predictions, the means of total aboveground biomass at each sown proportion were all close to the mean of cereal rye alone, except at the highest vetch proportions when total aboveground biomass declined

(Figure 3.1). On South Farm in 2013, the total biomass at the 0.6/0.4 hairy vetch/cereal rye sown proportion was marginally significantly greater than cereal rye monoculture biomass ($P<0.10$).

Relative to North Farm 2012 and South Farm 2013, cereal rye was even more dominant in mixtures on North Farm in 2013. Equivalent biomass of both cover crop species was predicted around a 0.95/0.05 hairy vetch/cereal rye sown proportion. The North Farm 2013 RCCs showed similar trends as North Farm 2012 and South Farm 2013, but values for both species grown in this site-year were distributed even further apart. The cereal rye biomass in mixture at the 0.4/0.6 hairy vetch/cereal rye sown proportion slightly exceeded the cereal rye monoculture biomass, but the de Wit models did not accurately reflect this upward curvature. The inability of the de Wit model to capture greater productivity of a species in mixture relative to monoculture has been recognized previously (Williams and McCarthy 2001) and thus the RCC product may not be a reliable indicator for overyielding on this site-year.

South Farm 2012 produced cover crop mixtures dominated by hairy vetch rather than cereal rye (equivalent biomass of species predicted around 0.45/0.55 hairy vetch/cereal rye sown proportion), with the RCC of hairy vetch significantly greater than one and that of cereal rye significantly less than one ($P<0.05$). The RCC product was not different than one, and model predictions indicate the total biomass decreased as the low biomass producer (hairy vetch) replaced the high biomass producer (cereal rye). However, the means of total aboveground biomass at each sown proportion show a relatively constant level of cereal rye biomass and total biomass across mixtures, which the de Wit models did not fully capture (Figure 3.1).

Nitrogen content, biological N fixation and C/N ratios

In contrast to the biomass models which were based on the imposed seeding rates; N content was modeled as a function of the resulting species biomass proportions in the field. The dominance of cereal rye in most of the cover crop mixtures resulted in a relatively narrow distribution of proportions across the targeted response surface that could be used to predict N content in mixtures (Figure 3.2). Therefore, the N content of each species, biologically fixed N, total N and C/N ratios were modeled between hairy vetch biomass proportions of: 0-0.55 (North Farm 2012), 0-1 (South Farm 2012), 0-0.33 (North Farm 2013) and 0-0.54 (South Farm 2013).

Within these ranges, hairy vetch N content increased significantly with increasing proportion of hairy vetch biomass, reaching a maximum with the greatest hairy vetch biomass proportion ($P<0.05$, Figure 3.2). Within each site-year, the N content of the hairy vetch monoculture was greater than the maximum N content of hairy vetch in mixtures. Nitrogen contents of monoculture hairy vetch ranged from 145 to 222 kg ha^{-1}, and averaged 180 (mean of four site-year averages). Biologically fixed N followed similar trends as hairy vetch N content, but slopes of biologically fixed N tended to be lower than those of total hairy vetch N. Slope differences between hairy vetch N content and fixed N were significant on North Farm in 2012 and South Farm in 2013 ($P<0.05$). On South Farm in 2012 and 2013, the biologically fixed N content of the hairy vetch monoculture was lower than that of some mixtures.

Cereal rye monoculture N content ranged from 49 to 86 kg ha^{-1}, and averaged 63 (mean of four site-year averages). Cereal rye N content decreased linearly with increasing hairy vetch biomass in mixture on South Farm 2012 ($P<0.05$). However, cereal rye N content did not show a significant trend in the other site-years because the decreasing cereal rye biomass was offset by increasing N concentration over the modeled hairy vetch biomass proportions.

Total aboveground N content increased significantly with increasing hairy vetch biomass proportion over the range of species proportions that were modeled ($P<0.05$). On South Farm 2012, a maximum N content of 177 kg ha^{-1} was predicted at a hairy vetch biomass proportion of 0.92. On South Farm 2013, a maximum N content of 191 kg ha^{-1} was achieved at a hairy vetch biomass proportion of 0.54. In the remaining two site-years, the maximum total N content was achieved in the hairy vetch monoculture treatments. However, within these two site-years, the total N content of hairy vetch/cereal rye mixtures at the highest hairy vetch biomass proportion achieved were just slightly less than the N contents of hairy vetch monoculture. Thus, it is expected that models over the full range of hairy vetch biomass proportions would be curvilinear, although the optimum of the curve cannot be defined without data in this range. The site-year with the highest aboveground biomass production (North Farm 2013) produced cover crops with the highest aboveground N content.

Hairy vetch pNdfa showed no trend over the ranges of hairy vetch biomass proportions modeled for all site-years except South Farm 2013 (Table 3.5). On South Farm in 2013, hairy vetch pNdfa increased significantly with increasing hairy vetch biomass proportion in mixture ($P<0.05$). This may reflect the fact that hairy vetch produced more biomass where rates of biological N fixation were greater, perhaps in N-deficient regions of the field. Means of the pNdfa across all mixtures and monocultures are presented in Table 3.5. Although there was not a consistent significant trend across mixture biomass proportions, the pNdfa means were consistently lower for hairy vetch grown in monoculture than for hairy vetch grown in mixture. The hairy vetch pNdfa ranged from 0.80 to 0.89 in mixture and from 0.16 (statistically equivalent to zero) to 0.80 in monoculture. Averaged across site-years, cereal rye pNdfa was 0.15 in monocultures and 0.24 in mixtures. There was no evidence that hairy vetch biologically fixed N was transferred to cereal rye, as the cereal rye pNdfa was equal in mixtures and monocultures within each site-year. Interestingly, on South Farm 2012, cereal rye pNdfa decreased significantly with increasing hairy vetch biomass proportion.

The natural log of cover crop C/N ratios declined significantly and in a curvilinear fashion with increasing hairy vetch biomass proportion over the ranges of biomass proportions modeled (Figure 3.3, Table 3.6). Hairy vetch and cereal rye monoculture C/N ratios were 12 and 83, respectively (means of four site-year averages, back-transformed from log scale). A C/N ratio of 25-30, which represents a threshold of N immobilization/mineralization (Clark et al. 1997a, Kuo et al. 1997a) was predicted at approximately 0.5/0.5 hairy vetch/cereal rye biomass proportion in the three site-years that achieved this biomass proportion.

Land Equivalent Ratios

Biomass LERs generally support the de Wit model predictions of the relative performance of each species in mixture and overall mixture performance (Figure 3.4). On North Farm 2012 and South Farm 2013, hairy vetch biomass partial LERs were similar to or slightly below corresponding hairy vetch sown proportions in mixture. On South Farm 2012 and North Farm 2013, hairy vetch biomass partial LERs were above and below the corresponding imposed sown proportions, respectively. On all site-years and for all sown proportions, the sum of both species' LERs exceeded one, suggesting that the mixture biomass was greater than expected based on the sown proportion-weighted average of monocultures. Mixture biomass LERs were significantly greater than one in at least one sown proportion of each site-year ($P<0.05$), and no trends in mixture biomass LERs were detected across the sown proportions.

Nitrogen LERs showed similar trends as the biomass LERs, except that cereal rye N partial LER values tended to be greater than cereal rye biomass partial LER values for the same treatments (Figure 3.5). As a result, mixture N LER values tended to be greater than mixture biomass LER values, and there were more cases of mixture N LERs that significantly exceeded one ($P<0.05$).

Overall, North Farm 2012 and South Farm 2013 had the most sown proportions with mixture biomass or N LER values significantly greater than one, and South Farm 2012 had the fewest. Interestingly, North Farm 2013 LER results indicated mixture overyielding at some sown proportions, which contradicts the relatively low RCC product calculated for North Farm 2013. It seems that the LERs calculated for each sown proportion more accurately reflected the mixture performance on North Farm 2013 than the de Wit model predictions, which did not predict the slightly greater cereal rye biomass observed in mixture relative to monoculture (Figure 3.1).

Discussion

We evaluated total aboveground cover crop biomass and species biomass proportions in response to different hairy vetch/ cereal rye sown proportions. Cover crop biomass ranged from approximately 5.0 to 15.0 Mg ha^{-1}, which is high relative to the biomass levels of hairy vetch/cereal rye mixtures and monocultures reported in other studies. In a review of nine published hairy vetch/cereal rye cover crop mixture studies representing 29 site-years in the southeast, mid-Atlantic, mid-West and Pacific Northwest U.S., cover crop biomass of hairy vetch monocultures, cereal rye monocultures and hairy vetch/cereal rye mixtures ranged from 0.7-6.7 (mean = 3.4), 1.0-12.6 (mean = 4.3) and 1.7-9.3 (mean = 5.1) Mg ha^{-1}, respectively (Clark et al. 1994, Clark et al. 1997a, Ranells and Wagger 1996, Teasdale and Abdul-Baki 1998, Kuo and Jellum 2002, Ruffo and Bollero 2003, Sainju et al. 2005, Parr et al. 2011, Hayden et al. 2014). Planting dates among site-years ranged from early September to November, and termination dates ranged from early April to late May. Across all studies reviewed, there was a positive correlation between later termination dates and biomass of monocultures and mixtures. Therefore, the late termination date in the present study (as required for effective roller/crimper use) probably contributed to the relatively high biomass production. The hairy vetch monoculture seeding rates used in this experiment were similar to those used in the reviewed studies (7-45 kg ha^{-1}, mean = 24 kg ha^{-1}); however, our cereal rye seeding rates in monoculture and mixtures were greater than those used in the literature reviewed (mixtures: 45-94 kg ha^{-1}, mean = 59 kg ha^{-1}; monocultures: 45-134 kg ha$^{-1,}$ mean = 98 kg ha^{-1}). A higher cereal rye seeding rate may not necessarily correspond to greater biomass accumulation because cereal rye planted at lower densities often produces more tillers (Boyd et al. 2009). We speculate that the relatively high biomass measured in this study was mainly due to the large pool of plant-available N provided by the preceding soybean crop that was incorporated prior to cover crop establishment. Similar biomass levels have been achieved by cereal rye and hairy vetch/cereal rye mixtures with late cover crop termination dates and N fertilizer application (Mirsky et al. 2011, Reberg-Horton et al.

2011).

Although hairy vetch in monoculture produced about half the biomass of cereal rye in monoculture, mixtures produced at least 80% of the monoculture cereal rye biomass, and sometimes produced slightly greater biomass than monoculture cereal rye. Comparable or greater productivity of hairy vetch/cereal rye mixtures relative to monocultures has observed in several other studies as well (Clark et al. 1994, Ranells and Wagger 1996, Clark et al. 1997a, Kuo and Jellum 2002, Sainju et al. 2005). The majority of hairy vetch/cereal rye mixture studies have used mixture seeding rates in which the sum of sown proportions of both species exceeds one (for example: the hairy vetch mixture seeding rate is 0.75x the hairy vetch monoculture seeding rate, while the cereal rye mixture seeding rate is 0.5x the cereal rye monoculture seeding rate; sum = 1.25). In the present replacement series, the seeding rate of one species decreased as the seeding rate of the other species increased, such that the sum of the sown proportions equaled one across all mixtures. A similar replacement series experiment was conducted by Hayden et al. (2014) using different monoculture seeding rates. Results from replacement series mixture designs are known to vary depending on plant densities (Snaydon 1991). However, our results support findings by Hayden et al. (2014) that in some site-years, mixture biomass may equal or exceed biomass of both monocultures even when the sum of sown proportions is maintained at one.

The high productivity of hairy vetch/cereal rye mixtures grown in this study may have been due in part to the fact that cereal rye, the more productive of the two species, was usually the dominant species in mixtures. A more dominant cereal rye component in mixture has been observed in many other hairy vetch/cereal rye cover crop mixture studies (some site-years of Ranells and Wagger 1997, Ruffo and Bollero 2003, Brainard et al. 2012, Lawson et al. 2012, some site-years of Hayden et al. 2012) but not in others (Ranells and Wagger 1996, one site-year of Ranells and Wagger 1997). In a Michigan study, Hayden et al. (2014) found that hairy vetch and cereal rye biomass proportions in mixture were well-predicted by sown proportions: halving the monoculture seeding rates of each species (monoculture seeding rates were 42 kg ha^{-1} for hairy vetch, 94 kg ha^{-1} for cereal rye) produced a mixture composed of 50% hairy vetch and 50% cereal rye biomass.

Based on our replacement series experimental design, it unclear the extent to which the observed dominance of cereal rye in mixtures was due to: a lower competitive effect of hairy vetch plants relative to cereal rye plants, a possible change in total plant density across sown proportions resulting from a lower hairy vetch monoculture seeding rate than cereal rye monoculture seeding rate, and/or other forms of interference or facilitation (Jolliffe 2000). However, because the monoculture seeding rates were selected for optimum biomass production, we can estimate that a change in plant density across sown proportions did not greatly affect mixture performance (Trenbath 1976). Assuming that at least some of the cereal rye dominance in mixture observed in three of the four site-years can be explained by competition dynamics, we explore some possible causes. First, although our cover crop planting dates were not particularly late for hairy vetch, we visually observed that cereal rye accumulated more fall growth than hairy vetch in these three site-years. Cereal rye plants growing in mixture with hairy vetch may have achieved more fall growth than cereal rye plants growing in a full monoculture stand, and may have developed an early competitive advantage over the slower-growing hairy vetch.

Because grasses tend to outcompete legumes when ample soil N is available (Haugaard-Nielson and Jensen 2001), a competitive advantage of cereal rye may be attributed to a large amount of plant-available N released by the soybean crops incorporated prior to cover crop planting each yaer. Among the four site-years, cereal rye was most aggressive and significantly suppressed hairy vetch growth on North Farm in 2013, which was the site-year with the most productive preceding soybean crop and greatest fall soil inorganic N concentrations. Cold weather is expected to increase the competitiveness of cereal rye because it is more cold-hardy than hairy vetch (Teasdale et al. 2004). Therefore, the relatively cool early spring in 2013 may also explain why cereal rye represented the larger component of cover crop mixtures in 2013. We observed that the dominance of cereal rye in mixtures did not necessarily correspond to suppression of hairy vetch (e.g. North Farm 2012, South Farm 2013), likely because of capacity of hairy vetch to fix atmospheric N and to climb cereal rye plants to access light (Keating and Carberry 1993).

Inconsistent with three of the four site-years in the present study, we observed that hairy vetch was the more dominant species in mixtures on South Farm in 2012. This was surprising, given the similar field conditions, geographical locations, planting and killing dates among all four site-years. We noticed that cereal rye was slower to establish on this site-year than the others due to cool and wet field conditions at the time of cover crop planting, while hairy vetch accumulated little fall biomass regardless of site-year. Fall cereal rye growth was further impacted by herbivory and trampling by wild Canada Geese (*Branta canadensis*) on South Farm in 2012. Thus, both species accumulated little fall biomass, and the warm spring may have given a competitive advantage to the less cold-hardy hairy vetch. At the time of termination on South Farm in 2012, the biomass of mixtures tended to be lower than cereal rye monocultures probably because hairy vetch, the less productive of the two species, was more aggressive than cereal rye in terms of biomass production.

Nitrogen contents of cereal rye and hairy vetch in this study were similar to or greater than the N contents of the respective species observed in other studies (Clark et al. 1997a, Ranells and Wagger 1996, Sainju et al. 2005, Parr et al. 2011). Total aboveground N content increased with increasing proportion of hairy vetch biomass, reaching a maximum between 50% hairy vetch biomass in mixture and monoculture hairy vetch. This is consistent with findings by Hayden et al. (2014). We did not measure N content of hairy vetch and cereal rye roots, which are estimated to contain an additional 10% of total hairy vetch N and 25% of total cereal rye N (Shipley et al. 1992, Kuo et al. 1997a). Several other studies have found N content of hairy vetch/cereal rye mixtures to be equal to or greater than N content of hairy vetch in monoculture (Clark et al. 1994, Ranells and Wagger 1996, Clark et al. 1997a, Sainju et al. 2005). However, most of these studies did not vary seeding rates to maintain a constant sum of sown proportions across mixtures and monocultures.

Hairy vetch fixed between 60% and 90% of its N for three of the four site-years. These figures are consistent with estimates of hairy vetch pNdfa in the literature, which range between 0.35 and 1.00, and fall mostly between 0.7 and 1.00 (Rochester and Peoples 2005, Parr et al. 2012, Hayden et al. 2014). Hairy vetch pNdfa estimates were lower in the hairy vetch monoculture on South Farm 2013, even though soil properties and weather conditions were similar to North Farm 2013. Evidence of Canada goose defecation on this field was observed in early March of 2013, which may have created a

N pulse. High soil N availability is known to limit legume N fixation (reviewed in Vlassak and Vanderleyden 1997).

We observed greater hairy vetch pNdfa in mixtures relative to hairy vetch monocultures, a finding that is consistent with other legume/grass mixture studies (Izaurralde et al. 1992, Karpenstein-Machan and Stuelpnagel 2000, Brainard et al. 2012). We did not find evidence of transfer of biologically fixed N from hairy vetch to cereal rye in this study, as cereal rye pNdfa values were statistically equivalent in mixtures and monocultures within each site-year. Transfer of biologically fixed N in annual legume/grass mixtures has been observed in some studies (Frey and Schuepp 1992, Jensen 1996), and not in others (Izaurralde et al. 1992, Schipanski and Drinkwater 2012). Nitrogen transfer from legumes to associated grasses has been detected more consistently in perennial mixtures, suggesting that substantial time is required for this facilitative interaction to develop (Ta and Faris 1987, Mallarino et al. 1990a, Schipanski and Drinkwater 2012). Although we did not find evidence for biologically fixed N transfer, the fact that hairy vetch was able to fix a majority evidently allowed cereal rye greater access to soil N (in three of the four site-years, cereal rye N content did not change even as its biomass in mixture decreased). Surprisingly, we observed that, on average, 0.24 of the cereal rye N grown in monoculture was biologically fixed, perhaps originating from the incorporated soybean residues. The fact that cereal rye acquired some of its N from previously biologically fixed N present in the soil suggests that some of the hairy vetch biologically fixed N may have been derived from the previously incorporated soybean residues as well. On one site-year, the pNdfa of cereal rye decreased with increasing hairy vetch biomass in mixture, suggesting that cereal rye took up N from different pools when grown in monoculture vs. when grown in mixture with hairy vetch.

We tested whether hairy vetch/cereal rye mixtures were more productive than the sown proportion-weighted mean of monocultures in terms of biomass and N content using mixture LER and RCC products. Mixture biomass LERs and RCC products were never less than one, and significantly greater than one in 40% and 50% of the cases, respectively. Mixture N LERs were never less than one, and significantly greater than one in the majority of cases. Other studies of annual legume/grass mixtures have found that mixture LERs, measured by both biomass and N, generally exceed 1.0, ranging from 0.95 – 1.75 (Karpentstein-Machan and Suelpnagel 2000, Szumigalski and Van Acker 2008, Bedoussac and Justes 2010). While the partial LERs of mixture components varied across sown proportions, mixture LERs were relatively consistent among sown proportions. However, the site-year in which hairy vetch was most aggressive (South Farm 2012) had the least evidence for mixture overyielding.

The high biomass levels achieved by cover crop mixtures in the present study provided excellent weed suppression during cover crop growth, and would be expected to provide excellent weed suppression in a subsequent no-till crop. Other authors have found that approximately 8-9 Mg ha^{-1} of biomass is required to achieve reliable weed suppression in a no-till system (Mohler and Teasdale 1993, Teasdale and Mohler 2000, Smith et al. 2011), a level that was met at even the 0.8/0.2 hairy vetch/cereal rye sown proportion in three out of four site-years. Achieving maximum cover crop N and fixed N required at least 50% hairy vetch biomass component, which was usually produced at the 0.8/0.2 hairy vetch/cereal rye sown proportion. Thus, the 0.8/0.2 hairy vetch/cereal rye sown proportion provided near-optimal N content and sufficient biomass for reliable weed suppression. Considering the cost of seed used in this study (\$6.61 and \$0.75 kg^{-1} for hairy vetch and cereal rye, respectively), this mixture can accumulate N levels similar to a hairy vetch cover crop and enhanced weed control at a lower cost than the hairy vetch monoculture. A cover crop mixture with 50% hairy vetch biomass would be expected to have a C/N ratio near 25 at the late termination date used in this study, which would allow for slower release of N than the hairy vetch monoculture (Ranells and Wagger 1996).

Conclusions

Cereal rye monocultures produced approximately twice as much biomass as hairy vetch monocultures. Despite this, in three of the four site-years, biomass of mixtures was usually nearly equal to or greater than biomass of cereal rye monocultures. Hairy vetch in monoculture had 2-4x the N content of monoculture cereal rye, yet our data suggest that total cover crop N content may plateau or peak in mixture, between 50% and 100% hairy vetch biomass. The high level of hairy vetch biological N fixation in most site-years (~0.85 of aboveground N content), which was evidently stimulated in mixtures vs. monocultures, reduced competition for soil N for cereal rye. The cover crop mixtures accumulated more N than would be expected based on sown densities and N contents of the monocultures. Overall, the results suggest that a wide range of hairy vetch/cereal rye sown proportions can provide high biomass production, but that maximum N content is most reliably achieved with a hairy vetch/cereal rye seeding rate of 27 kg ha^{-1}/34 kg ha^{-1}. Further research is needed to further elucidate how soil edaphic properties and climate drive species biomass proportions in cover crop mixtures.

Table 3.1 Soil properties of study sites in the 2012 and 2013 cover crop mixture experiments at Beltsville Agricultural Research Center. Properties were measured on samples collected to 30 cm depth. Standard errors are presented in parentheses.

	------------------ 2011-2012		----------------		----------------- 2012-2013		----------------	
	North Farm		South Farm		North Farm		South Farm	
		Suf†		Suf†		Suf†		Suf†
USDA texture classification	Loam		Loam		Loam		Loam	
NO_3^--N + NH_4^+-N, mg kg^{-1}	8.3(0.6)		9.4(1.1)		42.7 (3.4)		37.2 (2.1)	
Total N, g kg^{-1}	0.6(0.1)		0.4(0.1)		0.6(0.1)		0.7(0.1)	
Total C, g kg^{-1}	11.5(1.1)		6.7(0.6)		11.4(0.9)		10.0 (1.7)	
Mehlich 3-extractable								
P, mg kg^{-1}	56.7(23.8)	O	67.3(3.3)	O	46.0(9.7)	O	76.7 (13)	O
K, mg kg^{-1}	74.7(6.9)	M	93.0(4.0)	O	55.0(2.6)	L/M	111.7 (5.2)	O
Ca, mg kg^{-1}	975.0(33.1)	O	760.7(60.1)	O	931.7(33.4)	O	899.0 (8.0)	O
Mg, mg kg^{-1}	176.7(5.2)	E	126.3(8.9)	O	13.7(2.3)	E	118.0 (5.5)	O
Mn, mg kg^{-1}	31.0(2.6)	A	142.0(5.0)	A	43.7(3.4)	A	111.3 (3.5)	A
pH, 1:1 soil:water	6.7(0.1)		6.2(0.2)		5.7(0.1)		5.7 (0.1)	
CEC, meq 100 g^{-1}	6.8(0.4)		5.9(0.3)		7.7(0.1)		7.4 (0.3)	

†Sufficiency based on University of Maryland Soil Fertility Index Values and micronutrient requirements for most crops: L = low, M= moderate, O = optimal, E = excessive, A = adequate (micronutrient)

Table 3.2 Monthly growing degree days (GDD) and rainfall totals at Beltsville, MD North Farm (NF) and South Farm (SF) for two cover crop growing seasons, 2011-2013. Thirty-year averages are based on 1980-2010.

	------------- Monthly cumulative GDD† -----------					---------------------- Rainfall, mm ------------------				
	2011-2012		2012-2013		30-yr avg	2011-2012		2012-2013		30-yr avg
	NF	SF	NF	SF		NF	SF	NF	SF	
September‡	-	-	193	85	458	-	-	32	10	91
October‡	241	198	311	304	282	84	73	191	100	89
November	187	181	76	71	118	47	38	17	9	97
December	72	68	79	79	0	108	75	67	54	79
January	49	47	43	44	0	46	42	63	48	71
February	53	51	17	18	0	48	43	40	32	74
March	247	244	51	49	76	35	34	62	40	89
April	241	231	265	263	242	45	29	44	37	89
May‡	247	463	415	276	410	37	53	80	48	114
Total	1337	1483	1450	1189	1586	450	387	596	378	793

† Cover crop growing degree days were computed as the average daily temperature (calculated using daily maximum and minimum temperatures) minus 4^{o} C. Days with average temperatures below 4^{o} C were assigned a GDD of zero.

‡ Beginning after fall cover crop planting and ending the day of cover crop termination in May. However, thirty-year averages represent averages for the full months.

Table 3.3 Monoculture biomass yields, Relative Crowding Coefficients (RCCs) of hairy vetch and cereal rye, and de Wit model coefficients of determination for four site-years in Beltsville, MD. All RCC estimates were significantly different than zero (*P*<0.05). For both the RCC and the RCC products, bolded values are significantly different than one (*P*<0.05). Standard errors are presented in parentheses.

	------------- Hairy vetch -------------			--------------- Cereal rye ----------------			
Site-year	Monoculture, Mg ha^{-1}	RCC	R^2	Monoculture, Mg ha^{-1}	RCC	R^2	RCC product
NF 2012	5.889(3.37)	0.95(0.17)	0.69	10.300 (7.92)	**3.88**(1.03)	0.73	**3.69**
SF 2012	5.802(2.85)	**3.85**(0.83)	0.78	10.403(7.18)	**0.43**(0.12)	0.76	1.65
NF 2013	7.076(2.04)	**0.11**(0.02)	0.92	12.776(7.74)	**11.0**(4.01)	0.81	1.19
SF 2013	4.981(2.11)	0.76(0.11)	0.75	10.376(5.78)	**5.63**(1.21)	0.76	**4.29**

Table 3.4 Parameter estimates and coefficients of determination for aboveground nitrogen (N) content of cover crop mixtures and their component species as related to proportion of hairy vetch biomass in cover crop for four site-years in Beltsville, MD. Linear or quadratic models were fit only over the range of hairy vetch biomass proportions at which N data was available (NF 2012: 0-0.55, SF 2012: 0-1, NF 2013: 0-0.33, SF 2013: 0-0.54). All linear and quadratic coefficients shown are significantly different than zero (*P*<0.05), unless indicated with italicized font. Standard errors are presented in parentheses.

Site-year	-------------------------------- Hairy vetch N, kg ha^{-1} --------------------------------			
	Monoculture N	Linear coefficient	Quadratic coefficient	R^2
NF 2012	183(8.8)	237(11.0)	----	0.79
SF 2012	171(9.8)	302(18.4)	-127(22.7)	0.78
NF 2013	222(6.2)	335(18.5)	----	0.85
SF 2013	145(7.2)	258(13.6)	----	0.74
	------------------- Hairy vetch biologically fixed N, kg ha^{-1} -----------------------			
	Monoculture N	Linear coefficient	Quadratic coefficient	R^2
NF 2012	124(13.4)	202(13.1)	----	0.62
SF 2012	125(14.2)	284(25.5)	-152 (32.4)	0.33
NF 2013	140(10.8)	294(17.9)	----	0.82
SF 2013	38(11.8)	206(14.1)	----	0.68
	------------------------------ Cereal rye N, kg ha^{-1} -----------------------------------			
	Monoculture N	Linear coefficient		R^2
NF 2012	49(6.3)	*-10(11.0)*		0.10
SF 2012	55(4.4)	-52(3.1)		0.58
NF 2013	86(14.0)	*-15(63.0)*		0.11
SF 2013	61(6.6)	*-22(16.4)*		0.12
	--------------------------------- Total N, kg ha^{-1} -------------------------------------			
	Linear coefficient	Quadratic coefficient		R^2
NF 2012	225(19.8)	----		0.53
SF 2012	264(23.4)	-143(28.4)		0.54
NF 2013	311(78.0)	----		0.19
SF 2013	239(26.4)	----		0.36

Table 3.5 Proportion of nitrogen derived from atmosphere (pNdfa) in hairy vetch and cereal rye grown in mixtures and monocultures for four site-years in Beltsville, MD. Significant differences in means of pNdfa in mixture vs. monoculture within each site-year and species are indicated by different lowercase letters (P<0.05). All means were significantly different than zero unless indicated with italicized font. Standard errors are presented in parentheses.

	------------------------------------ pNdfa ------------------------------------			
Site-year	------------ Hairy vetch ------------		---------------- Cereal rye ------------	
	In mixture	In monoculture	In mixture	In monoculture
NF 2012	0.88(0.02)a	0.80(0.03)b	0.16(0.04)a	0.12(0.05)a
SF 2012	0.89(0.06)a	0.80(0.08)a	*0.13(0.15)*a§	0.23(0.17)a
NF 2013	0.86(0.02)a	0.63(0.05)b	0.19(0.07)a	0.32(0.11)a
SF 2013	0.80(0.07)a†	*0.16(0.10)*b	*0.10(0.31)*a	0.29(0.32)a

†South Farm 2013: Hairy vetch pNdfa increased (P<0.05) with increasing hairy vetch biomass proportion in mixture ($y = 0.69 + 0.49 * hairy\ vetch$, $R^2 = 0.45$) over hairy vetch biomass proportions between 0.03 and 0.54.

§South Farm 2012: Cereal rye pNdfa decreased (P<0.05) with increasing hairy vetch biomass proportion in mixture ($y = 0.23 - 0.42 * hairy\ vetch$, $R^2 = 0.38$) over hairy vetch biomass proportions between 0 and 0.77.

Table 3.6 Parameter estimates and coefficients of determination for natural log of cover crop C/N ratio as related to proportion of hairy vetch biomass in cover crops. Quadratic models were fit only over the range of hairy vetch biomass proportions at which N data was available (NF 2012: 0-0.55, SF 2012: 0-1, NF 2013: 0-0.33, SF 2013: 0-0.54). All quadratic coefficients shown are significantly different than zero (*P*<0.05). Standard errors are presented in parentheses.

	-------------------------- Natural log of C/N -------------------------------				
Site-year	Hairy vetch monoculture	Cereal rye monoculture	Linear coefficient	Quadratic coefficient	R^2
NF 2012	2.73(0.07)	4.63(0.07)	-5.18(0.27)	5.39(0.69)	0.89
SF 2012	2.80(0.06)	4.50(0.06)	-3.20(0.12)	1.52(0.13)	0.91
NF 2013	2.67(0.08)	4.16(0.07)	-4.65(0.75)	7.97(2.82)	0.66
SF 2013	2.78(0.05)	4.38(0.05)	-4.39(0.31)	4.88(0.72)	0.88

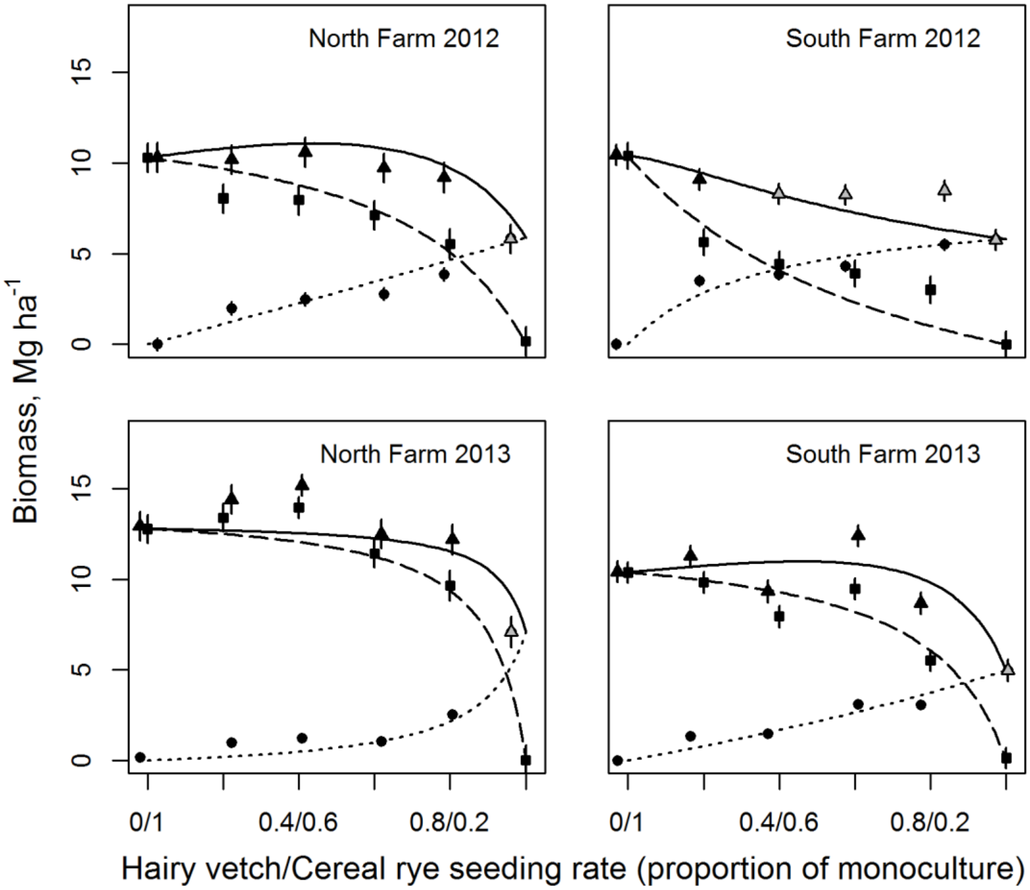

Figure 3.1 Cover crop aboveground biomass as a function of hairy vetch/cereal rye sown proportions for four site-years in Beltsville, MD. Lines represent de Wit model predictions (parameter estimates presented in Table 3.3). Circles and dotted lines represent hairy vetch biomass, squares and dashed lines represent cereal rye biomass, and triangles and solid lines represent total biomass. Within each site-year, total biomass estimates of mixtures and the hairy vetch monoculture were compared to biomass of cereal rye monoculture: grey triangles represent biomass values significantly less than the cereal rye monoculture biomass, and black triangles represent biomass values equal to cereal rye monoculture biomass (*P*<0.05). None of the mixtures produced biomass that significantly exceeded cereal rye monoculture biomass (*P*<0.05). Error bars are ± one standard error. Noise was added to points and error bars on the x-axis to allow better visual interpretation.

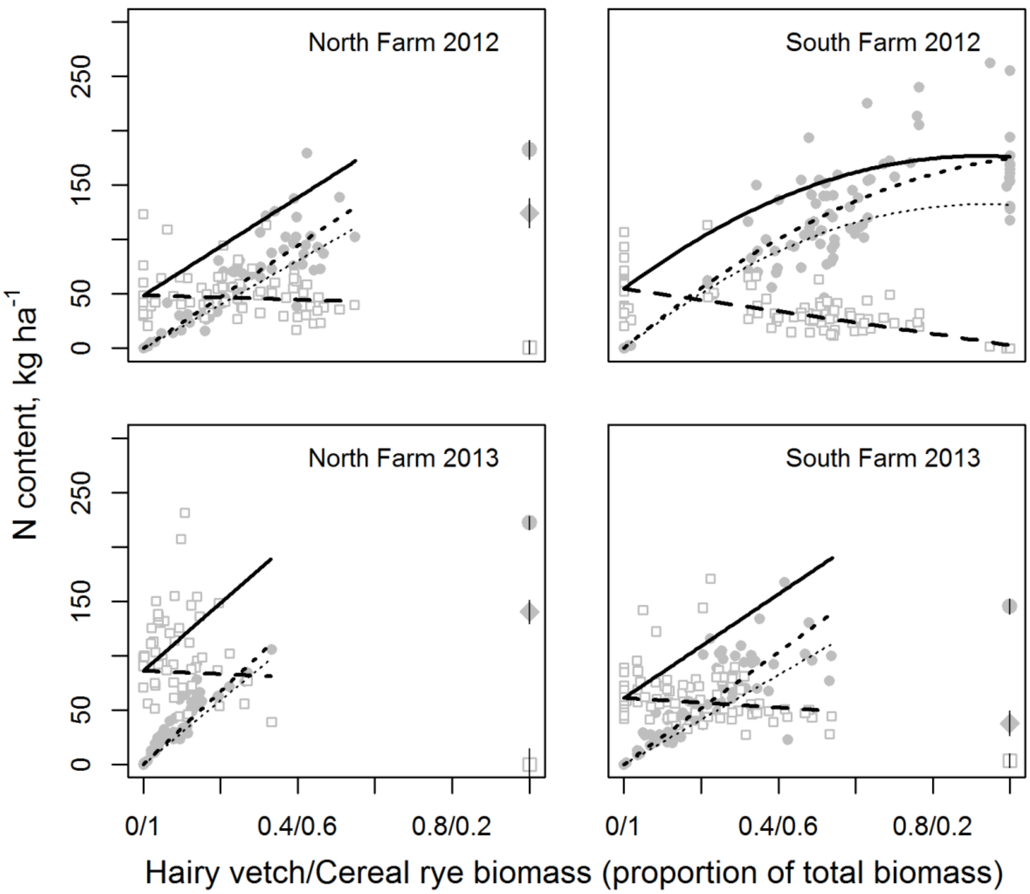

Figure 3.2 Cover crop aboveground nitrogen (N) content as related to hairy vetch biomass proportion for four site-years in Beltsville, MD. Lines represent linear or quadratic model predictions (model coefficients are presented in Table 3.4). Grey circles and dotted lines represent hairy vetch N content (thin dotted line indicates the hairy vetch biologically fixed N), white squares and dashed lines represent cereal rye N, and the solid line represents the total aboveground N content. Models were fit only over the range of hairy vetch proportions in which N data was collected. The circle, diamond and square at the highest hairy vetch proportion in each plot represent mean hairy vetch N content, fixed N and cereal rye N content calculated for the hairy vetch monoculture treatment, respectively. Error bars are ± one standard error.

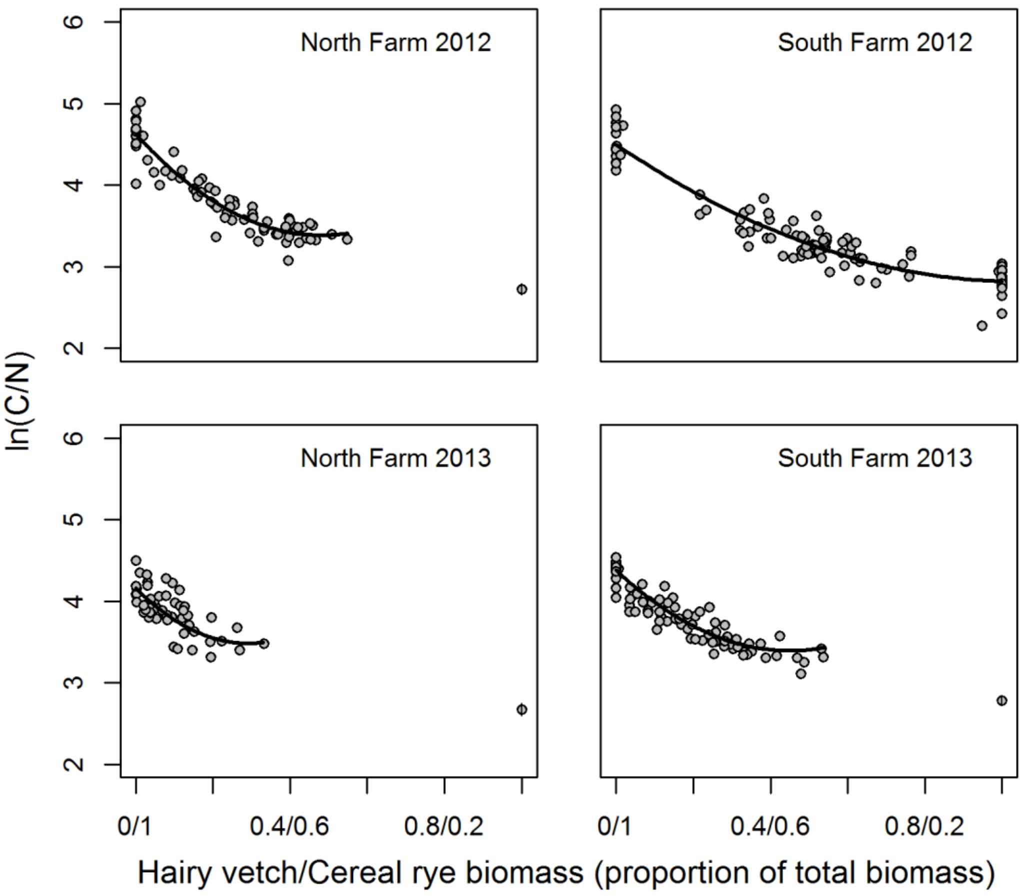

Figure 3.3 Natural log of cover crop C/N ratio as related to hairy vetch biomass proportion in cover crop for four site-years in Beltsville, MD. Lines represent quadratic model predictions (model coefficients are presented in Table 3.6). Models were fit only over the range of hairy vetch proportions at which N data was available. The circle at the highest hairy vetch proportion in each plot represents mean hairy vetch C/N ratio calculated for the hairy vetch monoculture treatment, respectively. Error bars are ± one standard error.

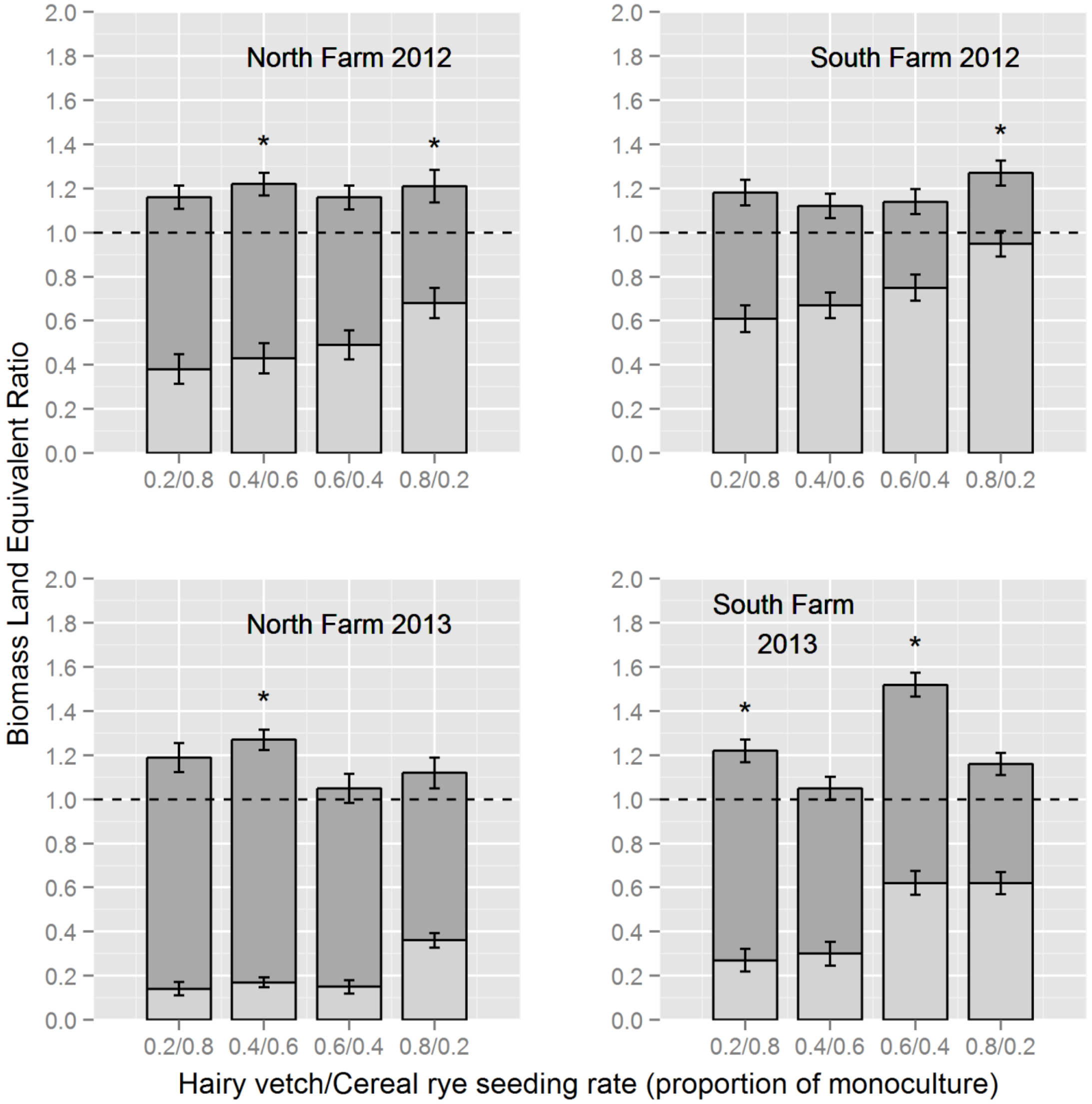

Figure 3.4 Mean biomass Land Equivalent Ratios (LERs) of hairy vetch/cereal rye mixtures for four site-years in Beltsville, MD. Dark grey and light grey segments represent the partial LERs of cereal rye and hairy vetch, respectively. Mixture LERs significantly greater than one are designated with asterisks above them (*P*<0.05). Error bars are ± one standard error of the individual species' partial LERs.

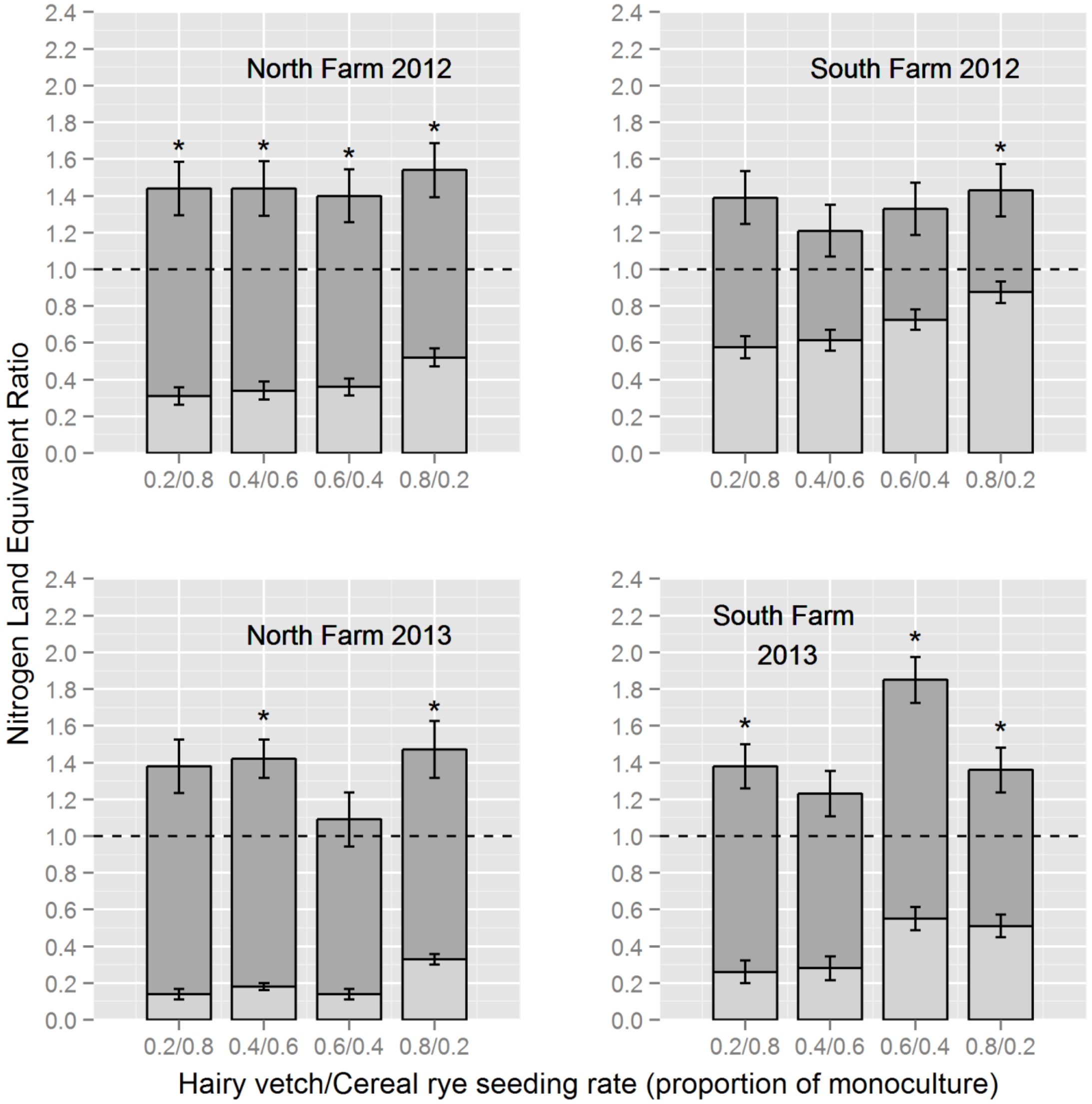

Figure 3.5 Mean nitrogen (N) Land Equivalent Ratios (LERs) of hairy vetch/cereal rye mixtures for four site-years in Beltsville, MD. Dark grey and light grey segments represent the partial LERs of cereal rye and hairy vetch, respectively. Mixture LERs significantly greater than one are designated with asterisks above them (*P*<0.05). Error bars are ± one standard error of the individual species' LERs.

Chapter 4 Decomposition and nitrogen release of hairy vetch/cereal rye monocultures and mixtures as influenced by tillage and pelletized poultry litter placement

Abstract

Cereal rye (*Secale cereale* L.), a winter small grain cover crop, scavenges nitrogen (N) during fall, winter and early spring, while hairy vetch (*Vicia villosa* Roth), a winter annual legume, fixes atmospheric N and releases it during the following summer. A mixture of cereal rye and hairy vetch will therefore provide N scavenging and N provisioning services. Despite the fact that additional N is often needed to supplement hairy vetch N in a subsequent corn (*Zea mays* L.) growing season, especially when the cover crop also contains a grass, little research has been done to evaluate the effects of manure management on cover crop decomposition and N release. The objective of this research was to determine, under field conditions, the effects of hairy vetch/cereal rye proportions, pelletized poultry litter (PPL) application (0 vs. 67 kg plant-available N ha^{-1}), PPL placement (broadcast vs. subsurface band), and tillage (till vs. no-till) on cover crop decomposition. In 2012 and 2013, nylon mesh bags were filled with cover crop residues at five specific species proportions and placed in corn plots with corresponding cover crop residue proportions and either no PPL, ~3.5 Mg PPL ha^{-1} subsurface banded at sidedress, ~3.5 Mg PPL ha^{-1} pre-plant broadcast, or ~3.5 Mg PPL ha^{-1} pre-plant broadcast-incorporated by tillage. The bags were collected during the corn growing season to quantify the rate and cumulative proportion of mass and N loss. Increasing hairy vetch proportion in cover crop residues led to a greater proportional mass loss (~0.4 of pure cereal rye to 0.8 of pure hairy vetch) and proportional N loss (~0.2 of pure cereal

rye and 0.8 of pure hairy vetch) from cover crop residues during the season, as well as higher rates of biomass decomposition. In the absence of broadcast PPL amendment, cover crop residues that contained hairy vetch had greater N release rates than pure cereal rye, but cover crop species proportions did not otherwise affect rates of N loss. Broadcast PPL application increased the N release rate from cereal rye surface mulches, and increased proportions of mass and N lost from residues containing a high cereal rye proportion relative to no PPL and subsurface band PPL. Relative to no-till treatments, incorporation of residues and PPL with tillage increased the effects of cover crop species proportions on biomass decomposition rate and cumulative proportional N loss, and increased the cumulative N release rates across cover crops containing hairy vetch. Tillage also increased cumulative proportional mass loss relative to no PPL and subsurface PPL treatments across all cover crop proportions. Subsurface band PPL application did not affect decomposition patterns of surface residues relative to no PPL.

Introduction

Cover crops can play an important role in mediating nitrogen (N) retention and supply in agroecosystems (Meisinger et al. 1991, Decker et al. 1994). Small-grain cover crops, such as cereal rye (*Secale cereale* L.), take up residual soil N in the fall, winter and spring when N would otherwise be vulnerable to leaching (Meisinger et al. 1991, Shipley et al. 1992, Staver and Brinsfield 1998). Winter annual legumes, such as hairy vetch (*Vicia villosa* Roth), are not effective N scavengers but fix atmospheric N and release biologically fixed N during decomposition, reducing fertilizer N requirements for corn (*Zea mays* L.) 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 provisioning 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, some plant-available N (PAN) is required at planting, but the majority of N uptake begins at the sixth-leaf stage, when corn reaches a phase of rapid N uptake. If inorganic N is released from cover crops too early or too late, it can be potentially lost to leaching or denitrification rather than taken up by the corn crop (Rosecrance et al. 2000). Hairy vetch, a legume cover crop, can release between 80 and 180 kg PAN ha^{-1} during the subsequent growing season, an amount which usually meets some, but not all, of a corn crop’s N requirements (Elbehar et al. 1984, Stute and Posner 1995, Clark et al. 1997b, Cook et al. 2010, Parr et al. 2011). Nitrogen from hairy vetch is released rapidly during decomposition, making it susceptible to early-season losses (Rosecrance et al. 2000, Sarrantonio 2003). Mixing grasses such as cereal rye with hairy vetch may provide better synchrony of N release and 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, Ruffo and Bollero 2003).

Time of cover crop termination affects decomposition dynamics of hairy vetch and cereal rye, due to changes in residue quality with increasing maturity (Wagger 1989b). However, studies on hairy vetch and cereal rye decomposition have primarily been performed when these cover crops were in vegetative stages (Wagger 1989b, Stute and Posner 1995, Ranells and Wagger 1996, Ruffo and Bollero 2003). There is increasing evidence by researchers on the value of, and interest by farmers in, extending the services cover crops provide by maximizing their biomass production. Recent research has been directed toward developing cover crop-based no-till grain production systems, which use mechanical termination by a roller/crimper of mature cover crops forming a thick unidirectional mulch (Reberg-Horton et al. 2011, 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. Greater knowledge is needed on residue decomposition dynamics in such systems with high cover crop biomass and late cover crop termination.

Despite the fact that additional N is often needed to supplement legume N in a corn growing season, little research has been done to evaluate the effects of manure management on cover crop decomposition. Poultry litter is usually incorporated in conventional tillage systems, or broadcast applied in no-till systems prior to corn planting. Recent developments in subsurface banding technology may soon provide farmers the option of localized subsurface application of dry manures 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 effects of manure amendment and application method on cover crop decomposition are currently not well-known.

The objectives of this study were to determine the effects of hairy vetch/cereal rye proportions, pelletized poultry litter application (PPL; 0 vs. 67 kg PAN ha^{-1}), PPL placement (broadcast vs. subsurface band) and tillage (till vs. no-till) on the decomposition and N release of aboveground cover crop biomass during the subsequent corn growing season. We hypothesize that increasing hairy vetch proportion in cover crop residues, incorporating residues and PPL through tillage, and broadcast PPL amendment will increase both the rate and cumulative loss of biomass and N. However, we expect that subsurface band PPL application will not influence the decomposition of cover crop surface residues.

Methods

Field management

A field experiment was conducted at the Beltsville Agricultural Research Center in fall 2011 and replicated in fall 2012. The experiment included six hairy vetch/cereal rye sown proportions (four different mixtures and two monocultures) established each fall prior to corn planting. In the spring, these cover crop treatments were overlaid by four PPL treatments: 0 Mg PPL ha^{-1}, ~3.5 Mg PPL ha^{-1} subsurface banded at sidedress, ~3.5 Mg PPL ha^{-1} pre-plant broadcast, and ~3.5 Mg PPL ha^{-1} pre-plant broadcast and incorporated, in a split-block design. The incorporated treatment was tilled to incorporate the cover crop residues and broadcast PPL in the spring, whereas the other treatments were managed without tillage during the corn season. The 2011-2012 experiment was conducted on 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 conducted on South Farm, which is under conventional agricultural management (39.02 N, 76.94 W). Both sites have a long history of using cover crops and animal manure. Soils on North Farm are classified as fine-loamy, mixed, mesic Typic Endoaquults (Hatboro series) and soils on South Farm are classified as fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts (Codorus series). Three replicates were evaluated each year.

A soybean (*Glycine max* (L.) Merr.) cover crop was planted in spring 2011 and 2012 and incorporated by disking in late summer to reduce spatial heterogeneity of soil inorganic N and provide some residual N for the subsequent cover crops. After incorporating soybeans, fields were cultivated and cultimulched to prepare a uniform seedbed prior to seeding cover crops. The fields also received 56 kg potassium (K) ha^{-1} as K_2SO_4 prior to cover crop planting. The hairy vetch/cereal rye sown proportions were: 0/1, 0.2/0.8, 0.4/0.6, 0.6/0.4, 0.8/0.2, 1/0. The monoculture hairy vetch and cereal rye seeding rates were 34 kg ha^{-1} and 168 kg ha^{-1}, respectively and the mixture sown proportions represent proportions of each species' monoculture seeding rate. The two cover crop species were planted in separate, sequential passes using a grain drill (19 cm row spacing) on October 7, 2011 and on September 25, 2012. Hairy vetch seed was inoculated with *Rhizobia* just prior to planting. Cover crops were terminated on May 17, 2012 and on May 22, 2013 using a roller/crimper in the no-till plots. The roller/crimper consists of a hollow steel cylinder 30-60 cm in diameter with blades along the outside of the cylinder designed to crush and crimp the cover crop, forming a dense, unidirectional mulch (Ashford and Reeves 2003). 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 10 days prior to rolling.

Pelletized poultry litter was broadcast just prior to corn planting in the pre-plant broadcast and incorporated treatments using a Stoltzfus (W-Chain Sower spreader, Morgantown, PA) manure spreader at 3.6 Mg ha^{-1} in 2012 and 3.4 Mg ha^{-1} in 2013. These rates corresponded to 67 kg PAN ha^{-1}, assuming 50% mineralization of organic N during the corn growing season and 90% of PPL NH_4^+-N available. The incorporated treatment was mechanically spaded (Imants 27sx, Reusel, Netherlands) to 20 cm and cultimulched just before planting. Corn was planted in the incorporated and no-till treatments the same day as the cover crops were rolled. All corn received ~10 kg PAN ha^{-1} as starter PPL. In the subsurface band treatment, PPL was sidedressed at the same rate as the broadcast and incorporated treatments using a custom-fabricated prototype subsurface band applicator at the eighth-leaf growth stage on July 3, 2012 on North Farm and at the fifth-leaf growth stage on June 25, 2013 on South Farm. In 2012, the incorporated plots were rotary hoed on May 18 and May 24, and between-row cultivated on June 6, June 10 and June 19. The no-till plots were high-residue cultivated on June 25 and July 2. In 2013, the South farm field received glyphosate applications on May 31 and June 26 at 2.8 kg active ingredient ha^{-1}. North Farm was irrigated with approximately 2.5 cm on July 5, 2012; South Farm received 4 cm on June 27, July 29, and September 8, 2013.

Litter bag methods

We used nylon mesh “litter bags” (30 x 30 cm dimensions, 1 mm mesh size) filled with cover crop residues, placed in the field and collected over time to study cover crop decomposition. To determine the target residue dry weights and appropriate fresh weights of each species to place in the litter bags, cover crop samples were collected in monocultures and a subset of mixtures five days prior to mowing the incorporated treatment. For each sample, all aboveground biomass within a 50 cm x 50 cm frame was collected. The samples were weighed fresh and dried for biomass and moisture content determination. Moisture contents for hairy vetch and cereal rye were used to determine the fresh weights required to achieve the total targeted dry weight biomass level, based on average field cover crop biomass (8.0 Mg ha^{-1} in 2012 and 9.0 Mg ha^{-1} in 2013) and the following hairy vetch/cereal rye biomass proportions: 0/1, 0.25/0.75, 0.50/0.50, 0.75/0.25, and 1/0.

Just prior to mowing the incorporated treatment, hairy vetch and cereal rye biomass was harvested from experimental border areas, avoiding partially decomposed hairy vetch material near the soil surface. The fresh material was cut to 10 cm lengths (the approximate length of flail-mowed residues). To fill each litter bag, the appropriate fresh mass of each species was weighed, mixed and placed in the bag. Six litter bags were prepared for each cover crop proportion in each rep. The litter bags were buried at a slight angle at a depth of 20 cm in the cover crop treatments with roughly corresponding proportions (sown proportions of 0/1, 0.2/0.8, 0.6/0.4, 0.8/0.2 and 1/0 hairy vetch/cereal rye) immediately after mowing and disking the incorporated treatment. The burial depth was selected so that litter bags were within the depth of cover crop incorporation by disking but below the depth of the interrow cultivator.

Litter bags for the no-till plots were prepared in the same way just prior to rolling, only the material was cut to 25 cm to lay flat in the bag. Litter bags in the broadcast poultry litter treatment received poultry litter within the bag at the same rate as applied to the larger plots. Immediately after corn planting, the no-till litter bags were placed in the plots with roughly corresponding cover crop proportions (sown proportions of 0/1, 0.2/0.8, 0.6/0.4, 0.8/0.2 and 1/0 hairy vetch/cereal rye) and designated as either no PPL, subsurface band or broadcast. Existing residue in the area that was to be occupied by the litter bags was clipped and removed, and the bags were pinned in each corner to ensure good contact with the soil surface. During broadcast PPL application, the litter bags within the broadcast treatment were covered so that did not receive 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 spading of the incorporated treatment, subsurface band application and high residue cultivation. Soil temperature and moisture sensors logged hourly readings in a subset of cover crop and PPL treatments from corn planting through corn harvest (Decagon, 5TE soil moisture, temperature, EC sensors, Pullman, WA). Sensors were placed just below the soil surface (3-5 cm depth) in the 0/1, 0.6/0.4 and 1/0 hairy vetch/cereal rye sown proportions within the subsurface band treatment to measure conditions experienced by microbes near the soil surface/mulch interface. Readings collected in this treatment were assumed to be representative of the three no-till PPL treatments (no PPL, subsurface band, and broadcast). Sensors were placed at a 20 cm depth in the same cover crops within the incorporated treatment.

One bag was collected from each plot at each of six approximate sampling times: cover crop termination, corn emergence, and corn third-leaf stage, eighth-leaf stage, silking and physiological maturity. The litter bag contents were oven-dried and ground to pass a 1 mm sieve. A subsample of the ground material was ashed for 4 hours at 550° C to quantify soil contamination in each bag. The ground litter bag contents were analyzed for C and N concentrations by total combustion analysis (Leco CHN analyzer, St. Joseph, MI). Soil collected from the outside of the litter bags in the incorporated and no-till plots was also analyzed for total organic matter, C and N concentration. Ash-free mass was computed as:

$$M_{AF} = (1 - A_{sample})M_{sample}$$

where M_{AF} is the ash-free mass, A_{sample} is the proportion of ash in the litter bag sample, and M_{sample} is the dry weight of litter bag contents. The N and C concentrations were also adjusted to an ash-free basis to correct for a possible "dilution effect" of soil contamination on litter N and C concentrations:

$$N_{AF} = \frac{N_{sample} - N_{soil}\left(A_{sample}\right)}{(1 - A_{sample})}$$

where N_{AF}, $N_{sample}$and N_{soil} are the N or C concentrations of the ash-free sample, litter bag sample, and soil, respectively. The ash adjustments did not account for the ash proportion of clean plant material taken during bag preparation because the ash proportion of clean plant material is expected to change as the organic plant components decay. Also, the ash proportions of hairy vetch and cereal rye differ, and the mixed cover crop residues within the bag may not have maintained their proportions during decay.

Statistical analysis

First, the effects of cover crop species proportions on initial litter bag total biomass, N and C concentrations were evaluated for each of the PPL treatments using ANOVA. Plant N concentrations were log-transformed to meet the homogeneity of variance assumption (means and 95% confidence intervals were back-transformed for presentation). Linear mixed models were constructed separately for each year using the lme function in R (R Development Core Team 2014). Rep was included as a random effect because litter bags were prepared in order by rep. Means were calculated using lsmeans and contrasts were performed using glht in R package multcomp (R Development Core Team 2014).

The proportions of mass and N remaining were calculated for each litter bag by dividing the ash-free mass and ash-free N content of each bag by the ash-free mass and ash-free N content of the initial litter bags for each respective cover crop mixture and rep. The proportions of mass and N remaining for each cover crop and PPL treatment were modeled over soil growing degree days (GDD), calculated by summing the mean daily soil temperatures above 0°C (Honeycutt et al. 1988). The soil GDD for the no-till treatments were based on average daily soil surface temperatures from the subsurface band treatments containing the temperature sensors. The soil GDD for the incorporated litter bags were based on average daily soil temperatures at 20 cm depth from the incorporated treatments containing the temperature sensors. An asymptotic exponential decay function was used to model proportion of mass and N remaining over soil GDD. This model is based on the concept that plant litter contains both readily decomposable components that disappear rapidly and resistant components that remain:

$$P(t) = Pe^{-kt} + (1 - P)$$

where $P(t)$ is the proportion mass or N remaining at a given time, t (in units of soil GDD), P is the proportion of mass or N loss and k is the exponential decay constant. P and k were both estimated parameters. Model fitting was done separately for each cover crop and PPL treatment in each year using the nlme function in R (nlme package, R Development Core Team 2014). A random rep effect on the decay constant was included in the models. Half-lives (the soil GDD required for 50% of original mass or N to be lost) were calculated using the proportional loss and decay constants estimated by exponential decay model fitting as:

$$t_{1/2} = \frac{\ln\left(\frac{0.5-(1-P)}{P}\right)}{-k}$$

Both parameters (P and k) were then modeled as a function of initial cover crop species proportion by each PPL treatment. This analysis was done to provide further insights into how the rate of decay and the proportional mass and N loss were influenced by initial cover crop species proportion and its interaction with PPL management. However, the estimated proportional mass and N loss (P) from the exponential decay functions were not used in the regression analysis because not all treatment combinations reached an asymptote during the corn growing season. Instead, we used the difference between the proportion of mass and N remaining at corn maturity and one, the proportion present at cover crop termination to provide a better estimate of "cumulative" proportional loss for single corn growing season. The cumulative proportional loss and decay constants were analyzed using linear regression that included the effects of PPL treatment and initial cover crop proportion, and their interactions. Quadratic terms for cover crop proportion and interactions of the quadratic term with PPL treatment were included based on their significance. Initial biomass was not included in the model as a covariate due to lack of significance. Year was included as a random effect in the models according to its interactions with the other factors when first evaluated as a fixed effect. Linear mixed effects model fitting was performed using the lmer function in R (package lme4, R Development Core Team 2014). Nitrogen cumulative proportional loss (l_N) was further modeled using a rectangular hyperbolic model, which provided a better fit to the data:

$$l_N = N_r + (\frac{sva}{a + sv})$$

where N_r is an estimated intercept parameter representing the proportional N loss for pure cereal rye, s is a shape parameter representing the initial slope of the curve, a is an estimated asymptote parameter representing the maximum proportional N loss observed, and v is the proportion hairy vetch present in mixture at the time of litter bag preparation. Parameter estimates were made separately 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 (package nlme, R Development Core Team 2014). 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 R (package multcomp, R Development Core Team 2014).

Results

Environmental conditions and initial litter bag properties

The 2012 corn growing season had higher temperatures and less rainfall than 30-year averages for all months (Table 4.1). The 2013 season was cooler and wetter than 2012, with temperatures and total rainfall largely consistent with 30-year averages. Soil GDD accumulated at a similar rate whether soil temperature was measured at 5 cm depth in the no-till plots (subsurface band treatment) or at 20 cm depth in the incorporated plots (Figure 4.1). However, greater total soil GDD accumulated in the incorporated plots relative to the no-till plots in both years because the cover crops were terminated 6 or 10 days earlier in the incorporated treatment. Soil temperatures were slightly greater in the hairy vetch cover crop treatment than in the cereal rye and mixtures in the no-till and incorporated treatments in 2012 and in the no-till treatments in 2013. Soil volumetric moisture ranged from 10% to 30% in 2012 and from 18% to 40% in 2013, with more moisture variation at 5 cm depth in no-till than at 20 cm depth in the incorporated treatment. Soil moisture was particularly high during the month of June in 2013. Soil moisture tended to be greatest in the cereal rye cover crop treatment in 2012 and in the mixture cover crop treatment in 2013.

The litter bags in the no PPL, subsurface band and incorporated treatments contained an average initial cover crop biomass level of 7.7 Mg ha^{-1} in 2012 and 8.8 Mg ha^{-1} in 2013 (oven dry-weight basis; Tables 4.2 and 4.3). The litter bags in the broadcast treatment received PPL in addition to the cover crop biomass, increasing the average mass to 10.9 Mg ha^{-1} in 2012 and 11.9 Mg ha^{-1} in 2013. There was a trend of decreasing litter bag biomass with increasing hairy vetch proportion for all PPL treatments in 2012 ($P<0.05$). In 2013, there was approximately 10% greater cover crop biomass in the incorporated litter bags than no PPL and subsurface band bags ($P<0.05$). These slight inconsistencies in the cover crop biomass placed in litter bags among cover crop species proportions and between the no-till and incorporated treatments may have arisen due to inaccuracy of moisture content estimates used to determine the fresh mass of hairy vetch and cereal rye placed in each bag. The measured cover crop proportions in the litter bags matched the targeted proportions well, especially in 2013. Nitrogen concentrations of litter bag contents increased significantly with increasing hairy vetch biomass proportion in all PPL treatments in both years ($P<0.05$). The PPL amendment in the broadcast treatment increased N concentrations in the cereal rye and 0.25/0.75 hairy vetch/cereal rye mixture relative to the other PPL treatments in 2012, and increased the N concentration of the cereal rye litter in 2013 ($P<0.05$). Nitrogen concentrations were approximately 10% greater in the incorporated bags than in the no-till bags in 2012 ($P<0.05$), and up to 43% greater in 2013 than in 2012. The greater N concentrations observed in these instances were likely associated with the earlier termination of the cover crops in the incorporated treatment relative to no-till treatments in 2012 and the earlier termination of cover crops in 2013 relative to 2012.

Exponential decay predictions

The exponential decay models provided excellent fits to the proportion of mass remaining over soil GDD (all R^2 >0.88, Figures 4.2 and 4.3, Appendix 2). The proportion of mass remaining in cover crop residues at any given time decreased with increasing hairy vetch proportion. For example, in 2012, exponential decay models predicted 50% of hairy vetch mass remained in the no PPL treatment at 893 soil GDD, while 68% and 87% of the 0.50/0.50 mixture and cereal rye mass remained, respectively. In 2013, a similar pattern was observed, but decomposition proceeded more rapidly overall: the half-life of hairy vetch mass in 2013 was 367 soil GDD, when 70% and 83% of the 0.50/0.50 mixture and cereal rye remained at this time, respectively. The biomass decomposition patterns of the cover crop residues were similar in the subsurface band treatment as in the no PPL treatments in both years. However, for cover crops 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, causing the prediction lines to be more similar among cover crop proportions in the broadcast treatments (Figures 4.2 and 4.3). Incorporation of residues and PPL through tillage also tended to decrease the mass remaining of cover crops relative to the no PPL and subsurface band treatments for all cover crops, except for cereal rye in the first 2000 soil GDD of the 2013 season.

Coefficients of determination for the exponential decay equations fit to the proportion N remaining over soil GDD ranged from 0.64 to 0.99, with73% of R^2 values above 0.90 (Figures 4.4 and 4.5, Appendix 2). The proportion of N remaining over time in pure cereal rye was not modeled using the exponential decay model for the no PPL, subsurface band, and incorporated treatments because the proportion of N remaining tended to oscillate around 1.0 rather than declining in an exponential pattern over soil GDD. Consistent with the proportional mass remaining predictions, increasing hairy vetch proportion resulted in a lower proportion of N remaining at any given time during the corn growing season. However, N loss proceeded more rapidly than mass loss in both years. For example, the half-lives for proportional N remaining in hairy vetch and the 0.50/0.50 mixture in 2012 were 470 and 604 soil GDD, respectively relative to 893 and 1837 soil GDD for 50% mass remaining. The rapid rate of N release early in the 2012 and 2013 seasons meant that the proportion of N remaining in cover crop residues had reached a stable level by 1500 soil GDD in 2012 and 1000 soil GDD in all 2013. Visual inspection of Figures 4.4 and 4.5 suggest that subsurface band PPL application did not alter N release patterns of the cover crops relative to no PPL, but that broadcast application decreased the proportion N remaining at any given time in residues with high cereal rye composition (>0.50) throughout both seasons relative to the no PPL, subsurface band and incorporated treatments. Incorporating the residues and PPL appeared to reduce the proportion N remaining over time in residues with greater than 50% hairy vetch composition, but increase the proportion N remaining in residues with mostly cereal rye relative to the other PPL treatments.

Cumulative proportional mass and N loss

Cumulative proportional mass loss is defined as the proportion of cover crop mass lost during the corn growing season. The quadratic equation provided an excellent fit to cumulative proportional mass loss as a function of cover crop species proportions ($R^2 = 0.98$). All model terms were highly significant across PPL treatments (Table 4.4). In the no PPL treatment, the cumulative proportional mass loss increased significantly from 0.4 to 0.8 as proportion hairy vetch in mixture increased ($P<0.05$, Figure 4.6, Table 4.4). Subsurface band application of PPL did not affect any of the model terms. Broadcast PPL application and incorporating residues and PPL significantly increased the intercept estimates ($P<0.05$), which correspond to the cumulative proportional mass loss by pure cereal rye residue. The broadcast treatment also had a significantly lower linear coefficient than the no PPL and subsurface band treatments ($P<0.05$), while the incorporated treatment had a linear coefficient intermediate between that of the broadcast and other no-till treatments. This suggests that the broadcast treatment disproportionately affected the cumulative proportional mass loss of residues with high cereal rye composition, with no effect for the pure hairy vetch residue. The incorporated treatment increased proportional mass loss across all species proportions relative to no PPL and subsurface band, but also had a slightly more pronounced effect on residues with high cereal rye composition than high hairy vetch composition. Cumulative proportional mass loss was greater in 2013 than 2012, and the effect decreased with increasing hairy vetch proportion ($P<0.05$).

Proportional N loss during the corn growing season increased with increasing hairy vetch proportion, following a hyperbolic function to a maximum of around 0.8 in pure hairy vetch (shape parameter <0.05 for all PPL treatments, $R^2 = 0.96$, Figure 4.6,

Table 4.4). Pelletized poultry litter management had significant effects on intercept estimates (*P*<0.05), which correspond to the proportion N lost during the corn growing season from pure cereal rye residue. The incorporated treatment resulted in no N loss from pure cereal rye, while the broadcast treatment resulted in 44% N loss from the pure cereal rye + PPL, and the intercept estimates for the no PPL and subsurface band treatments were intermediate between these extremes. The asymptote estimates for the no PPL and subsurface band treatments were similar, while the broadcast treatment had a significantly lower asymptote estimate (*P*<0.05) and the incorporated treatment had a significantly higher asymptote estimate (*P*<0.05). The higher intercept estimate and lower asymptote estimate for the broadcast treatment suggests that broadcast application of PPL made the proportional N loss among cover crop treatments more similar. In contrast, the incorporated treatment made the proportional N loss among cover crop treatments more different relative to the no PPL treatment. The cumulative proportional N loss was higher in 2013 than in 2012 (*P*<0.05).

Decay constants

Mass decay constants increased linearly with increasing hairy vetch proportion (*P*<0.05 for all PPL treatments, $R^2 = 0.90$, Figure 4.6, Table 4.4). The intercepts of linear equations fit to mass decay constants across cover crop species proportions represent the mass decay constant estimates for pure cereal rye residue. There were no differences in intercept estimates among PPL treatments. However, the incorporated treatment increased the slope of the relationship between mass decay constant and hairy vetch proportion in residue (*P*<0.05). There was a significant year x PPL treatment interaction effect on mass decay constants, where the influence of year was greater in the no-till PPL treatments than in the incorporated treatment (*P*<0.05). In all PPL treatments except the broadcast treatment, N decay constants were greater for cover crops containing hairy vetch than pure cereal rye, which did not release substantial N throughout the season. However, trends in N decay constant could not be detected across the cover crop proportions containing hairy vetch, or across all species proportions in the broadcast treatment. Across all cover crops containing hairy vetch, N decay constants were significantly greater in the incorporated treatment relative the other three PPL treatments, which were similar to each other (*P*<0.05). Nitrogen decay constants were also greater in 2013 than in 2012 (*P*<0.05).

Discussion

Residue loading rate and year effects

` The objectives of this study were to determine the effects of hairy vetch/cereal rye proportions, tillage and PPL application and placement on the decomposition and N release of aboveground cover crop biomass during the subsequent corn growing season. We modeled the exponential decay of cover crop residues over soil GDD for two years, and evaluated the exponential decay parameters across cover crop species proportions and by PPL treatment. Although there was some variability in the initial mass placed in litter bags among cover crop species proportions, this did not contribute to explaining variance associated with the cumulative proportional loss and decay constants (initial biomass covariate was non-significant). Some studies have found that decomposition occurs faster when less residue is added to a soil (Broadbent and Bartholemew 1945 using oat straw), while other studies have found no effect of loading rate (Jenkinson 1977 using ryegrass, Honeycutt et al. 1993 using hairy vetch). The loading rate of high C/N-ratio residues is likely to be more influential on decomposition than the loading rate of lower C/N ratio residues because N may increasingly limit decay as the mass of C-rich residues increases. However, Jenkinson (1977) notes that over a period of 3-6 months, even in N limiting conditions, larger residue additions are likely to catch up with the decay of smaller additions of the same plant material.

Greater cumulative proportional losses and decay constants were observed in 2013 relative to 2012. The use of soil GDD as a timescale has been shown to reduce the effect of temperature differences on C and N mineralization (Honeycutt et al. 1988). However, temperatures in both years were similar, and inter-annual differences in decomposition were more likely due to differences in moisture. Doel et al. (1990) found that heat units were useful to predict N mineralization within a soil water potential range of -0.03 to -0.01 Mpa (essentially, field capacity), but not at -0.30 Mpa. The low soil moisture and low rainfall in 2012, resulting in water potentials well below field capacity, limited the usefulness of soil GDD in predicting decomposition. Timescales have been developed to account for moisture conditions of surface residues, such as “decomposition days” (Stroo et al. 1989) and “adjusted growing degree days” (Quemada 2004) and to account for moisture conditions experienced by buried residues (Andren and Paustian 1987). However, the use of separate moisture-adjusted timescales for no-till and buried residues may have limited interpretation of treatment effects in the present study. Regardless, the large moisture differences between 2012 and 2013 provide insight into how much decomposition can be expected of hairy vetch/cereal rye cover crop residues in a relatively wet year and a relatively dry year. Other factors that may have contributed to inter-annual differences in decomposition include slight differences in residue C/N ratios, and differences in weed management between years (cultivation on North Farm in 2012 vs. chemical control on South Farm in 2013). The more frequent removal and resetting of no-till litter bags for high-residue cultivation in 2012 may have disrupted fungal hyphae. Fungi play a more important role in decomposition of no-till surface residues than incorporated residues (Holland and Coleman 1987) because they have a high tolerance for dry conditions (Griffin 1972) and the ability to translocate N from soil to the C source (Ames et al. 1984).

The year effect on cumulative proportional mass loss was greater for residues with higher cereal rye composition. The decomposition of pure cereal rye residue was most strongly affected by N additions in the form of broadcast PPL, implying that inter-annual differences in cereal rye N concentration and/or environmental conditions that favor greater soil N availability would also have a greater effect on decomposition of cereal rye than on the cover crops containing hairy vetch. The year effect on mass decay constants was greater in the no-till treatments than in the incorporated treatment, in which residues were buried. This observation was also made by Wilson and Hargrove (1986). It is likely that burying the residues at ~20 cm depth exposed the residues to more constant moisture than placing them on the soil surface, moderating the effects of low rainfall on rate of decay in 2012.

Factors influencing cumulative proportional mass and N loss

We found that cumulative proportional mass and N loss increased with increasing hairy vetch proportion in both years. This trend supports the findings of Starovoytov et al. (2010), who reported that adding 1 to 2 Mg ha^{-1} of small grain residue to hairy vetch residues increased the proportion of mass remaining at the end of the corn season by approximately 0.10. On the other hand, Ranells and Wagger (1996) did not find clear trends in proportion of mass lost with hairy vetch/cereal rye proportion, perhaps because the range of C/N ratios of residues was much narrower than in the present study. The proportional mass loss after one growing season ranged from 0.60 to 0.90 across both studies, estimates which are consistent with ours for hairy vetch and mixtures, but greater than cumulative proportional mass loss for pure cereal rye in the present study. In terms of proportional N loss, Wagger (1989b) also found that hairy vetch lost a greater proportion of its initial N than cereal rye. Wagger (1989b) estimated that the proportion of N lost from pure cereal rye (C/N = 27-44) ranged from 0.13 to 0.47, while the proportion of N lost from hairy vetch (C/N = 8-12) ranged from 0.73 to 0.87. Similarly, Stute and Posner (1995) estimated a proportional N loss for hairy vetch of 0.8 during a corn growing season. These proportional N loss estimates are consistent with the ranges we observed for the respective species. Furthermore, Ranells and Wagger (1996) found that the proportional N loss from a hairy vetch/cereal rye mixture was intermediate between that of the monocultures, although the proportional N loss estimates for pure cereal rye were higher (~0.82) in their study than in the present study.

Subsurface application of PPL did not affect the cumulative proportional mass loss or N loss, indicating that this method of PPL application may best conserve surface residues, which can contribute to weed suppression and moisture conservation. Amending soil with PPL by broadcast application increased the cumulative proportional mass and N loss from the pure cereal rye + PPL surface mulch. The surface application of PPL decreased the initial C/N ratio of litter contained within the cereal rye litter bags from 86 to 33 in 2012 and from 63 to 36 in 2013, making the C/N ratios more similar to residues containing hairy vetch. Interestingly, the broadcast application resulted in a lower cumulative proportional N loss from the pure hairy vetch residue and 0.75/0.25 hairy vetch/cereal rye mixture relative to these species proportions in the other PPL treatments. Several other studies have reported that added N may decrease the decomposition of some residues (Fog 1988).

Incorporation of residues and PPL by tillage increased the cumulative proportional mass loss from residues relative to the no PPL and subsurface band treatments. The cumulative proportional N loss from pure cereal rye residue decreased with incorporation, while the cumulative proportional N loss from pure hairy vetch residue increased relative to the no-till treatments. One could argue that a slightly greater accumulation of soil GDD in this treatment may have affected the cumulative proportional mass and N loss relative to the other PPL treatments. However, model predictions of proportional mass and N loss at a soil GDD-equivalent of 10 days earlier in the incorporated treatment reveal that the PPL treatment effects hold regardless of the greater duration of decomposition in the incorporated treatment. Burying the plant litter probably increased interaction of plant litter with soil microbes and provided a more constantly moist environment, resulting in faster decomposition and N release of high-quality residues (Holland and Coleman 1987). However, the greater cumulative proportional mass loss of cereal rye residues in the incorporated treatment relative to no-till treatments may have caused greater N immobilization (less net N loss) in the incorporated treatment.

Factors influencing decay constants

Mass decay constants in the no PPL and subsurface band treatments ranged from

0.00014 to 0.0013 for pure cereal rye residue and from 0.0012 to 0.0031 for pure hairy vetch residue. Ruffo and Bollero (2003) also modeled decomposition of surface residues over GDD and estimated biomass decay constants of cereal rye (C/N = 25-35) between 0.00038 to 0.00057 and hairy vetch (C/N = 10-25) between 0.00025 and 0.0030. Our hairy vetch biomass decay constants fall within the range of estimates by Ruffo and Bollero, while our cereal rye mass decay constants fall below (2012) and above (2013) the range of their estimates. The cereal rye used in the present study had higher C/N ratios than in the Ruffo and Bollero (2003) study, and thus would be expected to have lower decay constants. However, the year x cover crop proportion effect on cumulative proportional mass loss suggests that the decomposition of residues with high C/N ratios may be more susceptible to variability in environmental conditions than residues with low C/N ratios. We found that mass decay constants increased with increasing hairy vetch proportion, and the response was greatest in the incorporated treatment. Nitrogen decay constants were also greater in the incorporated treatments than 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 (C/N ratio <16) lost mass and N 2-5x faster when buried than when placed on the soil surface.

Nitrogen decay constants were usually greater than mass decay constants, except for pure cereal rye residues with no broadcast PPL. The initial rapid loss of N from the litter may have reflected the water-soluble N component of hairy vetch (estimated to make up approximately 30% of tissue N concentration by Kuo and Sainju 1998) and, in the case of PPL, the mineral fraction of N. Both of these N pools may have been lost from the litter bags through leaching or volatilization and thus not accompanied by C mineralization and mass loss. Residues containing hairy vetch achieved 50-100% of their cumulative proportional N loss by the sixth-leaf growth stage (~700 soil GDD) in 2012 and greater than 90% of their cumulative proportional N loss by the sixth-leaf growth stage in 2013. Thus, our data suggest that cover crop residues containing hairy vetch may not contribute a substantial “slow release” N pool once the corn begins taking up N. The finding that only a small proportion of the cumulative proportional N loss from hairy vetch residues is released after approximately four weeks supports the body of literature on this subject (Wagger 1989b, Varco et al. 1993, Ranells and Wagger 1996, Stute and Posner 1995). 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. Other cereal rye decomposition studies have used exponential models for cereal rye N loss over time, but the C/N ratios of cereal rye used in other studies are usually lower than the present study (Wagger 1989b, Ranells and Wagger 1996, Ruffo and Bollero 2003).

While mass decay constants increased with increasing hairy vetch proportion, N decay constants did not display a consistent trend in response to cover crop mixture proportion (although mass decay constants were greater for residues containing hairy vetch or PPL relative to pure cereal rye). This result contradicts the findings of incubation studies conducted using hairy vetch/cereal rye residues at varying proportions. These studies reported decreasing net N mineralization rates with increasing cereal rye biomass proportions, likely because hairy vetch N is immobilized during the decomposition of cereal rye (Kuo and Sainju 1998, Lawson et al. 2012). It appears that, in the present study, the N decay constants of the mixtures reflected the N decay constant of the hairy vetch component of the mixture without any interaction with the cereal rye. Similarly, Quemada and Cabrera (1995) found that a mixture of high C/N-ratio clover stems and low C/N-ratio clover leaves had similar N mineralization rates as clover leaves in a field study using intact cores. We speculate that the response of N mineralization constants to hairy vetch/cereal rye proportions observed in lab incubations is an artifact of the physical proximity of hairy vetch N and cereal rye residues. In contrast, in the field, N released from hairy vetch is susceptible to losses prior to 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 initial N imbilization of legume N in a laboratory incubation.

Study implications

Results from this study were presented as proportion of initial biomass or N remaining over soil GDD. Although there were significant differences in cumulative proportional losses between the dry and wet years, these differences were actually relatively minor in the context of making general loss predictions. We note that the total biomass and N content, rather than proportion of initial, is an important consideration in understanding residue cover and N contribution of cover crops. For example, hairy vetch released a greater proportion of N than cereal rye, and also began with greater N content. Total N released by pure cereal rye, 0.25/0.75, 0.50/0.50, 0.75/0.25 hairy vetch/cereal mixtures and pure hairy vetch in the no PPL and subsurface band treatments were: 4-10, 42-89, 107-176, 153-263 and 230-328 kg N ha^{-1}, respectively. The N release estimates for the 0.75/0.25 hairy vetch/cereal rye mixture and pure hairy vetch exceed fertilizer N rates usually required for corn. These estimates do not consider N release by roots, which are estimated to contain an additional 10% of total hairy vetch N and 25% of total cereal rye

N (Shipley et al. 1992). The hairy vetch material used to fill the bags was strictly non-decomposed material, with a higher 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). Also, equivalent biomass levels were targeted across treatments in this experiment, but cereal rye has the potential to produce more biomass (maximum biomass = ~12 Mg ha^{-1}) than hairy vetch (maximum biomass = ~6 Mg ha^{-1}) in systems where cover crops are terminated during reproductive stages (reviewed in Mirsky et al. 2012).

Nitrogen released from organic residues is susceptible to N cycling in microbial biomass or losses after release and prior to corn uptake. Rosecrance et al. (2000) found that the high N mineralization rate of hairy vetch resulted in 3x and 10x greater potential for N losses through leaching and denitrification than a hairy vetch/cereal rye mixture and cereal rye monoculture, respectively in the absence of a crop. Nearly half of the losses occurred within the first 30 days after cover crop termination, which is prior to the period of rapid N uptake by corn. Even though hairy vetch N may be susceptible to losses prior to uptake, Varco et al. (1993) observed that hairy vetch N is probably less susceptible to losses than fertilizer N, partly because a greater proportion of N released from hairy vetch residues was immobilized with the breakdown of corresponding C additions. Due to the combination of N losses and microbial N cycling after residue N release, the increase in corn shoot N with the addition of hairy vetch and hairy vetch/cereal rye mixture residues has generally been 15-30% of total cover crop N content (Wagger 1989a, Wagger 1989b, Decker et al. 1994, Clark et al. 1997a).

Conclusions

In conclusion, we found that the cumulative proportional mass and N loss and rate of mass loss during subsequent corn growing seasons was strongly related to the hairy vetch/cereal rye species proportions of cover crop residues, while the rate of N loss was not well-explained by species proportions. Therefore, adding cereal rye to hairy vetch is expected to reduce the cumulative proportion of N lost from residues during a corn growing season, but may not affect how quickly the N is released. Subsurface application of PPL did not affect decomposition relative to no PPL application, suggesting that subsurface band application may best conserve surface residues while providing additional N to corn. Broadcast PPL application increased the cumulative proportional mass and N loss from residues containing mostly cereal rye. Relative to no-till treatments (no PPL, subsurface band and broadcast), incorporation of residues and PPL increased the effects of cover crop species proportions on biomass decomposition rate and cumulative proportional N loss, and increased the cumulative N release rates across cover crops containing hairy vetch. Incorporation also increased cumulative proportional mass loss relative to no PPL and subsurface PPL treatments across all cover crop proportions.

Table 4.1 Monthly mean temperature and cumulative precipitation at North Farm in 2012 and South Farm in 2013. Thirty-year average monthly temperature and rainfall totals are also presented from 1980-2010.

	------------------------ Mean temp, °C	--------------------		------------------------ Precipitation, mm	--------------------	
Month	North Farm 2012	South Farm 2013	30-year avg	North Farm 2012	South Farm 2013	30-year avg
May	20	17	17	57	71	114
June	23	23	22	66	180	91
July	27	26	24	90	87	94
August	24	23	23	47	57	81
September	20	19	19	51	75	91
Total				311	470	471

Table 4.2 Species proportions, mass, nitrogen (N) concentrations, and carbon (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. Ninety-five percent confidence intervals are presented in parentheses.

		---------------- Mass, Mg ha^{-1} --------------		------ N concentration, g kg^{-1} -----		---- C concentration, g kg^{-1} ----	
HV/CR† target	HV/CR achieved	Oven-dried	Ash-free	Oven-dried	Ash-free	Oven-dried	Ash-free
No PPL and Subsurface band treatments							
0/1	0/1	8.58(8.08-9.07)	8.34(7.82-8.86)	5.2(4.9-5.6)	5.3(4.9-5.7)	446(443-450)	459(455-463)
0.25/0.75	0.21/0.79	8.35(7.85-8.85)	8.00(7.48-8.51)	11.4(10.6-12.3)	11.8(11.0-12.7)	441(437-444)	459(455-464)
0.50/0.50	0.43/0.57	7.91(7.42-8.41)	7.53(7.01-8.05)	20.2(18.8-21.7)	21.3(19.7-22.9)	440(437-444)	463(458-467)
0.75/0.25	0.67/0.33	7.35(6.85-7.84)	6.79(6.28-7.31)	29.0(27.0-31.2)	31.0(28.8-33.4)	438(435-441)	472(467-476)
1/0	1/0	6.42(5.92-6.92)	5.86(5.34-6.38)	43.8(40.8-47.1)	48.0(44.5-51.8)	431(428-435)	471(466-475)
Broadcast (includes PPL)							
0/1	0/1	11.73(11.22-12.24)	10.56(10.04-11.09)	12.7(11.5-14.1)	13.9(12.5-15.4)	416(412-419)	460(455-465)
0.25/0.75	0.21/0.79	11.50(11.00-12.01)	10.22(9.69-10.75)	20.5(18.5-22.7)	22.9(20.6-25.5)	410(406-414)	460(455-465)
0.50/0.50	0.43/0.57	11.07(10.56-11.57)	9.75(9.23-10.28)	22.8(20.6-25.2)	25.4(22.9-28.2)	410(406-414)	463(458-469)
0.75/0.25	0.67/0.33	10.50(9.99-11.01)	9.02(8.49-9.54)	31.7(28.6-35.1)	37.4(33.7-41.6)	408(404-411)	472(467-478)
1/0	1/0	9.57(9.07-10.08)	8.08(7.56-8.61)	40.3(36.4-44.6)	47.4(42.7-52.7)	401(397-405)	472(466-477)
Incorporated							
0/1	0/1	8.55(8.04-9.06)	8.34(7.81-8.86)	5.4(4.9-6.0)	5.5(4.9-6.1)	447(443-451)	458(453-463)
0.25/0.75	0.22/0.78	8.32(7.82-8.83)	8.00(7.47-8.52)	13.1(11.9-14.6)	13.6(12.3-15.2)	441(438-445)	458(453-464)
0.50/0.50	0.39/0.61	7.89(7.38-8.39)	7.53(7.00-8.06)	22.8(20.6-25.3)	23.9(21.5-26.6)	441(438-443)	462(457-467)
0.75/0.25	0.64/0.36	7.32(6.81-7.83)	6.79(6.27-.7.32)	33.5(30.2-37.1)	35.6(32.1-39.6)	439(435-443)	471(466-476)
1/0	1/0	6.39(5.89-6.90)	5.86(5.33-6.38)	48.4(43.7-53.6)	52.4(47.2-58.3)	432(428-436)	470(465-475)

†HV/CR = hairy vetch/cereal rye

Table 4.3 Species proportions, mass, nitrogen (N) concentrations, and carbon (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. Ninety-five percent confidence intervals are presented in parentheses.

		Mass, Mg ha^{-1}		N concentration, g kg^{-1}		C concentration, g kg^{-1}	
HV/CR† target	HV/CR achieved	Oven-dried	Ash-free	Oven-dried	Ash-free	Oven-dried	Ash-free
No PPL and Subsurface band treatments							
0/1	0/1	8.64(8.21-9.06)	8.26(7.85-8.68)	7.2(6.6-7.9)	7.5(6.9-8.2)	437(432-442)	456(451-462)
0.25/0.75	0.25/0.75	8.82(8.41-9.23)	8.36(7.97-8.76)	16.4(15.2-17.7)	17.2(15.8-18.6)	434(429-439)	457(452-463)
0.50/0.50	0.50/0.50	8.73(8.32-9.14)	8.22(7.82-8.62)	26.2(24.2-28.3)	27.7(25.6-30.1)	433(428-437)	458(453-464)
0.75/0.25	0.75/0.25	8.67(8.26-9.08)	8.08(7.68-8.48)	37.0(34.2-40.0)	39.6(36.5-42.9)	431(426-435)	460(454-466)
1/0	1/0	8.26(7.85-8.67)	7.59(7.20-7.99)	46.6(43.1-50.3)	50.3(46.4-54.5)	428(423-433)	462(457-468)
Broadcast (includes PPL)							
0/1	0/1	11.86(11.41-12.31)	10.71(10.27-11.15)	11.8(10.6-13.2)	12.9(11.5-14.4)	417(412-421)	458(452-463)
0.25/0.75	0.25/0.75	12.05(11.60-12.49)	10.81(10.37-11.24)	19.4(17.4-21.6)	21.3(19.0-23.9)	414(409-419)	458(452-464)
0.50/0.50	0.50/0.50	11.96(11.51-12.40)	10.66(10.23-11.10)	26.6(23.9-29.7)	29.6(26.4-33.2)	412(407-417)	459(453-465)
0.75/0.25	0.75/0.25	11.90(11.45-12.34)	10.52(10.09-10.96)	31.7(28.4-35.3)	35.5(31.7-39.8)	410(405-415)	461(455-467)
1/0	1/0	11.49(11.04-11.93)	10.04(9.60-10.47)	43.1(38.6-48.0)	49.5(44.2-55.5)	407(403-412)	464(458-469)
Incorporated							
0/1	0/1	9.47(9.02-9.93)	9.05(8.61-9.49)	6.6(5.9-7.4)	6.9(6.2-7.7)	437(432-442)	458(452-464)
0.25/0.75	0.23/0.77	9.66(9.22-10.11)	9.15(8.71-9.58)	16.1(14.4-17.9)	17.0(15.2-19.1)	434(429-439)	458(453-464)
0.50/0.50	0.47/0.53	9.57(9.13-10.02)	9.00(8.57-9.44)	24.1(21.6-26.8)	25.5(22.8-28.6)	433(428-438)	459(454-465)
0.75/0.25	0.72/0.28	9.51(9.07-9.96)	8.86(8.43-9.30)	35.9(32.2-40.0)	38.5(34.3-43.1)	431(426-436)	461(455-467)
1/0	1/0	9.10(8.65-9.54)	8.38(7.94-8.81)	46.3(41.5-51.6)	50.1(44.7-56.2)	428(423-433)	464(458-470)

†HV/CR = hairy vetch/cereal rye

Table 4.4 Parameter estimates of cumulative proportional mass loss and cumulative proportional nitrogen (N) loss and mass and N decay constants for each pelletized poultry litter (PPL) treatment as a function of hairy vetch/cereal rye proportions. Cumulative proportional mass loss and mass decay constants were modeled using polynomial equations; cumulative proportional N loss was modeled using a rectangular hyperbolic function. Standard errors of the parameter estimates 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 exponential decay variable and column ($P<0.05$).

PPL application	-------------------------------- Proportional mass loss ------------------------		
	------- Intercept -------	--- Linear coefficient ---	Quadratic coefficient
No PPL	0.42(0.06)b	0.57(0.06)a	-0.23(0.04)a
Subsurface band	0.43(0.06)b	0.56(0.06)a	-0.23(0.04)a
Broadcast	0.55(0.06)a	0.44(0.06)b	-0.23(0.04)a
Incorporated	0.58(0.06)a	0.46(0.06)ab	-0.23(0.04)a
	-------------------------------- Proportional N loss ----------------------------		
	------- Intercept -------	---- Shape parameter ----	----- Asymptote -----
No PPL	0.19(0.03)b	2.88(0.45)a	0.83(0.05)b
Subsurface band	0.13(0.03)b	3.53(0.52)a	0.89(0.05)b
Broadcast	0.44(0.03)a	2.03(0.70)a	0.39(0.04)c
Incorporated	*-0.02(0.03)*c	4.07(0.45)a	1.16(0.05)a
	------------------------ Mass decay constant, soil GDD^{-1} ---------------------		
	------------ Intercept x 10^{-3} -----------	---- Linear coefficient x 10^{-3} ----	
No PPL	*0.70(0.46)*a	1.20(0.22)b	
Subsurface band	*0.57(0.52)*a	1.63(0.22)b	
Broadcast	*0.78(0.53)*a	1.40(0.22)b	
Incorporated	*0.37(0.14)*a	3.33(0.23)a	
	--------------------- Nitrogen decay constant, soil GDD^{-1} -------------------		
	No trend		

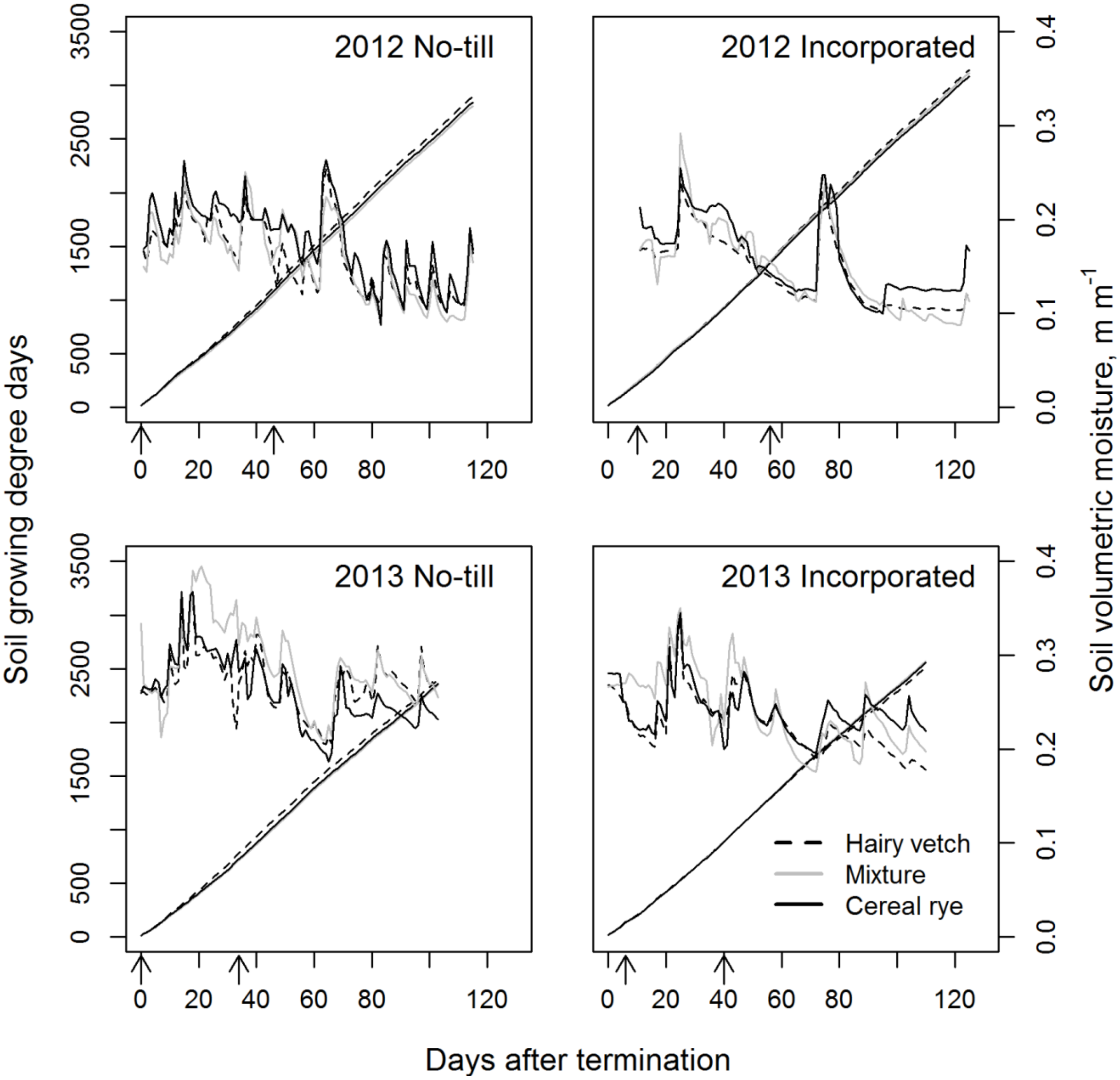

Figure 4.1 Cumulative soil growing degree days (GDD; 0° C base temperature) and daily volumetric moisture content between cover crop termination and corn maturity at North Farm in 2012 and South Farm in 2013. Each line represents the average of three replicates. Soil temperature and moisture sensors were placed just below the soil surface (<5 cm depth) in the subsurface band treatment ("no-till") and 20 cm depth in the incorporated treatment with cover crop residues composed of hairy vetch, cereal rye or a mixture (approximately 0.5/0.5 hairy vetch/cereal rye in 2012 and 0.25/0.75 hairy vetch/cereal rye in 2013). The first and second arrow on each x axis marks corn planting and subsurface band pelletized poultry litter application, respectively.

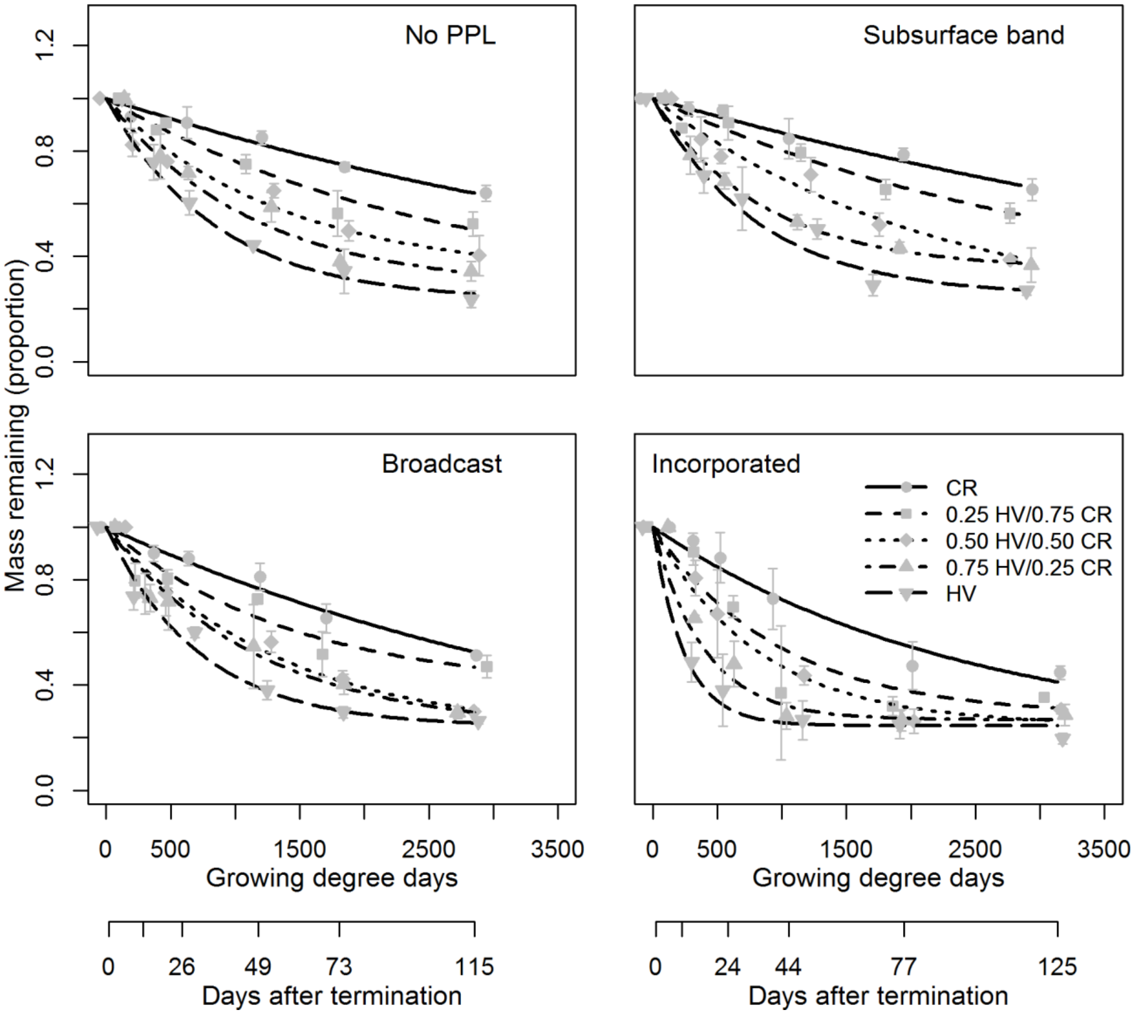

Figure 4.2 Proportion of mass remaining in litter bags containing a range of hairy vetch (HV)/cereal rye (CR) proportions and subjected to different manure management during the 2012 corn growing season. Each symbol represents the mean of three replicates of a particular cover crop proportion and pelletized poultry litter (PPL) treatment at a given time. Lines represent exponential decay models fit to each cover crop species proportion within each PPL treatment. Error bars indicate ± one standard deviation. Noise in the x direction was added to aid in visual interpretation of overlapping symbols and error bars.

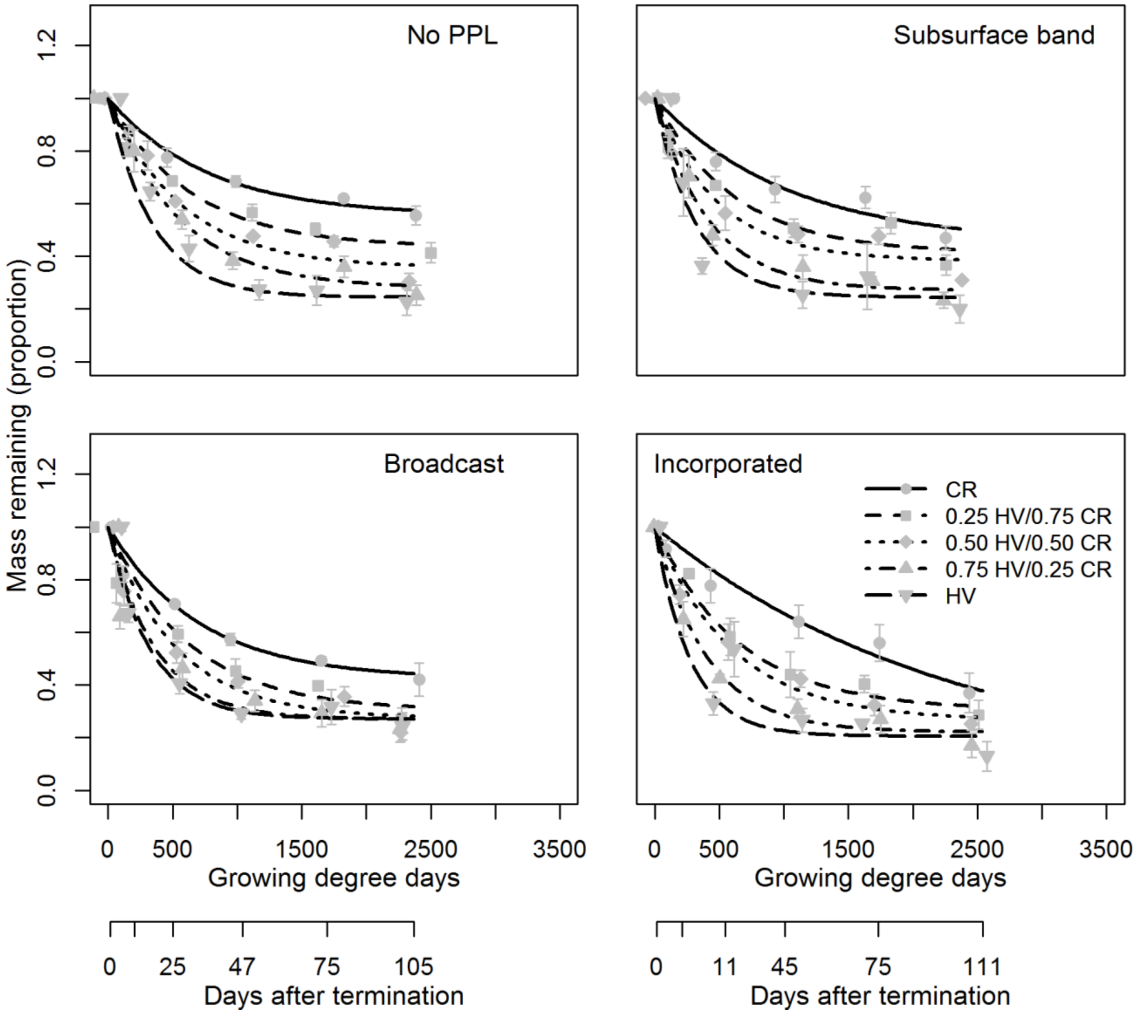

Figure 4.3 Proportion of mass remaining in litter bags containing a range of hairy vetch (HV)/cereal rye (CR) proportions and subjected to different manure management during the 2013 corn growing season. Each symbol represents the mean of three replicates of a particular cover crop proportion and pelletized poultry litter (PPL) treatment at a given time. Lines represent exponential decay models fit to each cover crop species proportion within each PPL treatment. Error bars indicate ± one standard deviation. Noise in the x direction was added to aid in visual interpretation of overlapping symbols and error bars.

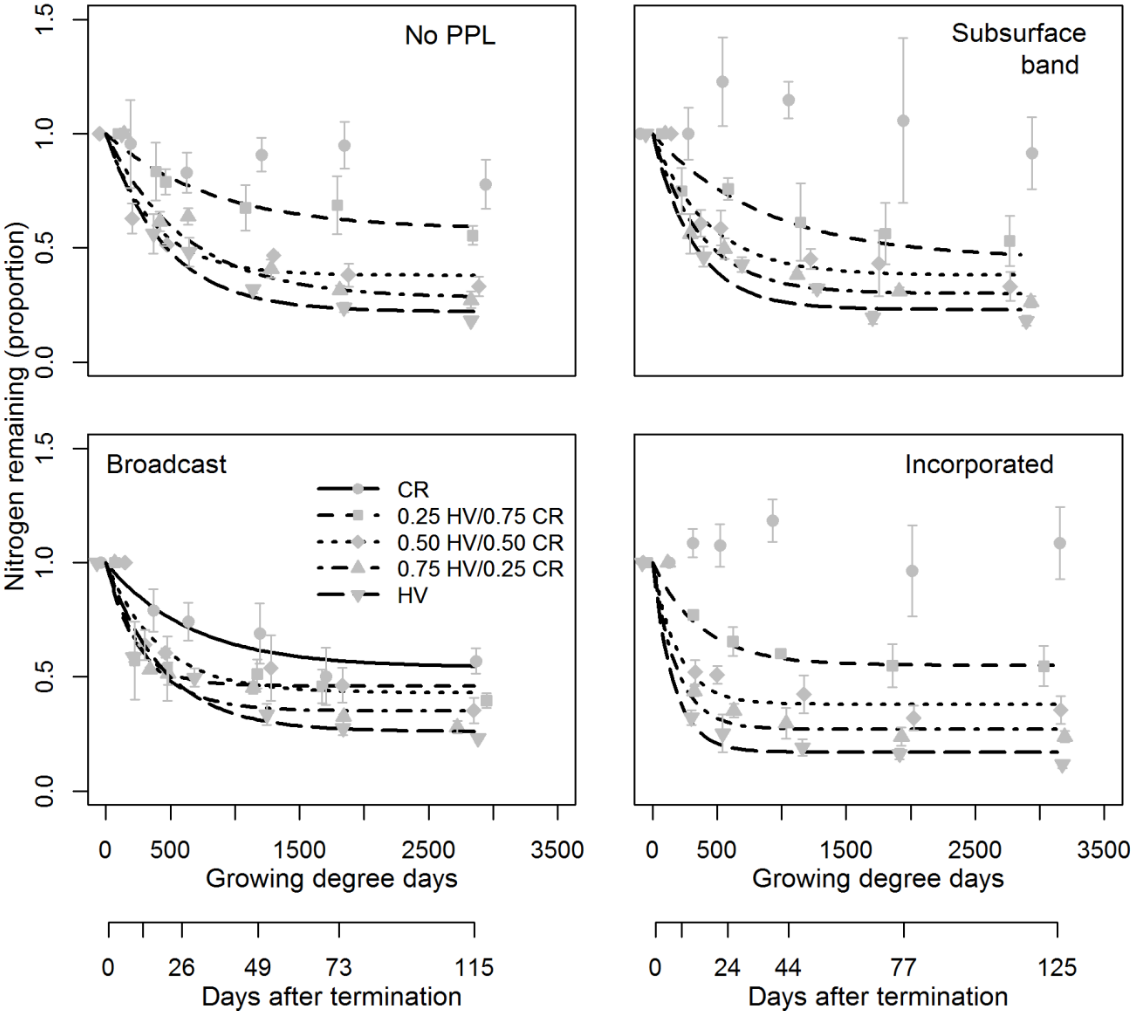

Figure 4.4 Proportion of nitrogen (N) remaining in litter bags containing a range of hairy vetch (HV)/cereal rye (CR) proportions and subjected to different manure management during the 2012 corn growing season. Each symbol represents the mean of three replicates of a particular cover crop proportion and pelletized poultry litter (PPL) treatment at a given time. Lines represent exponential decay models fit to each cover crop species proportion within each PPL treatment. Error bars indicate ± one standard deviation. Noise in the x direction was added to aid in visual interpretation of overlapping symbols and error bars.

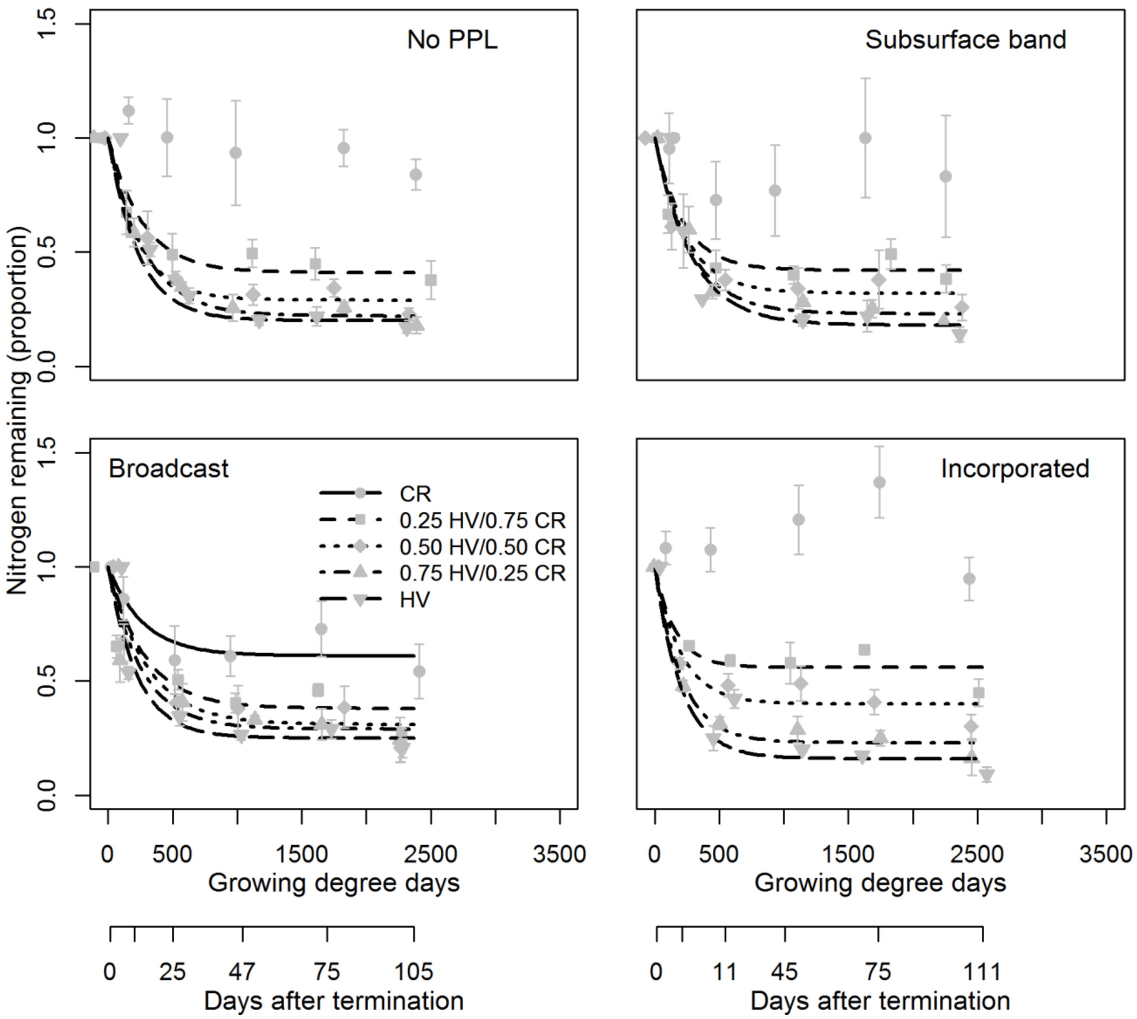

Figure 4.5 Proportion of nitrogen (N) remaining in litter bags containing a range of hairy vetch (HV)/cereal rye (CR) proportions and subjected to different manure management during the 2013 corn growing season. Each symbol represents the mean of three replicates of a particular cover crop proportion and pelletized poultry litter (PPL) treatment at a given time. Lines represent exponential decay models fit to each cover crop species proportion within each PPL treatment. Error bars indicate ± one standard deviation. Noise in the x direction was added to aid in visual interpretation of overlapping symbols and error bars.

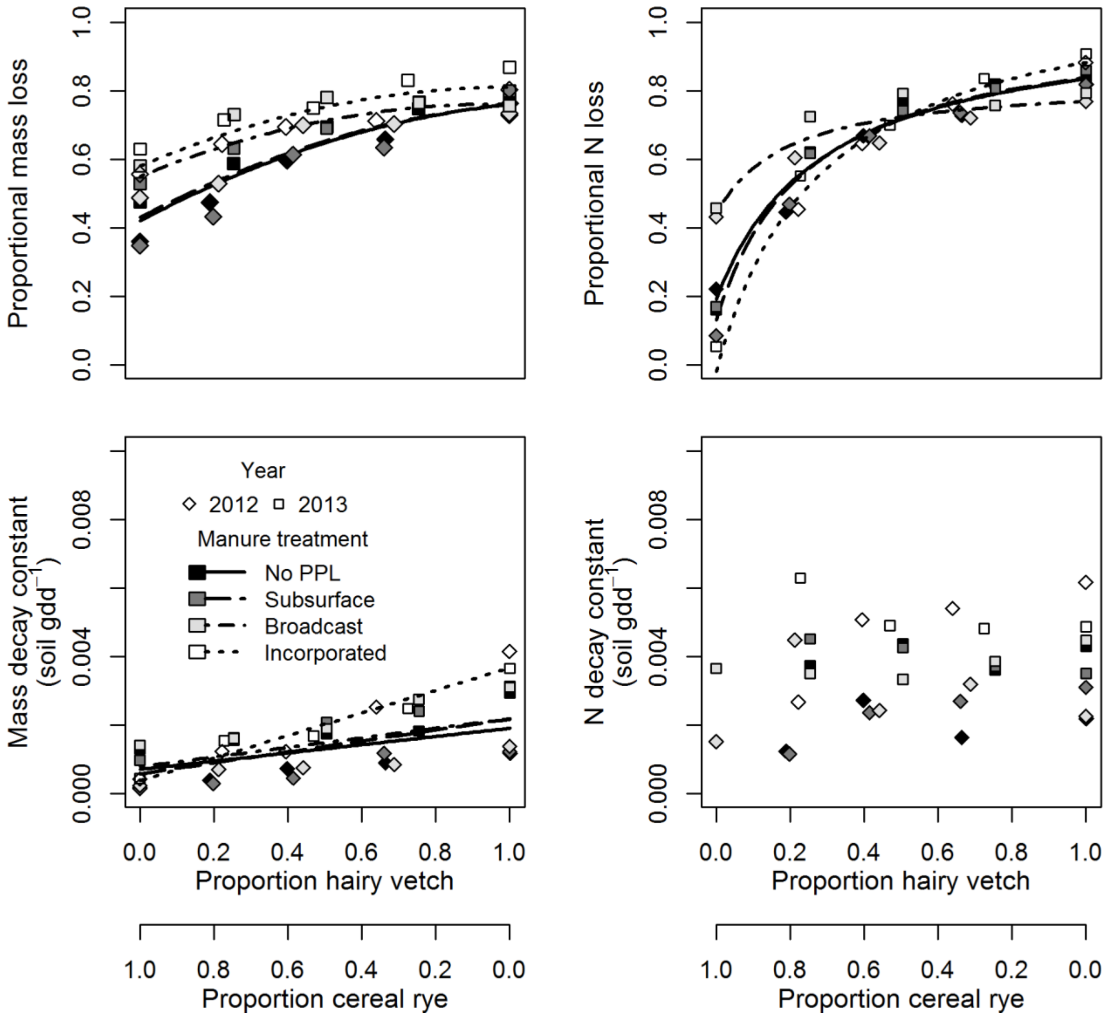

Figure 4.6 Cumulative proportional loss of cover crop mass and nitrogen (N), and mass and N decay constants across hairy vetch/cereal rye proportions. Cumulative proportional mass loss was modeled using a quadratic equation, cumulative proportional N loss was modeled using a rectangular hyperbolic equation, and mass decay constant was modeled using a linear equation. Pelletized poultry litter (PPL) treatments are differentiated using different lines and symbol shades, and years are differentiated using different symbols. Noise in the x direction was added to aid in visual interpretation of overlapping symbols.

Chapter 5 Spatiotemporal distribution of topsoil nitrogen as influenced by pelletized poultry litter placement and cover crop residues in no-till corn

Abstract

Green and animal manures provide nitrogen (N) in annual cropping systems and contribute to improved soil quality. The recent development of an implement to apply dry manure below the soil surface in a band offers a more efficient delivery method for poultry litter relative to broadcast application. The objective of this study was to model the spatiotemporal dynamics of soil inorganic N (IN; NO_3^- -N + NH_4^+-N) in a no-till corn (*Zea mays* L.) system receiving both cover crop and pelletized poultry litter (PPL) amendments. The study tested three cover crop residues – hairy vetch (*Vicia villosa* Roth) monoculture, cereal rye (*Secale cereale* L.) monoculture and a hairy vetch/cereal rye mixture; and four PPL treatments – pre-plant broadcast 0 Mg PPL ha^{-1}, ~3.5 Mg PPL ha^{-1} pre-plant broadcast, ~3.5 Mg PPL ha^{-1} subsurface banded at sidedress, and ~3.5 Mg PPL ha^{-1} pre-plant broadcast-incorporated by tillage, in a split-block design. Soil cores were collected at three or five corn interrow locations and four or five depths at each of five corn growth stages. Gravimetric soil moisture, NO_3^--N, and NH_4^+-N concentrations were measured on each sample. Spatial IN predictions were made using a Random Walk diffusion/dispersion model and inverse-distance weighted interpolation. At corn emergence, IN quantities under the hairy vetch residue with no PPL amendment were 35 kg ha^{-1} in 2012 and 50 kg ha^{-1} in 2013. At the same growth stage under the cereal rye residue with no PPL, IN quantities were 12 kg ha^{-1} in 2012 and 14 kg ha^{-1} in 2013. The 2012 cover crop mixture provided IN levels similar to 2012 hairy vetch, while the 2013 mixture provided IN levels similar to 2013 cereal rye. Immediately after application (emergence), broadcast and incorporated PPL amendment increased soil IN by ~50% and by 100-200%, respectively, relative to no PPL for all cover crop residues. At most growth stages in the no-till treatments, IN was generally concentrated near the soil surface under the cover crop residues and decreased with depth, except in the cereal rye, which did not usually show a depth effect unless broadcast PPL was applied. Sidedress subsurface PPL application provided similar or greater IN concentrations as the broadcast and incorporated treatments at fifth-leaf stage, and soil IN remained localized to the delivery location throughout the growing season. In the incorporated treatment, soil IN was generally concentrated to a depth of 20 cm (plow layer). Soil inorganic N levels were greatest at corn emergence or fifth-leaf and lowest at silking and milk growth stages. The subsurface band PPL application at sidedress avoided early-season N losses in 2013, the wetter year, providing 1.3-2.6x the soil IN as the broadcast and incorporated treatments at the fifth-leaf stage.

Introduction

No-till cropping is a widely-adopted conservation practice used to reduce labor, minimize soil erosion, improve soil physical structure, conserve water, and increase soil organic matter in previously tilled croplands (Blevins et al. 1983, Chan and Mead 1988, Pimentel et al. 1995, Franzluebbers and Arshad 1997, Six et al. 2002, Spargo et al. 2008). These conservation benefits, along with fuel cost savings (Kern and Johnson 1993), have led to increasing farmer adoption of no-till cropping, with an estimated 30% of U.S. corn (*Zea mays* L.) cropland in no-till production in 2009 (Horowitz et al. 2010). Obstacles hindering further adoption of no-till production include reduced nitrogen (N) fertility and weed control challenges (Grandy et al. 2006). Nitrogen mineralization rates are often lower in no-till than in tilled systems, at least in the short-term (Rice et al. 1986, Christensen et al. 1994), and N losses may be greater due to NH_3 volatilization of surface-applied fertilizer or manure (Keller and Mengel 1986, Sharpe et al. 2004). Also, no-till production largely relies on the use of chemical herbicides, which has led to weed resistance and limited adoption of no-till production in cropping systems that do not use herbicides (i.e. minor crops and organic production systems, Brainard et al. 2013).

Precision manure management and cover crop surface mulches are two tactics that may address N fertility and weed control challenges in no-till production. Poultry litter, a widely available manure product in the mid-Atlantic U.S. and other locations, contains 30-60 kg N Mg^{-1} of fresh material (Sims 1987, Robinson and Sharpley 1995) and can increase soil organic matter and improve soil physical properties relative to mineral fertilizers (reviewed in Edmeades 2003). Winter annual legume cover crops biologically fix between 50 and 180 kg N ha^{-1} (Parr et al. 2011) and release 50 to 150 kg N ha^{-1} during the following season (Ebelhar et al. 1984, Ranells and Wagger 1996, Cook et al. 2010). Although winter cereals do not release substantial N during decomposition (Ranells and Wagger 1996, Clark et al. 1997a), they produce high biomass and decompose slowly, providing effective weed control in addition to, or instead of, herbicides (Mischler et al. 2010a, Reberg-Horton et al. 2011, Mirsky et al. 2012). A mixture of legume and grass cover crops can provide both N provisioning and weed control (Hayden et al. 2014). However, cover crops, even legume cover crops, often do not supply enough N to fully meet in-season corn demands (Stute and Posner 1995, Clark et al. 1997b, Lawson et al. 2012), while animal manures, particularly poultry litter, tend to oversupply phosphorus (P; Preusch et al. 2001, Toth et al. 2006). Integrating cover crops with animal manures applied at P-based rates may allow for improved N supply while avoiding excess soil P. Agricultural P, like N, is a major pollutant in surface waters (Carpenter et al. 1998).

The spatial and temporal distributions of N inputs are important factors controlling N losses and crop response to N. Although incorporating N inputs reduces NH_3 volatilization, N release from legume residues is likely better synchronized with crop uptake when residues are left on the soil surface than incorporated due to rapid early-season N mineralization of incorporated residues (Varco et al. 1993, Poffenbarger et al., in preparation). A large pool of available N prior to the beginning of rapid corn N uptake is vulnerable to losses. In no-till systems, subsurface band application of manure reduces NH_3 volatilization relative to surface application, but may increase denitrification losses due to higher moisture in the location of manure delivery and the close proximity of available carbon (C) and NO_3^--N, the substrates required for denitrification (Comfort et al. 1988, Dosch and Gutser 1995, Wulf et al. 2002). Denitrification in agricultural soils is an important source of the greenhouse gas, N_2O (Venterea et al. 2012). Research suggests that subsurface application of N inputs may also reduce N losses to weeds (Di Tomaso 1995) and prevent N immobilization in surface mulches (Mengel et al. 1982). A recently-developed poultry litter subsurface band applicator has been shown to reduce NH_3 volatilization by ~90% in no-till systems and substantially reduce nutrient run-off losses; thus leading to improved corn yields relative to surface poultry litter application (Pote et al. 2011, Adeli et al. 2012, Pote and Meisinger 2014). Split N applications, where a portion of N fertilizer is applied pre-plant and the remainder is applied at sidedress when corn is at fifth-eighth leaf stage, is a common strategy employed to increase N use efficiency compared to a single pre-plant applications in no-till corn production (Cassman et al. 2002, Dinnes et al. 2004).

Despite the importance of spatiotemporal N dynamics on agronomic outcomes, little work has been performed to model the location and timing of N availability as affected by manure placement and cover crop management. Several researchers have reported location-specific and/or temporal dynamics of soil properties associated with localized application of fertility inputs (Comfort et al. 1988, Sawyer et al. 1990, Zebarth et al. 1999, Tewolde et al. 2013), but to our knowledge, none have used diffusion/dispersion models to predict soil N availability over time and space. A better understanding of soil inorganic N spatiotemporal distribution is relevant not only in the context of efficient crop N use and minimizing environmental hazards, but will also contribute to establishing appropriate soil sampling methods with concentrated N sources.

In the overarching context of developing a no-till corn system with improved N use efficiency, we evaluated spatiotemporal soil inorganic N dynamics in a factorial experiment including pelletized poultry litter (PPL) application methods and cover crop residues. The PPL treatments included the recently-developed method of subsurface banding PPL performed at sidedress at a P-based rate against three checks: pre-plant broadcast PPL application at a P-based rate, pre-plant broadcast-incorporated PPL application at a P-based rate, and no PPL. We evaluated these PPL treatments in residues of three cover crops: the winter-annual legume, hairy vetch (*Vicia villosa* Roth), the winter-annual grass, cereal rye (*Secale cereale* L.), and a mixture of hairy vetch and cereal rye. We collected gravimetric water content in addition to soil inorganic N concentration (IN; NO_3^- -N + NH_4^+-N) data because moisture conditions greatly affect soil N transformations and movement. The specific objectives of this study are to: 1) model the spatial distribution of soil IN at five important developmental stages of corn as affected by cover crop residue type and PPL application method, and 2) use models to estimate and compare IN in soil profiles as affected by cover crop residue type and PPL application method. Our hypotheses regarding IN were as follows: Within each PPL treatment, profile IN (the average IN to 30 cm depth and between corn rows) will be greatest with hairy vetch, intermediate with hairy vetch/cereal rye mixture, and least with cereal rye residues. In the no PPL and broadcast treatments, IN will be greatest at the soil surface at corn emergence and will decrease and diffuse downward over time. In the subsurface band treatment, IN will be localized to a region 5-10 cm below the soil surface and in the center of the interrow space in the subsurface banded treatments immediately after sidedress application. Inorganic N in the band will decrease over time and diffuse downward and in the direction of crop roots. In the incorporated treatment, IN will be evenly distributed throughout the soil profile at corn emergence and will become depleted over time, particularly near the corn row. Finally, we hypothesize that PPL treatment will have a significant effect on profile IN throughout the corn growing season, following this order: incorporated > subsurface band > broadcast > no PPL.

Methods

Experimental design and sampling

A randomized split-block field experiment was conducted at the Beltsville Agricultural Research Center South Farm (39.02 N, 76.94 W) in the fall of 2011 and replicated in the fall of 2012 to evaluate spatiotemporal distribution of IN in a factorial experiment including PPL application methods and different cover crops. Soils on South Farm are classified as fine-loamy, mixed, active, mesic Fluvaquentic Dystrudepts (Codorus series). The first and second year experiments were conducted in adjacent fields. Three replicates were planted each year.

Prior to cover crop planting, a soybean (*Glycine max* (L.) Merr.) cover crop was incorporated by disking, 56 kg potassium (K) ha^{-1} was applied as K_2SO_4 and fields were cultivated and cultimulched to prepare a cover crop seedbed. 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. The relatively high monoculture cereal rye seeding rate is that required by the Maryland nutrient management cover crop program. Hairy vetch seed was inoculated with *Rhizobia.* The cover crop treatments were randomly assigned within each of three reps. Cover crops were planted using a grain drill, forming 19 cm rows on October 10, 2011 and September 25, 2012. The two species within the mixture were planted in separate, sequential passes.

On November 21, 2011 and October 12, 2012, soil samples were collected in each rep to a depth of 30 cm for routine soil testing. The soil samples were sieved fresh through a 64 mm sieve, air-dried, passed through a 2 mm sieve and analyzed for pH, cation exchange capacity, and Mehlich 3-extractable nutrient concentrations at A&L Eastern Labs (Richmond, VA). Selected soil properties are presented in Table 5.1.

Pelletized poultry litter treatments were applied in random strips perpendicular to cover crop treatments. Each unique combination of cover crop residue type x PPL application x rep formed a plot. Plots were assigned location coordinates based on relative distances apart. In the no-till PPL treatments (no PPL, “No”; broadcast, “Brd”;

subsurface band, “SSB”) cover crops were terminated on May 29, 2012 and May 22, 2013 using a roller/crimper. Hairy vetch was in full flower and cereal rye was in the soft dough stage in 2012, and vetch was 50% flowering and rye was in the milk stage in 2013. In the incorporated treatment, “Inc”, cover crops were flail-mowed and disked 7-10 days prior to when the other plots were rolled. Aboveground biomass was collected at cover crop termination by clipping all material within a 76 cm x 67 cm frame in four to six locations within each cover crop strip. The cover crop mixture biomass samples were separated by species, weighed fresh, oven-dried (60°C) and weighed dry.

Pelletized poultry litter was obtained from Perdue Agricycle, LLC (Seaford, DE). To pelletize poultry litter, raw broiler litter was first heated and pasteurized, removing moisture. The dried material was ground to a powder and moisture ws returned as the material passed through a pelletizing mill. Pelletized poultry litter was broadcast using a Stoltzfus boom drop fertilizer spreader (W-Chain Sower spreader, Morgantown, PA) at 3.6 Mg ha^{-1} in 2012 and 3.4 Mg ha^{-1} in 2013 just prior to corn planting in the pre-plant broadcast and incorporated treatments. These rates were estimated to provide 67 kg ha^{-1} plant-available N, with plant-available N calculated as:

$$PAN = 0.9\left(NH_4{}^{+} - N\right) + 0.5(organic\ N)$$

where PAN is the concentration of N estimated to become available in one growing season, $NH_4{}^{+}$-N and organic N are the concentrations of $NH_4{}^{+}$-N and organic N in the PPL. Fifty percent of organic N was assumed to mineralize during the first season of application according to University of Maryland recommendations for raw broiler litter. Poultry litter pellets were assumed to have a similar proportion of mineralizable N as raw broiler poultry litter during a single growing season according to Spargo et al.

(unpublished). The NH_4^+-N availability factor was based on NH_3-N losses expected with immediate incorporation or subsurface band application (Abaye et al. 2006). Pelletized poultry litter nutrient composition and cover crop biomass and N content for each year are presented in Table 5.1. The incorporated treatment was spaded (Imants 27sx, Reusel, Netherlands) to 20 cm and cultimulched just before planting. Glyphosate-resistant corn seed (TA657-13VP, 111 d in 2012; TA522-22DP, 105 d in 2013) was planted the same day as the cover crops were rolled. All treatments received 10 kg PAN ha^{-1} as starter PPL delivered at planting through the dry fertilizer boxes. In the subsurface band treatments, PPL was sidedressed at the same rate as the broadcast and incorporated treatments using a prototype subsurface band applicator at the fifth-leaf growth stage on June 27, 2012 and June 25, 2013. Glyphosate was applied on June 1 and June 21, 2012 and on May 31 and June 26, 2013 at 2.8 kg active ingredient ha^{-1}. The field received 2.5 cm of irrigation water using a traveling gun system on July 10, August 1, and September 29, 2012 and 4 cm on June 27, July 29, and September 8, 2013.

Soil samples were collected at the following corn growth stages: emergence (June 7-8, 2012 and June 4-5, 2013), fifth-leaf post-sidedress application (June 28-29, 2012 and June 26-27, 2013), silking (July 31-August 1, 2012 and July 18, 23-24, 2013), milk (August 16, 2012 and August 7, 2013) and physiological maturity (October 1 and 4, 2012 and September 10-11, 2013). In all cover crop residue treatments and all PPL treatments except subsurface band, 2 cm diameter soil cores were taken at 0, 20 and 38 cm from the interrow center and split at four depths (0-5, 5-10, 10-20, 20-30 cm). In the plots receiving subsurface banded PPL, soil cores were taken at 0, 5, 10, 25, and 38 cm from the band and split at five depths (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 band or interrow composited. Immediately after sampling, soil samples were sieved fresh through a 64 mm sieve, a ~10 g subsample was collected for gravimetric moisture content determination, and the remaining sample was air-dried and passed through a 2 mm sieve. The moisture content subsample was weighed fresh, dried at 105°C for 24 hours, and weighed oven-dry. Gravimetric moisture content was calculated as:

$$MC = \frac{(M_f - M_d)}{M_d}$$

where M_f and $M_d$are the fresh and oven-dry weights, respectively of the moisture content subsample.

Inorganic N in a two-gram subsample of air-dried soil from each sample was extracted using 20 mL of 1 M KCl by shaking for one hour. Filtered extracts were analyzed 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).

In addition to collecting soil cores at several times during the growing season, soil temperature, volumetric moisture (capacitance) and electrical conductivity sensors (Model 5TE sensors Decagon, Pullman, WA) were placed at several soil profile locations to collect continuous data from sidedressing through the dent growth stage (July 3-September 3, 2012 and July 3-September 13, 2013). The sensors were placed in the cereal rye and hairy vetch residue treatments that received subsurface banded PPL at 0, 10 and 25 cm horizontally from the band and 5, 10 and 20 cm depths.

Statistical analysis

Soil moisture

Soil moisture values for each soil profile sampling location were pooled into three interrow classes and three depth classes of equal size to provide equal weighting of all soil profile regions in calculating means. The soil moisture data set was split by year and analyzed using repeated measures ANOVA using the lme function in R (R Development Core Team 2014). The following factors and their interactions were included in the model as fixed effects: corn growth stage, residue type, PPL treatment, interrow class, depth class, and plot coordinates. Non-significant interactions and/or factors were removed in a step-wise fashion. Time (days after emergence) was assigned as a random covariate using the CAR1 correlation structure, with plot as a grouping factor and random effect. Growth stage was a significant factor in both years, so the data were further split by growth stage and analyzed using the lme function in R (R Development Core Team 2014). In each growth stage model, residue type, PPL treatment, depth class and interrow class, their interactions, and plot coordinates were included as fixed effects. Non-significant interactions and/or factors were removed in a step-wise fashion. Rep was included as a random effect and plot location was assigned to the corExp correlation structure. To address lack of randomization in soil samples taken by depth (because samples at different locations were acquired by splitting cores), repeated measures over depth using the corSymm correlation structure was also evaluated for inclusion in each growth stage model. However, the plot coordinates were determined to be the more important source of correlation. Means were computed using the lsmeans function in R, and multiple comparisons were made using contrast statements in glht (R Development Core Team 2014).

Soil inorganic N

Soil inorganic N concentrations of samples collected at the location of starter PPL delivery (0-5 cm depth in corn row) were removed from the data set at emergence to simplify modeling the spatial distribution of IN. High variability in soil IN concentrations was detected from samples taken at the location of subsurface band PPL delivery at fifth-leaf in both years. This was estimated to arise from variability in the proportion of the PPL band captured in each soil core. We reasoned that immediately after application, the IN concentration of the PPL band should not differ among treatments, and thus the samples with the greatest IN concentration represent the samples that most accurately and fully captured the PPL band. Therefore, within each rep and year, all soil samples taken in the PPL band at the fifth-leaf growth stage were assigned the maximum IN concentration measured.

Euclidean distance from the IN source was calculated using the Distance Formula:

$$d = \sqrt{x^2 + y^2}$$

where d is the Euclidean distance from the IN source, x is the horizontal distance from the IN source, and y is the vertical distance from the IN source (assigned as the midpoint of the sample's depth interval). The IN source was considered to be the soil surface for the broadcast and no PPL treatments, and the PPL band for the subsurface band treatment after immediately after application (fifth-leaf growth stage).

The effect of Euclidean distance from the IN source on the natural log of IN at all corn growth stages was modeled for each residue type and PPL treatment combination, with the exception of the incorporated treatment, which did not have a distinct IN source. A Gaussian (normal curve) Random Walk model for diffusion/dispersion was used (Appelo and Postma 2010):

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

where y is the natural log of IN at a given Euclidean distance d from the band, 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's peak. These parameters will hereafter be referred to as "peak height", "background IN" (soil IN away from the peak), and "peak width", respectively. A dummy variable was added for distance below the band vs. distance in all other directions from the band to evaluate whether model parameters were affected by direction in the subsurface band treatment.

To estimate Random Walk model parameters and standard errors, non-linear modeling was performed using the nlme function in R (R Development Core Team 2014). Rep was included as a random effect on the a parameter. Models were evaluated with rep assigned to other parameters and combinations of parameters, but assigning rep to the a parameter reliably resulted in the lowest Akaike Information Criterion. Parameter estimates were compared using unequal variance t-tests:

$$t = \frac{P_1 - P_2}{\sqrt{{SE_1}^2 + {SE_2}^2}}$$

where P_1 and P_2 are parameter estimates for the treatments of interest, respectively, and SE_1 and SE_2 are the standard errors reported in nlme output for the same parameter estimates. Degrees of freedom were conservatively estimated as the minimum nlme-reported degrees of freedom among the two treatments, minus one. A Bonferroni adjustment was performed on t-test p values to account for multiple comparisons.

To generate spatial soil predictions, Random Walk non-linear model fitting was also performed separately for each individual plot at each growth stage using the nls function in R (R Development 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 subsurface band treatment, Random Walk model residuals were modeled as a function of distance from the soil surface to account for cover crop residue IN as well as PPL band IN. Semivariograms were produced using Random Walk model residuals for the no PPL, broadcast, and subsurface band treatments and natural log of IN for the incorporated treatment using the variogram function of R package gstat (R Development Core Team 2014). The semivariograms did not produce detectable trends and could not be accurately modeled with spherical, exponential or Gaussian models, possibly due to a limited number of pairs at each lag distance (<30). Therefore, inverse distance-weighted interpolation (gstat function) rather than kriging was used to predict variability not accounted for by the Random Walk models. Inverse distance weighing computes a weighted average:

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

$$w(s_i) = \| s_i - s_0 \|^{-p}$$

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 $\|\cdot\|$ indicates Euclidean distance, and p an inverse distance weighting power. A p

value of 10 was selected based on visual interpretation of the smoothness of prediction surfaces and considering the intensity of soil sampling.

The predicted values from each treatment and sampling date were averaged across replicates, back-transformed, and plotted on a 38 cm wide x 30 cm deep grid (1 cm spacing), forming a profile half the width of a corn interrow. The predictions generated from the Random Walk models and inverse distance-weighted interpolation were used to calculate means of IN for each replicate of each treatment ("profile IN"). Profile IN concentrations were statistically analyzed in the same manner as soil moisture, except that the analysis was performed on log-transformed data and depth and interrow location effects were not included in the analysis. The proportion of IN as NO_3^--N ("NP") was computed for each observation logit-transformed, and analyzed in the same manner as soil moisture. Profile IN and NP means were back-transformed for presentation in this paper.

Results

Weather conditions and soil, cover crop and pelletized poultry litter properties

Temperatures during the 2012 and 2013 growing seasons were generally greater than 30-year averages for Beltsville, MD. While 2012 was a relatively dry year, rainfall accumulation in the 2013 corn growing season was close to the 30-year average cumulative rainfall. The month of June was particularly wet in 2013 (Figure 5.1). Soil properties were similar between the two years because the fields were located adjacent to each other and have been subjected to similar management. Mehlich 3-extractable P and K tested optimal for corn growth (Table 5.1).

Cover crops were highly productive in both years (Table 5.1), 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 both monocultures. The N contents of the mixtures and hairy vetch monocultures were 2-3x those of cereal rye monocultures. The C/N ratios of hairy vetch (average across years = 16.5) and cereal rye (average across years = 86) were below and above the mineralization/immobilization threshold of ~25 (Clark et al. 1997a, Kuo et al. 1997a), respectively, while the C/N ratios of the mixtures were close to (2012 = 26) or above (2013 = 37) this threshold. The PPL applied in 2012 and 2013 was estimated to contain 2% PAN (Table 5.1). The PPL used in 2013 had a greater P concentration than the PPL used in 2012, but P deficiency was not a concern on these fields because they tested optimal for soil Mehlich 3 P concentration.

Soil moisture

Greater precipitation in the spring and summer of 2013 relative to 2012 led to greater gravimetric soil moisture content in 2013 than in 2012. Corn growth stage significantly affected soil moisture content within each year ($P<0.05$). Overall in 2012, soil moisture was greatest at corn emergence and maturity (mean = 0.180, standard error = 0.002), and declined throughout the season, to an average moisture content of 0.111 (standard error = 0.003) at the milk stage. The soil moisture trends over time reveal that as the 2012 corn growing season progressed, the periodic rain events did not sufficiently counteract the high rates of evapotranspiration. Once the crop had reached maturity and was no longer taking up water, the soil water was replenished. In 2013, average soil moisture was relatively high and similar among all growth stages (0.235, standard error = 0.002) except at silking (mean = 0.187, standard error = 0.002). In 2013, all sampling events occurred after a heavy rainfall or irrigation event, except at the silking stage. For reference, field capacity and permanent wilting point estimates for this soil are 0.182 and 0.092, respectively (Saxton et al. 1986).

Residue type, PPL treatment, depth class and interactions of residue type x PPL treatment, and PPL treatment x depth class were the dominant factors affecting soil moisture within individual growth stages in both years ($P<0.05$). Interrow class also affected soil moisture at some growth stages in 2012 ($P<0.05$). In 2013, a residue type x depth class interaction was detected ($P<0.05$), which reflected magnitudinal rather than directional differences in the moisture trend with depth among the different cover crop residues (i.e. within each PPL treatment, all residues showed greatest moisture content in the same depth class, but magnitude of differences between depth classes sometimes differed). For the purpose of providing values to inform IN interpretation, we present moisture content for each residue type x PPL treatment and the PPL treatment x depth class interaction (Tables 5.2 and 5.3).

There were significant residue type x PPL treatment interaction effects on soil moisture at emergence and fifth-leaf in both years. In 2012, soil moisture was significantly greater in the cereal rye residue than in the hairy vetch residue, but only in the incorporated treatment. Incorporating cover crop residues and PPL significantly reduced soil moisture (up to 35%) relative to the other PPL treatments for all residues at fifth-leaf, but only for the mixture and hairy vetch residues at emergence ($P<0.05$). The effect of incorporation on soil moisture relative to no-till treatments was also observed in the hairy vetch residue at silking in 2012 and at maturity in 2013. Incorporation altered the distribution of soil moisture with depth relative to the no-till PPL treatments at emergence and fifth-leaf in 2012, and at emergence and silking in 2013 ($P<0.05$).

At emergence and fifth-leaf in 2012, broadcast PPL application tended to increase soil moisture relative to the other no-till PPL treatments, but the effect was not observed in cereal rye and only significant for some of the remaining residue type x PPL treatment combinations. On the other hand, at the fifth-leaf stage in 2013, soil moisture was significantly lower in the hairy vetch residue than in the cereal rye residue only in the broadcast treatment ($P<0.05$).

At the fifth-leaf growth stage and subsequent growth stages in both years, soil moisture was significantly greater within the PPL band than away from the PPL band ($P<0.05$). Volumetric water content collected using soil sensors indicate that soil wetness was greater within the band than away from the band on a volumetric basis as well, but only for the first five to 15 days after application (Appendix 3). Overall, soil moisture in the subsurface band treatment generally responded similarly to residue type and depth effects as the no PPL treatment, except at the end of the 2012 season. At milk in 2012, soil moisture was depleted in the subsurface band treatment relative to the no PPL treatment, but only in the cereal rye residue ($P<0.05$). At maturity in 2012, soil moisture was significantly lower in the subsurface band treatment than the no PPL treatment for all residues ($P<0.05$).

The effects of residue type on soil moisture were most evident at the milk and maturity stages in 2012, when soil moisture was greater in the cereal rye residue than in the mixture and hairy vetch treatments ($P<0.05$). The only instance in which the trend did not hold was at milk the subsurface band treatment, when soil moisture was greater in the cereal rye treatment than in the mixture, but not different in the hairy vetch treatment.

Residue type did not have a significant effect on soil moisture at most growth stages in 2013.

Soil moisture was usually greatest at the soil surface in both years, except at emergence, fifth-leaf and milk stages in 2012, when no depth effect was observed for the no-till PPL treatments. Depth trends were generally consistent across no-till PPL treatments. In 2012, soil moisture was significantly depleted in the corn row relative to the interrow center for all residues and PPL treatments at fifth-leaf and milk stages ($P<0.05$). At maturity in 2012, greater soil moisture was also observed in the interrow center relative to the row for the subsurface band treatment only (all residues), and the opposite effect was observed in the incorporated treatment (all residues) ($P<0.05$).

Spatial distribution of soil inorganic N: Diffusion/dispersion model parameter estimates

Random Walk diffusion/dispersion equations were used to model the natural log of IN concentration as a function of Euclidean distance from IN sources (R^2 values ranged from 0.56 to 0.96, mean = 0.81). Within the no PPL and broadcast PPL treatments, and within the subsurface band treatment prior to sidedress, IN was usually greatest at the soil surface and declined with depth, although some exceptions were observed (Figures 5.2 and 5.3). Within the subsurface band treatment after the emergence sampling, IN was consistently greatest in the PPL band and declined with increasing distance from the band. Model parameters were compared among growth stages, PPL treatments and cover crop residues. The effects of these factors on model parameters are described below.

The a parameter represents an estimate of the natural log of background IN concentrations (“background IN”). Estimates across both years ranged from 0.10 to 2.89, corresponding to back-transformed concentrations of 1.1 mg kg^{-1} to 18.0 mg kg^{-1}. In both years, background IN tended to increase between emergence and fifth-leaf (Tables 5.4 and 5.5). In 2012, this trend was significant for hairy vetch in the no PPL treatment, all residues in the broadcast treatment, and the mixture and hairy vetch in the subsurface band treatment ($P<0.05$). In 2013, a significant difference between emergence and fifth-leaf stages was detected only for the mixture in the broadcast treatment ($P<0.05$). In 2012, background IN levels declined significantly between fifth-leaf and silking for all residues in the no PPL and subsurface band treatments that were modeled and for cereal rye in the broadcast treatment ($P<0.05$). This trend was also detected in 2013, but was significant only for cereal rye and the mixture within the subsurface band treatment ($P<0.05$). Background IN parameter estimates were relatively consistent between silking and maturity in both years.

At corn emergence, parameter estimates for background IN tended to be greater in the hairy vetch residue than in the cereal rye residue for all PPL treatments in which Random Walk models were fit to cereal rye. Differences in parameter estimates between the monocultures were significant in 2012 ($P<0.05$), but not significant in 2013 ($P\leq0.37$). Background IN was similar in the mixture residues as in the hairy vetch residues at emergence, except for the broadcast treatment in 2012 and no PPL treatment in 2013. Significant differences between monoculture background IN estimates were also observed at the fifth-leaf growth stage in 2012, and mixture estimates were similar to the hairy vetch residues or similar to both monocultures. At silking in 2012, the models also estimated significantly greater background IN for hairy vetch and the mixture relative to cereal rye in the subsurface band treatment ($P<0.05$). Differences among the cover crop residues were not detected at fifth-leaf and silking in 2013, and background IN estimates for fifth-leaf and silking tended to be lower for the 2013 data set than 2012. At the fifth-leaf stage in 2013, the no PPL treatment had significantly lower background IN estimates than the subsurface band treatments in the cereal rye residue ($P<0.05$). This suggests that the PPL applied in a band increased IN concentrations away from the site of delivery. At the milk stages in both years, background IN estimates were similar among all cover crop residues within each PPL treatment, and among both PPL treatments within each cover crop residue. At maturity in 2012, background IN levels were greater under hairy vetch than under the cover crop mixture, but only within the no PPL treatment ($P<0.05$). At maturity in 2013, background IN levels were significantly greater in the subsurface band treatment than in the broadcast treatment, but only for the mixture and hairy vetch residues ($P<0.05$).

The parameter estimates for IN source peak height represent the natural log of IN concentration at the IN source relative to background natural log of IN concentration. Peak width parameter estimates were positively correlated with peak height estimates ($r = 0.46$, $P<0.05$). The effects of cover crop residue type and PPL treatments on peak heights and widths are described for each growth stage below.

At emergence in 2012, peak heights were similar for hairy vetch and the cover crop mixture in all PPL treatments, and often greater for both of these treatments relative to the cereal rye residue (peaks not detected at all for cereal rye without broadcast PPL). In addition, the peak width of hairy vetch was greater than that of cereal rye in the broadcast treatment in 2012 ($P<0.05$), indicating that IN spread downward approximately 4 cm further in the profile for hairy vetch than for cereal rye with broadcast PPL. In 2012, broadcast PPL application resulted in a greater IN source peak height than the no PPL treatment for the cereal rye and cover crop mixture at emergence (no peak present for cereal rye with no PPL). However, in 2013, no differences in peak heights or widths were detected among the cover crops or between the broadcast and no PPL treatments, except that no peak was evident for cereal rye in the no PPL treatment.

The cereal rye residue maintained no depth trend within the no PPL treatment at the fifth-leaf growth stage in 2012. However at fifth-leaf in 2013, an IN source peak had developed in this treatment. Interestingly, the hairy vetch treatment did not demonstrate a depth effect within the no PPL and broadcast treatments in 2013. Peak heights associated with the PPL band were greater than the broadcast PPL peak heights for the cereal rye treatment in both years, and also for the mixture and hairy vetch residues in 2013 ($P<0.05$). The peak widths of the PPL bands were between 3 and 5 cm, which tended to be smaller than those of the no PPL and broadcast treatments at this growth stage (in 2012, broadcast > band in mixture; in 2013, no PPL > band in cereal rye, $P<0.05$). In 2012, the PPL band peak height was greatest in the cereal rye residue and least in the hairy vetch residue because background IN concentrations were the least and greatest in these treatments, respectively. However, band peak heights did not differ at fifth-leaf in 2013 among cover crop residues, presumably because background IN levels were more similar among cover crop residues in 2013 than in 2012. At fifth-leaf in 2013, PPL band peak height and width parameters were greater in the downward direction below the band than in all other directions for the cereal rye treatment ($P<0.05$).

At silking and milk growth stages in both years, the IN source peaks associated with the PPL band stayed relatively high and distinct (relatively short widths), while the peaks associated with the cover crop residue alone and cover crop residue + broadcast PPL became more subtle. In 2012, peak heights declined significantly between fifth-leaf and silking for all cover crop residues in the broadcast treatment and for hairy vetch in the no PPL treatment ($P<0.10$); however a peak developed for cereal rye in the no PPL treatment. In 2013 at silking, none of the cover crop residues in the broadcast and no PPL treatments had significant peaks, except hairy vetch in the broadcast treatment. Between fifth-leaf and silking in 2012, the band's peak height decreased significantly in the cereal rye residues, remained constant in the mixture, and increased significantly in the hairy vetch residues (peak width also increased in the hairy vetch residues; $P<0.05$). As a result, the band's peak height and width in the hairy vetch treatment were significantly greater than the band's peak height and width in cereal rye ($P<0.05$), while these parameters for the mixture were similar to both monocultures. The band's peak height and width were significantly greater in the downward direction than in all other directions for cereal rye at this growth stage and at milk ($P<0.05$). On the other hand, between fifth-leaf and silking in 2013, the band's peak height and width tended to increase in the cereal rye and mixture residues ($P<0.05$ for the peak widths), while these parameter estimates did not change in the hairy vetch residue. Therefore, the height of the band in the hairy vetch residue tended to be lower than cereal rye and mixture, and the peak width was significantly lower than in the mixture residue ($P<0.05$). The height and width of the band peaks in the mixture and hairy vetch residues were significantly greater downward than in all other directions ($P<0.05$). At maturity in 2012, the height and width of peaks for the no PPL, band and broadcast treatments were similar for all cover crop residues. In 2013, the band peak widths were significantly smaller than those in the broadcast and no

PPL treatments with cereal rye, and significantly smaller than the peak width in the broadcast treatment with hairy vetch residue ($P<0.05$).

Spatial distribution of soil inorganic N: Predictions

Random walk model predictions and inverse distance-weighted interpolation were used to generate a surface of IN concentrations for the soil profile of each treatment at each growth stage (Figures 5.4-13). The spatial distribution of soil IN for each cover crop residue and PPL treatment will be discussed by growth stage.

At corn emergence in both years, most no-till treatments exhibited a trend of decreasing IN from the soil surface to depth, with greatest IN concentrations within at a depth of approximately 0-10 cm (Figures 5.4 and 5.9). The IN concentrations at the soil surface, and/or the depth to which the pulse of elevated IN concentrations extended, increased with greater hairy vetch composition in the residue, and with broadcast PPL application. Without broadcast PPL application, a depth trend was not present for cereal rye and very little IN (<5 mg kg^{-1}) was present throughout the soil profile. Incorporating the cover crop residues and PPL caused a region of elevated IN concentrations to a depth of 20 cm (plow layer) relative to 20-30 cm for all three cover crops in both years. The IN concentrations within the plow layer were greater for hairy vetch and the mixture relative to cereal rye in 2012, and greater for hairy vetch relative to the mixture and cereal rye in 2013. There was a slight trend of decreasing IN with depth, even within the plow layer. Spatial predictions for the no-till treatments largely reflected the Random Walk model trends, except that in 2013, IN tended to be more concentrated at the soil surface near the corn row than away from the corn row. Although IN data from the point of starter PPL delivery was not included in the analysis, the effect of the starter may have affected sampling points around its delivery location in 2013, causing elevated IN in this region.

At the fifth-leaf stage in 2012, soil IN concentrations were greater overall relative to emergence, and the spatial trends observed at emergence remained evident (Figure 5.5). At fifth-leaf in 2013, spatial predictions revealed a trend of greater IN at the soil surface than at depth for the cereal rye and cover crop mixture in all PPL treatments, while this depth trend was not observed for the hairy vetch treatments (Figure 5.10). Within the subsurface band treatment, a region of high soil IN concentrations was present at the location of subsurface band PPL delivery. Inorganic N concentrations at the center of the band were 483 mg kg^{-1} (standard error = 79) in 2012 and 387 mg kg^{-1} (standard error =21) in 2013. Inorganic N concentrations decreased with distance from the center of the band, and the band's zone of influence extended to a radius of 5 cm; a distance that largely matched the Random Walk model estimates for peak width. Elongated regions of elevated IN concentrations were predicted below the subsurface bands, although concentrations in this region did not exceed 20 mg kg^{-1}. Slightly elevated EC readings 10 cm below the band at this growth stage confirm that some downward movement of IN or other solutes occurred (Appendix 3).

At silking in both years, other than the mixture and hairy vetch incorporated treatments in 2012, IN was generally below 10 mg kg^{-1} and only slightly elevated at the soil surface (0-10 cm) vs. at depth (Figures 5.6 and 5.11). Within the subsurface band treatments, soil IN remained elevated up to 160 mg kg^{-1} in the center of the PPL bands, and 40-80 mg kg^{-1} in the 5 cm radius surrounding the bands. In 2012, elevated IN concentrations of 5-10 mg kg^{-1} extending halfway to the corn row in the hairy vetch treatment, and 10 cm laterally in the mixture, provided evidence of IN movement away from the band. In 2013, there was no evidence of IN movement away from the bands. In the 2012 mixture and hairy vetch incorporated treatments, IN remained elevated (up to 40 mg kg^{-1} in mixture and 80 mg kg^{-1} in hairy vetch) at 0-20 cm relative to 20-30 cm. Within the mixture and hairy vetch incorporated treatments in 2012, depletion of IN was observed in the corn row, particularly at 20-30 cm depth relative to the rest of the interrow profile.

At the milk stage in both years, IN concentrations remained less than 10 mg kg^{-1} throughout the soil profiles for all cover crop residues in the no PPL treatment (Figures 5.7 and 5.12). In the subsurface band treatments, IN was elevated to between 40 and 80 mg kg^{-1} in 2012 and between 20 and 40 mg kg^{-1} in 2013. In both years, there was some evidence for IN movement away from the band in the hairy vetch residue, although concentrations were less than 10 mg kg^{-1} even in elevated regions away from the band.

At maturity in both years, IN was concentrated at the soil surface for nearly all cover crop and PPL treatments, except for the cereal rye residue with no PPL and the cereal rye incorporated treatment in 2012 (Figures 5.8 and 5.13). Inorganic N concentrations of 40-80 mg kg^{-1} were observed in the PPL bands in 2012, and 10-40 mg kg^{-1} in 2013. Inorganic N concentrations greater than 20 mg kg^{-1} were isolated to <5 cm surrounding the application site. In 2012, regions of IN concentrations between 5-20 mg kg^{-1} in the mixture incorporated treatment, and between 10 and 80 mg kg^{-1} in the hairy vetch incorporated treatment were observed extending from approximately 5 cm to 30 cm depth across the profile except in the corn row.

Soil profile inorganic N estimates

Profile IN estimates were computed using the predictions and compared among cover crop and PPL treatments (Tables 5.6 and 5.7). In 2012, profile IN levels averaged across treatments were intermediate at emergence (mean = 9.24 mg kg^{-1}, 95% confidence interval = 8.04-10.62), increased to fifth-leaf (mean = 17.3 mg kg^{-1}, 95% confidence interval = 15.10-19.95), and then decreased between fifth-leaf and silking and remained consistently low thereafter (mean for silking, milk, and maturity = 5.49 mg kg^{-1}, 95% confidence interval = 4.02-7.04). In 2013, average profile IN levels did not change between emergence and fifth-leaf (mean for emergence and fifth-leaf = 7.39 mg kg^{-1}, 95% confidence interval = 6.32-8.61), but decreased between fifth-leaf and silking (mean for silking and milk = 3.76 mg kg^{-1}, 95% confidence interval = 3.31-4.45) and increased to an intermediate level between milk and maturity (mean = 5.57 mg kg^{-1}, confidence interval = 5.03-6.16). Residue type, PPL treatment, and the interaction of residue type x PPL treatment significantly influenced profile IN levels at most growth stages ($P<0.05$).

The effect of residue type on profile IN was evident at emergence in both years (Tables 5.6 and 5.7). In 2012, hairy vetch and the cover crop mixture had similar profile IN and both had significantly greater (2-3x) profile IN than cereal rye for all PPL treatments. In 2013, cereal rye and the cover crop mixture had similar profile IN and hairy vetch had significantly greater (3-4x) profile IN than both for all PPL treatments. Hairy vetch IN contributions at emergence were ~ 30% greater in 2013 than in 2012. Broadcast and incorporated PPL application significantly increased profile IN relative to no PPL and subsurface band (prior to application) for all cover crop residues. Soil IN was significantly greater in the incorporated treatment relative to the broadcast treatment for all cover crop residues.

At fifth-leaf in 2012, profile IN was significantly greater for hairy vetch than cereal rye residues in all PPL treatments (Table 5.6). The cover crop mixture treatment had similar IN as hairy vetch, and significantly greater IN than cereal rye residues in all PPL treatments except the broadcast treatment ($P<0.05$). At the fifth-leaf stage in 2013, profile IN in the hairy vetch treatment was approximately a third of the levels in 2012 for all PPL treatments except subsurface band, which received additional PPL between the sampling events (Table 5.7). Profile IN concentrations in the cereal rye treatment in 2013 were also about half of the levels in 2012 within the broadcast and incorporated treatments. However, IN was still significantly greater with hairy vetch residues than cereal rye residues in the broadcast treatment, and greater than cereal rye and mixture residues in the incorporated treatment (Table 5.7; $P<0.05$). In 2012, subsurface band PPL application increased profile IN relative to the no PPL treatment, to levels similar to the broadcast and incorporated treatments for all three cover crop residues ($P<0.05$). In 2013, the subsurface band treatment had significantly greater profile IN than the other PPL treatments in the cereal rye residue, and significantly greater profile IN than the incorporated and no PPL treatments in the cover crop mixture (no PPL, broadcast and incorporated treatments had similar profile IN levels to each other) ($P<0.05$). In the hairy vetch residue in 2013, the subsurface band treatment had similar profile IN as the incorporated, and significantly greater profile IN than the broadcast and no PPL treatments ($P<0.05$). In the same year, the hairy vetch incorporated treatment had greater profile IN than the hairy vetch no PPL treatment ($P<0.05$).

The effect of residue type on profile IN largely diminished between the fifth-leaf and silking growth stages in both years, except in the incorporated treatment in 2012, in which profile IN levels were similar between hairy vetch and mixture residues and both residues provided significantly greater IN than cereal rye (Tables 5.6 and 5.7, $P<0.05$). Other than the mixture and hairy vetch incorporated treatments in 2012, profile IN was below 10 mg kg^{-1}. In 2012, average IN in the subsurface band treatment was similar to the other PPL treatments within the cereal rye and mixture cover crop residues, and lower than the incorporated treatment in the hairy vetch residue ($P<0.05$). In 2013, the subsurface band treatment had significantly greater profile IN than the other PPL treatments for cereal rye and mixture residues ($P<0.05$). Within the hairy vetch residue, the subsurface band and incorporated treatments had similar profile IN, and both means were greater than the no PPL and broadcast treatments.

A significant effect of the subsurface band treatment on profile IN was observed for all cover crop residues at milk in 2012 (Table 5.6). However, this difference between the subsurface band and no PPL treatments was only observed in the hairy vetch residue in 2013 (Table 5.7). At maturity in 2012, incorporated hairy vetch had significantly greater profile IN than incorporated cereal rye, and significantly greater profile IN than the hairy vetch no PPL and broadcast treatments ($P<0.05$). The profile IN remaining in the incorporated hairy vetch treatment at maturity in 2012 equated to ~100 kg N ha^{-1} to 30 cm. In 2013, profile IN was between 5 and 7 mg kg^{-1} for all PPL and residue treatments.

Spatial distribution of NO_3^--N proportion

While both NO_3^--N and NH_4^+-N are plant-available forms of N, they differ in loss pathways. Nitrate is susceptible to leaching losses as it moves readily with water, and to gaseous losses through denitrification. On the other hand, NH_4^+-N adsorbs to soil surfaces, making it relatively immobile in soil water, but is susceptible to gaseous losses through volatilization. Growth stage had a significant effect on NP ($P<0.05$): the greatest NP values were observed at emergence and fifth-leaf stages in both years (2012: mean = 0.71, 95% confidence interval = 0.51-0.85; 2013: mean = 0.63, 95% confidence interval = 0.59-0.67). In 2012, NP was lowest at silking and maturity (mean = 0.44, 95% confidence interval = 0.27-0.64), and intermediate at the milk stage (mean = 0.53, 95% confidence interval = 0.29-0.76). In 2013, NP was lowest at silking (mean = 0.35, 95% confidence interval = 0.33-0.38) and intermediate at milk and maturity stages (mean = 0.45, 95% confidence interval = 0.41-0.49). Within each growth stage, residue type, PPL treatment, depth class, interrow class, and interactions of residue type x PPL treatment, residue type x depth, PPL treatment x depth, and PPL treatment x interrow class were the dominant factors influencing NP. Means for each of these significant interactions are presented in Tables 5.8 and 5.9, and appendix 5. Because knowledge of how NO_3^--N and NH_4^+-N vary with depth is particularly relevant to understanding gaseous and leaching N losses, discussion of results will focus on vertical rather than horizontal spatial variability.

At emergence, NP was significantly greater for hairy vetch than cereal rye residues across all PPL treatments in both years ($P<0.05$). The effect was particularly pronounced in the no PPL and subsurface band (prior to sidedressing) treatments (1.5-5x the NP in hairy vetch as in cereal rye with no PPL). In 2012, NP estimates in the mixture treatments were intermediate between the monocultures or similar to hairy vetch; whereas in 2013 the NP estimates in the mixture treatments were similar to cereal rye. The incorporated and broadcast PPL treatments tended to have a greater proportion of NO_3^--N than the no

PPL treatment. This was significant for the cereal rye and mixture residues in 2012 and all residues in 2013 ($P<0.05$). In 2012, the difference between broadcast and no PPL treatments diminished with increasing hairy vetch composition of residues, such that in the hairy vetch residue, the incorporated treatment had significantly greater NP than the no-till treatments, but there was no difference among the no-till PPL treatments. The NP was greatest at the soil surface (0-10 cm) and least at depth (20-30 cm) in both years for all PPL treatments except the incorporated treatment in 2012. Incorporating residues and PPL made NP similar at all depth intervals in 2012.

At the fifth-leaf growth stage in both years, significant residue type effects on NP were observed. In 2012, NP was greater for the hairy vetch and mixture residues than for the cereal rye residue across all PPL treatments ($P<0.05$). The NP tended to be lower in the hairy vetch treatments at the fifth-leaf growth stage in 2013 relative to 2012, so the difference in NP between hairy vetch and cereal rye residues was not as pronounced. In 2013, the residue type effect was only detected for the broadcast and incorporated treatments at the fifth-leaf stage ($P<0.05$). Pelletized poultry litter was applied directly before the fifth-leaf sampling, and the high NH_4^+-N concentration reduced NP in the subsurface band treatment relative to the broadcast treatment for all residues in 2012 ($P<0.05$). In 2013, NP in the subsurface band treatment was only lower than the incorporated treatment in the hairy vetch residue ($P<0.05$). The NP within the bands were 0.17 in 2012 and 0.03 in 2013, which were significantly lower than NP away from the band ($P<0.05$). As a result, the differences in NP among the PPL treatments were particularly pronounced at the surface and mid depth classes, which were closest in proximity to the band, in 2012. In 2012, NP estimates were greater near the soil surface than at depth for all PPL treatments and cover crop residues. In 2013, there was a significant residue type x depth interaction, in which NP was greatest at depth and least at the soil surface, but only for the hairy vetch residue (*P*<0.05).

At the silking growth stages in both years, NP was significantly elevated in the hairy vetch residue relative to the cereal rye residue for all PPL treatments (*P*<0.05). In 2012, NP estimates in the mixture were either not different than either monoculture (no PPL and subsurface band treatments), similar to hairy vetch and greater than the cereal rye (incorporated treatment), or similar to cereal rye and less than hairy vetch (broadcast). In 2013, NP in the mixtures were not different than monocultures for any of the PPL treatments. Between fifth-leaf and silking, much of the NH_4^+-N associated with the PPL band had nitrified, increasing NP in this treatment relative to the other PPL treatments. In 2012, NP in the band treatment was greater than in the incorporated treatment for cereal rye residues (*P*<0.05). For the mixture and hairy vetch residues in 2012, and all residues in 2013, the NP tended to be greater in the band treatment and incorporated treatment (0.33-0.77) relative to the broadcast and no PPL treatments (0.16-0.54). In 2012, NP within the PPL bands was similar to the NP away from the bands for the mixture and hairy vetch treatments. In the cereal rye residue, NP was greater in the band than away from the band. In 2013, NP within the band was significantly lower than away from the band (*P*<0.05). The NP decreased with depth in 2012, but only in the incorporated PPL treatment (averaged across residues) and cereal rye residues (averaged across PPL treatments); and in 2013 for all residues and the no PPL and broadcast treatments.

The effects of residue type and PPL treatments diminished between the silking and milk stages in 2012. At milk in 2013, NP was significantly greater for the hairy vetch residue than for the mixture and cereal rye residues, which were similar to each other, but this effect was only detected in the subsurface band treatment ($P<0.05$). Also at milk in 2013, NP in the hairy vetch subsurface band treatment was significantly greater than in the hairy vetch no PPL treatment ($P<0.05$). The NP within the PPL band exceeded NP away from the band in all residues at milk in 2012 ($P<0.05$). However, in 2013, NP within the band was actually lower than away from the band, but only for the cereal rye residue ($P<0.05$). Although significant depth effects were detected in both years, the difference in NP over depth were not numerically great (2012: 0.42-0.54, 2013: 0.34-0.50).

At maturity in 2012, NP estimates were similar for hairy vetch and mixture residues, and significantly lower for the cereal rye residue within all PPL treatments. Also, the NP was significantly greater (~2x as great) in the incorporated treatments for all residues than in the no-till PPL treatments ($P<0.05$). In 2013, residue type and PPL effects on NP were not detected, except that greater NP was observed for the cover crop mixture relative to monocultures at 20-30 cm. At maturity, there were no differences in NP within the bands and away from the bands in either year. In 2012, NP either did not change or decreased with depth for all PPL and residue treatments, except for the incorporated treatment, in which NP was greatest at a depth of 10-20 cm. Nitrate-N proportions declined with depth for all residues and PPL treatments in 2013.

Discussion

The first objective of this study was to measure and model the spatial distribution of IN over five corn growth stages as affected by cover crop residue type and PPL application methods. We used a systematic soil core sampling approach to collect gravimetric moisture and IN data at a range of distances from IN sources. This is similar to the approach used by Sawyer et al. (1990) and Zebarth et al. (1999). Other authors have collected soil samples at specific locations on exposed soil faces (McCormick et al. 1983, Comfort et al. 1988, Sawyer et al. 1990). The core sampling provided data for 5- or 10-cm depth increments, which may have diluted some location-specific effects relative to point sampling on exposed faces. It is likely that the measured IN concentrations for cores taken within the PPL bands were lower than if more "pure" PPL band samples were collected by sampling into an exposed soil face. However, collecting soil cores is a common and practical method for soil sampling, and our detailed core sampling approach likely captured the full range of IN concentrations that could be observed using the core method. Thus, the predictions generated using this sampling approach should be appropriate to develop systematic soil core sampling methods for fields with PPL bands.

We modeled IN concentrations over space using a Random Walk model, which allowed us to quantify three relevant parameters: 1) the background IN concentration; 2) the magnitude of the IN peak; and 3) the width of the IN peak. We then compared parameter estimates among treatments and growth stages. The spatial IN predictions developed from the Random Walk model + interpolation of residuals were then combined to generate means that were unbiased by the number of cores taken at any specific location. In doing this, we achieved our second objective; to use models to estimate and compare IN in soil profiles as affected by cover crop residue type and PPL application method.

We hypothesized that within each PPL treatment, profile IN would be greatest with hairy vetch residues, intermediate with hairy vetch/cereal rye mixture, and least with cereal rye residues.Our results suggest that hairy vetch did provide greater IN than cereal rye, particularly in 2012. This is supported by the fact that parameter estimates for background IN, IN peak heights and profile IN levels were greater for hairy vetch than cereal rye at early growth stages prior to corn uptake. Just prior to the phase of rapid corn N uptake (fifth-leaf), IN under hairy vetch and cereal rye with no PPL equated to 73.5 kg IN ha^{-1}, and 20.0 kg IN ha^{-1} to 30 cm, respectively (using bulk density to convert soil mass to soil area). At fifth-leaf in 2013, they were 26.7 kg IN ha^{-1}, and 17.4 kg IN ha^{-1}, respectively. Other studies have estimated IN levels of 40-100 kg IN ha^{-1} to 20 or 30 cm under hairy vetch cover crop residues (Huntington et al. 1985, Cook et al. 2010) and 25 kg IN ha^{-1} to 20 cm under cereal rye residues (Huntington et al. 1985) at this growth stage. The spatial distribution of IN and profile IN estimates of the cover crop mixtures were more similar to hairy vetch in 2012 and more similar to cereal rye in 2013. This trend is consistent with the greater C/N ratio of the mixture in 2013 relative to 2012.

We hypothesized that in the broadcast and no PPL treatments, IN would be greatest at the soil surface at corn emergence and would decrease and diffuse downward over time. We found greater IN concentrations at the soil surface than at depth for almost all data subsets. One important exception was cereal rye with no broadcast PPL. Early in the season in both years, soil IN was low at all depths in this treatment. We did not measure IN in a bare-soil treatment to determine whether the low IN was due to net immobilization near the soil surface. The presence of grass cover crop surface residues has been shown to either not affect (Huntington et al. 1985) or decrease IN during the corn growing season relative to bare soil (Rosecrance et al. 2000, Sarrantonio 2003, Wells et al. 2013). The addition of ~3.5 Mg PPL ha^{-1} to the cereal rye residue stimulated

N release from the surface.

Several studies in no-till corn systems have reported an increase in IN between emergence and fifth-leaf stage (Elbehar et al. 1984, Huntington et al. 1985, Cook et al. 2010), and our 2012 results for the no PPL and broadcast treatments match this trend. However, between emergence and fifth-leaf in 2013, IN levels decreased in treatments with greater IN levels at emergence and remained relatively constant in treatments with lower IN levels at emergence, diminishing differences between the no PPL and broadcast treatments and among the cover crop residues. We also found no depth effect on IN for hairy vetch in the no PPL and broadcast treatments at fifth-leaf in 2013. Gravimetric soil moisture at this growth stage ranged from 0.190 to 0.255, corresponding to relative saturation values ranging from 0.47 to 0.58. We estimate that relative saturation exceeded 0.60 immediately following the rain events in early June 2013 between emergence and fifth-leaf. At the fifth-leaf growth stage, distribution of NO_3^--N was uniform throughout the profile, and greater at depth in the hairy vetch residue. It appears that the wet conditions between emergence and fifth-leaf caused NO_3^--N to move around, and possibly leach out of the top 30 cm. Also, the relatively wet conditions coupled with the release of soluble C and IN from hairy vetch and/or broadcast PPL likely facilitated denitrification losses in the treatments with greater available N. Other authors have reported maximum denitrification rates of 6 mg N kg^{-1} day^{-1} for surface-applied hairy vetch residues and 20-40 mg N kg^{-1} day^{-1} for incorporated hairy vetch residues at 0.90 relative saturation (Aulakh et al. 1991a, Aulukh et al. 1991b). Although the cereal rye residue with no PPL posed the least risk for such early-season losses, the low N delivery of cereal rye would require increasing PPL amendments to above P-based rates to meet corn N requirements.

After fifth-leaf in both years, pulses of IN at the soil surface tended to decrease and profile IN levels declined overall. Very little downward movement of IN was observed in the broadcast and no PPL treatments after fifth-leaf because corn N demand increased. In both years, IN concentrations at the soil surface were generally slightly increased at maturity relative to silking and milk due to increased mineralization relative to corn uptake.

We hypothesized that IN would be localized to a region 5-10 cm below the soil surface and in the center of the interrow space in the subsurface band treatments immediately after sidedress application. We also hypothesized that IN in the band would decrease over time and diffuse downward and in the direction of crop roots. Averaged across years, IN at the center of the PPL band was 440 mg kg^{-1} immediately after application, and decreased to 100 mg kg^{-1} at silking. At the milk and maturity growth stages, IN in the band averaged 35 mg kg^{-1}. Inorganic N in the band was predominantly in the NH_4^+-N form immediately after application. In the drier soil conditions in 2012, nitrification occurred rapidly within the band, and by silking most of the IN in the band was in the NO_3^--N form. In the wetter conditions of 2013, NH_4^+-N was the dominant IN species in the band throughout the season, and the NO_3^--N fraction was generally greater away from the band than in the band. Within the PPL band, high C concentrations stimulate high microbial activity, leading to O_2 depletion. Depletion of O_2 within the band was probably exacerbated by wet conditions in 2013, particularly within the PPL bands, causing greater inhibition of nitrification or increased denitrification relative to 2012 (Bateman and Baggs 2005).

Inorganic N associated with the PPL band remained relatively localized near the point of delivery (within 10 cm) throughout the growing seasons. In cases where elevated IN levels were observed extending out of this zone of influence, the concentrations were generally no more than 15 mg kg^{-1} above background levels. Although there were a few cases of significant directional effects on Random Walk parameter estimates, and significantly greater background IN in the subsurface band vs. other no-till treatments, the spatial IN predictions suggest that these effects were probably not meaningful in terms of N loss risk. It appears that corn plants generally took up IN from the PPL as it was released, allowing little time for movement throughout the profile.

We hypothesized that in the incorporated treatment, IN would be evenly distributed throughout the soil profile at corn emergence and would become depleted over time, particularly in the corn row (where roots may have the greatest effect). At emergence in both years, we observed a distinct plow layer at 20 cm, above which IN concentrations were greater than below. Inorganic N tended to decrease slightly with depth, even within the plow layer. Profile IN concentrations within the incorporated treatments (all residues) were greatest at emergence and fifth-leaf in 2012, and at emergence in 2013. Profile IN in the incorporated treatments in both years declined after fifth-leaf, except for the hairy vetch treatment in 2012, which remained above 28 mg kg^{-1} throughout the growing season. The region of high IN concentrations in the 2012 hairy vetch incorporated treatment moved downward in the profile between silking and maturity, and the NP was particularly elevated (0.82) between 10 and 20 cm at maturity. The high NO_3^--N (~85 kg ha^{-1}) remaining at corn maturity in the hairy vetch incorporated treatment poses a risk for NO_3^--N leaching losses. In 2012, depletion of IN near the corn row developed, but this was not observed in 2013, possibly due to the wetter conditions that facilitate IN movement. The combination of gravimetric soil moisture and rainfall data suggest that soil water potential was at or above field capacity for the majority of the season, providing ample time for NO_3^--N diffusion and mass flow.

Finally, we hypothesized that PPL treatment would have a significant effect on profile IN throughout the corn growing season, following this order: incorporated > subsurface band > broadcast > no PPL. We found that differences in profile IN among the PPL treatments depended on the residue type and climatic conditions. The dry conditions of 2012 did not facilitate N losses during the growing season, and profile IN estimates were statistically equivalent among the broadcast, subsurface band and incorporated treatments within each residue at fifth-leaf. At silking, profile IN tended to be greater in the incorporated treatment than in the subsurface band treatment, but only for the hairy vetch residue. The incorporated hairy vetch residues + PPL evidently mineralized more N than could be taken up by the corn crop, providing an opportunity for post-season N losses through leaching. The wetter conditions of 2013 apparently contributed to early-season N losses, so that the treatments with high IN levels at emergence had lower profile IN at fifth-leaf. The subsurface band application of PPL at sidedress resulted in generally greater profile IN than the other PPL treatments because substantial losses had occurred in the other treatments prior to sidedress.

Implications for soil sampling methods

A series of systematic sampling protocols for the subsurface band treatments at each growth stage were tested using the spatial IN predictions generated in this study (Appendix 6). A soil sample comprising one core (30 cm deep) within 5 cm of the band

and one core (30 cm deep) at least 10 cm away from the band was predicted to overestimate IN by ~100% at fifth-leaf. Increasing the number of cores taken away from the band for every core in the band decreased the IN estimate for the sample, following a hyperbolic function (R^2 values ranged from 0.68 to 0.96, average = 0.85) and decreased variability of the estimate. The effect of the number of cores taken away from vs. within the band decreased over time since PPL application. 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 IN at all growth stages. Tewolde et al. (2013) recommended that soil cores be taken every 5 cm between PPL bands for a sampling depth of 15 cm. Adjusting for differences in sampling depth, this represents a similar proportion to our recommendation.

Conclusions

Cover crop residue type had a significant effect on soil IN concentrations, with greater soil IN in the hairy vetch treatment than in the cereal rye treatment at emergence and fifth-leaf corn growth stages in both years. The 2012 cover crop mixture provided IN concentrations similar to 2012 hairy vetch, while the 2013 mixture provided IN concentrations similar to 2013 cereal rye at emergence and fifth-leaf stages in both years. Broadcast and incorporated PPL amendment increased soil IN by ~50% and by 100-200% at emergence, respectively relative to no PPL for all cover crop residues. At emergence and most subsequent growth stages in the no-till treatments, IN was generally concentrated near the soil surface under the cover crop residues and decreased with depth, except in the cereal rye residue, which did not usually show a depth unless broadcast PPL was applied. Sidedress subsurface PPL application provided similar or greater IN concentrations as the broadcast and incorporated treatments at fifth-leaf, and soil IN remained localized throughout the growing seasons. In the incorporated treatment, soil IN was generally concentrated to a depth of 20 cm (plow layer).

In 2012, the drier year, soil IN increased between emergence and fifth-leaf, decreased between fifth-leaf and silking and increased slightly between milk and maturity for most treatments. A similar pattern was demonstrated in 2013, the wetter year, except that soil IN remained constant or decreased between emergence and fifth-leaf. In 2012, substantial IN (100 kg N ha^{-1}) remained in the hairy vetch incorporated treatment profile after corn maturity. The subsurface band PPL application at sidedress avoided early-season N losses in 2013, providing 1.3-2.6x the soil IN as the broadcast and incorporated treatments at the fifth-leaf stage. However, high concentrations of NO_3^--N, C and increased soil moisture in the PPL band may have led to denitrification losses.

Table 5.1 Selected soil properties of study sites, cover crop residue biomass and nitrogen (N) content, and nutrient composition of pelletized poultry litter (PPL) applied in the 2012 and 2013 experiments at Beltsville Agricultural Research Center.

	-------------------- 2012	-------------------		--------------------- 2013	-------------------	
Soil properties, dry weight basis						
USDA texture classification	Loam			Loam		
Bulk density, g cm^{-3} (No-till/Inc)	1.26(0.03) /1.18(0.01)			1.32(0.02) /1.28(0.04)		
Total C, g kg^{-1}	6.7(0.6)			9.9(1.7)		
Total N, g kg^{-1}	0.4(0.1)			0.7(0.1)		
Mehlich 3-extractable P, mg kg^{-1}	67.3(3.3)			76.7(13)		
Mehlich 3-extractable K, mg kg^{-1}	93.0(4.0)			111.7(5.2)		
pH, 1:1 soil:water	6.2(0.2)			5.7(0.1)		
CEC, meq 100 g^{-1}	5.9(0.3)			7.4(0.3)		
Cover crop properties	Cereal rye	Mixture	Hairy vetch	Cereal rye	Mixture	Hairy vetch
Biomass, kg ha^{-1}	10712(560)	8592(695)	6256(706)	10567(591)	12875(738)	5561(727)
N content, kg ha^{-1}	56(10)	155(14)	173(14)	62(10)	163(12)	146(12)
C/N ratio	92(2.8)	26(2.8)	17(2.8)	80(2.2)	37(2.2)	16(2.2)
Pelletized poultry litter properties, fresh weight basis						
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)		
P, g kg^{-1}	8.3(0.5)			14.7(0.6)		
K, g kg^{-1}	15.3(0.9)			16.7(0.7)		

Table 5.2 Gravimetric soil moisture content as affected by growth stage, pelletized poultry litter (PPL) application method, cover crop residue type, and depth class in 2012. Different lowercase letters indicate significant differences among PPL treatments within the same residue type or depth class and growth stage ($P<0.05$). Different uppercase letters indicate significant differences among residue types or depth classes within the same PPL treatment and growth stage ($P<0.05$). For the subsurface band treatment, soil moisture was significantly greater in the band than away from the band, so soil moisture values from within the band (rows labeled "In") are presented separately from soil moisture means for the entire profile (rows labeled "SSB").

	Cover crop residue			Depth class		
PPL	Cereal rye	Mixture	Hairy vetch	Surface (0-10 cm)	Mid (10-20 cm)	Deep (20-30 cm)
Emergence						
No	0.184 aA	0.162 bA	0.171 abA	0.174 aA	0.180 aA	0.162 bA
Brd	0.187 aA	0.197 aA	0.189 aA	0.188 aA	0.193 aA	0.193 aA
SSB	0.188 aA	0.174 abA	0.184 aA	0.187 aA	0.184 aA	0.174 abA
Inc	0.186 aA	0.165 bAB	0.148 bB	0.141 bB	0.174 aA	0.183 abA
Fifth-leaf†						
No	0.167 aA	0.147 bA	0.161 abA	0.148 aA	0.167 aA	0.161 abA
Brd	0.163 aA	0.176 aA	0.182 aA	0.162 aA	0.179 aA	0.181 aA
SSB	0.160 aA	0.156 abA	0.154 bA	0.148 aA	0.162 abA	0.159 abA
In	0.181	0.178	0.181			
Inc	0.133 bA	0.136 bA	0.119 cA	0.101 bB	0.144 bA	0.143 bA
Silking						
No	0.180 aA	0.156 aA	0.145 abA	0.175 aA	0.158 aB	0.149 aB
Brd	0.169 aA	0.134 aA	0.147 abA	0.164 abA	0.147 abB	0.138 abB
SSB	0.179 aA	0.147 aA	0.163 aA	0.177 aA	0.160 aB	0.151 aB
In	0.229	0.193	0.207			
Inc	0.136 aA	0.153 aA	0.108 bA	0.147 bA	0.130 bB	0.121 bB
Milk†						
No	0.146 aA	0.100 aB	0.108 aB	0.118 aA	0.119 aA	0.118 aA
SSB	0.118 bA	0.100 aB	0.108 aAB	0.108 bA	0.110 bA	0.108 bA
In	0.164	0.141	0.153			
Maturity†						
No	0.207 aA	0.187 aB	0.180 aB	0.216 aA	0.192 aB	0.166 aC
Brd	0.198 abA	0.178 abB	0.171 abB	0.207 abA	0.184 abB	0.157 aC
SSB	0.192 bA	0.171 bB	0.165 bB	0.200 bA	0.177 bB	0.151 aC
In	0.232	0.209	0.213			
Inc	0.196 abA	0.175 abB	0.169 abB	0.204 abA	0.181 abB	0.154 aC

†Significant interrow effect (Fifth-leaf: Interrow center=0.161, Row=0.147; Milk: Interrow center =0.126, Row=0.104; Maturity: SSB Interrow center =0.187, SSB Row=0.169, Inc Interrow center =0.171, Inc Row=0.191.

Table 5.3 Gravimetric soil moisture content as affected by growth stage, pelletized poultry litter (PPL) application method, cover crop residue type, and depth class in 2013. Different lowercase letters indicate significant differences among PPL treatments within the same residue type or depth class and growth stage ($P<0.05$). Different uppercase letters indicate significant differences among residue types or depth classes within the same PPL treatment and growth stage ($P<0.05$). For the subsurface band treatment, soil moisture was significantly greater in the band than away from the band, so soil moisture values from within the band (rows labeled “In”) are presented separately from soil moisture means for the entire profile (rows labeled “SSB”).

	----------------- Cover crop residue -----------------			------------------------------ Depth class ----------------------------		
PPL	Cereal rye	Mixture	Hairy vetch	Surface (0-10 cm)	Mid (10-20 cm)	Deep (20-30 cm)
---------- Emergence ----------						
No	0.244 aA	0.231 abA	0.252 aA	0.279 aA	0.231 aB	0.216 abC
Brd	0.252 aA	0.252 aA	0.249 aA	0.290 aA	0.236 aB	0.226 aB
SSB	0.239 aA	0.229 abA	0.249 aA	0.279 aA	0.224 aB	0.217 aB
Inc	0.227 aA	0.217 bA	0.214 bA	0.237 bA	0.223 aA	0.198 bB
---------- Fifth-leaf ----------						
No	0.244 aA	0.244 abA	0.243 aA	0.270 aA	0.235 aB	0.226 aC
Brd	0.255 aA	0.252 aAB	0.223 aB	0.270 aA	0.235 aB	0.226 aC
SSB	0.251 aA	0.247 aA	0.231 aA	0.269 aA	0.235 aB	0.225 aC
In	0.293	0.248	0.242			
Inc	0.211 bA	0.216 bA	0.190 bA	0.232 bA	0.198 bB	0.188 bC
---------- Silking ----------						
No	0.196 aA	0.176 aA	0.190 aA	0.198 aA	0.181 aB	0.183 aB
Brd	0.194 aA	0.190 aA	0.167 aA	0.192 aA	0.177 aB	0.181 aB
SSB	0.204 aA	0.170 aA	0.190 aA	0.198 aA	0.178 aB	0.187 aB
In	0.249	0.188	0.207			
Inc	0.194 aA	0.190 aA	0.187 aA	0.190 aAB	0.195 aA	0.187 aB
---------- Milk ----------						
No	0.241 aA	0.242 aA	0.224 aA	0.263 aA	0.226 aB	0.217 aC
SSB	0.234 aA	0.234 aA	0.230 aA	0.260 aA	0.223 aB	0.215 aC
In	0.295	0.252	0.264			
---------- Maturity ----------						
No	0.258 aA	0.240 aA	0.246 abA	0.283 aA	0.244 aB	0.217 aC
Brd	0.246 aA	0.237 aA	0.234 abA	0.274 aA	0.234 aB	0.208 aC
SSB	0.237 aA	0.241 aA	0.250 aA	0.278 aA	0.238 aB	0.212 aC
In	0.299	0.267	0.278			
Inc	0.225 aA	0.219 aA	0.212 bA	0.254 bA	0.214 bB	0.188 bC

Table 5.4 Parameter estimates for diffusion/dispersion equations fitted to the 2012 natural log of soil inorganic nitrogen (IN) concentrations as a function of Euclidean distance from IN source. Inorganic N source is the soil surface for no pelletized poultry litter (PPL) and broadcast treatments, and PPL band for subsurface band treatments. The parameter $\boldsymbol{a}$ represents the natural log of background soil IN concentration, $\boldsymbol{x}$ is the curve peak height at the IN source, and $\boldsymbol{s}$ is the peak width, or distance affected by the IN source. Parameter estimates that are not significantly different than zero (P<0.05) are indicated with italicized font. Different lowercase letters indicate that estimates are significantly different (P<0.05) among PPL treatments within the same cover crop residue, growth stage, and parameter. Different uppercase letters indicate that estimates are significantly different (P<0.05) among different residues within the same PPL treatment, growth stage and parameter. For subsets within the subsurface band treatment in which model parameters differed in the vertical direction below the band relative to all directions, separate parameter estimates are presented for below the band (“Bel”). Standard errors are presented in parentheses.

	a, Background			x, Peak height			s, Peak width (cm)		
PPL	Cereal rye	Mixture	Hairy vetch	Cereal rye	Mixture	Hairy vetch	Cereal rye	Mixture	Hairy vetch
Emergence									
No	No trend	1.27(0.17)aA	1.62(0.13)aA	No trend	22.28(2.83)bA	25.88(4.82)aA	No trend	5.04(0.60)aA	7.96(1.25)aA
Brd	1.11(0.10)B	1.01(0.13)aB	1.76(0.12)aA	24.38(3.46)A	45.64(6.37)aA	38.87(4.87)aA	5.11(0.66)B	8.34(0.97)aAB	9.04(0.87)aA
SSB	No trend	1.45(0.15)aA	1.36(0.28)aA	No trend	32.48(4.94)abA	35.52(3.73)aA	No trend	8.84(1.01)abA	9.68(0.71)aA
Fifth-leaf									
No	No trend	1.76(0.27)aA	2.50(0.13)aA	No trend	*28.17(15.09)*aA	17.95(4.91)aA	No trend	9.95(3.80)abA	6.58(1.58)aA
Brd	1.80(0.12)aB	1.93(0.28)aAB	2.72(0.17)aA	24.92(2.62)bA	52.33(14.81)aA	22.72(7.43)aA	5.29(0.51)aA	11.53(2.07)aA	8.56(2.17)aA
SSB	1.59(0.09)aB	2.50(0.14)aA	2.89(0.19)aA	52.56(3.68)aA	37.91 (3.69)aAB	24.24(3.16)aB	5.08(0.35)aA	4.43(0.41)bA	2.96(0.32)aA
Silking									
No	0.78(0.18)aA	0.80(0.13)aA	1.28(0.08)aA	15.86(7.37)abA	19.73(5.80)abA	3.98(1.89)bA	10.64(3.33)aA	9.56(2.03)aA	*3.28(2.23)*aA
Brd	1.25(0.12)aA	1.31(0.17)aA	1.90(0.42)aA	7.81(3.53)bA	8.83(2.16)bA	*4.26(2.17)*bA	5.64(2.32)aA	3.91(1.00)aA	*3.00(2.89)*aA
SSB	1.11(0.09)aB	1.47(0.16)aA	1.56(0.16)aA	26.10(2.62)aB	35.19(2.66)aAB	46.28(5.15)aA	3.96(0.36)aB	5.38(0.40)aAB	8.09(0.88)aA
Bel	1.14(0.08)			40.43(4.32)			5.54(0.62)		
Milk									
No	1.00(0.21)aA	0.86(0.11)aA	0.95(0.26)aA	*4.00(2.48)*bA	9.30(3.02)bA	*8.08(4.81)*bA	*2.68(5.85)*aA	5.45(1.62)aA	*6.61(3.44)*aA
SSB	0.98(0.09)aA	1.22(0.16)aA	1.29(0.20)aA	24.45(2.44)aA	25.24(2.68)aA	27.48(3.65)aA	3.60(0.31)aA	3.56(0.32)aA	5.83(0.83)aA
Bel	0.99(0.09)			32.80(4.24)			4.70(0.64)		
Maturity									
No	*0.72(0.51)*aAB	*0.10(0.33)*aB	1.61(0.24)aA	*16.36(12.16)*aA	22.32(6.77)aA	10.26(4.62)aA	*9.13(5.02)*aA	4.20(1.23)aA	4.20(1.85)aA
Brd	1.15(0.52)aA	No trend	1.38(0.38)aA	*16.78 (8.17)*aA	No trend	16.34(6.82)aA	4.81(2.07)aA	No trend	6.92(2.51)aA
SSB	1.13(0.42)aA	1.06(0.39)aA	1.90(0.35)aA	26.25 (3.98)aA	27.06(6.49)aA	13.24(3.27)aA	4.29(0.61)aA	3.80(0.79)aA	3.20(0.63)aA

Table 5.5 Parameter estimates for diffusion/dispersion equations fitted to the 2013 natural log of soil inorganic nitrogen (IN) concentrations as a function of Euclidean distance from IN source. Inorganic N source is the soil surface for no pelletized poultry litter (PPL) and broadcast treatments, and PPL band for subsurface band treatments. The parameter $\boldsymbol{a}$ represents the natural log of background soil IN concentration, $\boldsymbol{x}$ is the curve peak height at the IN source, and $\boldsymbol{s}$ is the peak width, or distance affected by the IN source. Parameter estimates that are not significantly different than zero ($P<0.05$) are indicated with italicized font. Different lowercase letters indicate that estimates are significantly different ($P<0.05$) among PPL treatments within the same cover crop residue, growth stage, and parameter. Different uppercase letters indicate that estimates are significantly different ($P<0.05$) among different residues within the same PPL treatment, growth stage and parameter. For subsets within the subsurface band treatment in which model parameters differed in the vertical direction below the band relative to all directions, separate parameter estimates are presented for below the band ("Bel"). Standard errors are presented in parentheses.

	a, Background			x, Peak height			s, Peak width (cm)		
PPL	Cereal rye	Mixture	Hairy vetch	Cereal rye	Mixture	Hairy vetch	Cereal rye	Mixture	Hairy vetch
Emergence									
No	No trend	*0.51(0.25)*aB	1.61(0.16)aA	No trend	54.20(14.28)aA	40.21 (6.24)aA	No trend	10.95(1.99)aA	9.39(1.12)aA
Brd	0.80(0.25)aA	0.85(0.21)aA	1.58(0.23)aA	36.67(12.96)aA	39.63(11.36)aA	61.34(12.34)aA	10.38(2.63)aA	10.58(2.12)aA	11.78(1.52)aA
SSB	0.71(0.15)aA	0.77(0.16)aA	1.45(0.25)aA	27.51 (7.17)aA	37.15 (8.74)aA	39.81 (5.19)aA	9.09(1.75)aA	10.41(1.66)aA	8.96(0.87)aA
Fifth-leaf									
No	0.85(0.17)bA	0.77(0.33)aA	No trend	27.88(7.38)abA	*39.14(20.72)*abA	No trend	9.33(1.81)aA	12.98(3.99)aA	No trend
Brd	1.41(0.25)abA	1.54(0.10)aA	No trend	12.42(5.27)bA	15.88 (4.10)bA	No trend	6.91(2.54)abA	6.68(1.48)aA	No trend
SSB	1.79(0.11)aA	1.59(0.11)aA	1.90(0.25)A	34.01(3.21)aA	36.38 (3.34)aA	41.20(3.26)A	3.18(0.25)bA	3.49(0.28)aA	3.99(0.29)A
Bel	1.79(0.11)			43.71(5.43)			4.28(0.55)		
Silking									
No	No trend	0.42(0.23)aA	0.61(0.27)aA	No trend	*20.28(13.47)*aA	*24.24(14.55)*abA	No trend	11.11(4.82)aA	12.00(4.44)aA
Brd	No trend	No trend	0.84(0.17)a	No trend	No trend	13.48 (3.24)b	No trend	No trend	5.25(1.16)a
SSB	1.17(0.18)A	0.79(0.09)aA	1.29(0.20)aA	42.42(3.35)A	45.24 (3.50)aA	33.59 (3.12)aA	4.65(0.36)AB	4.97(0.38)aA	3.48(0.27)aB
Bel		0.77(0.08)	1.29(0.21)		64.06(8.37)	46.59(5.33)		7.40(1.05)	4.78(0.57)
Milk									
No	0.87(0.22)aA	0.72(0.29)aA	0.77(0.16)aA	*17.74(10.43)*aA	*28.67(17.78)*aA	13.56(3.65)aA	11.85(4.34)aA	12.02(4.59)aA	6.73(1.57)aA
SSB	1.24(0.22)aA	1.21(0.07)aA	1.41(0.20)aA	24.56 (2.26)aA	16.77 (1.93)aA	15.20(3.35)aA	4.21(0.36)aA	3.69(0.37)aA	4.69(1.00)aA
Maturity									
No	0.82(0.24)aA	1.00(0.17)abA	0.91(0.21)abA	49.66(12.66)aA	32.47(7.10)aA	34.58 (7.80)aA	12.11(1.86)aA	9.90(1.53)aA	9.93(1.58)abA
Brd	1.06(0.12)aA	0.80(0.10)bA	*0.40(0.29)*bA	34.19 (6.63)aA	39.37(5.22)aA	64.62(15.43)aA	11.30(1.39)aA	9.14(0.90)aA	13.37(1.82)aA
SSB	1.58(0.14)aA	1.46(0.15)aA	1.52(0.15)aA	21.27 (3.57)aA	21.84(5.05)aA	25.64 (3.82)aA	4.68(0.76)bA	7.88(1.75)aA	6.22(0.90)bA

Table 5.6 Profile soil inorganic nitrogen (IN) concentrations by growth stage, cover crop residue type, and pelletized poultry litter (PPL) treatment in 2012. Estimates were calculated using the mean soil profile IN concentration predictions of three replicates for each treatment. Different lowercase letters indicate significant differences among PPL treatments within the same cover crop residue and growth stage (*P*<0.05). Different uppercase letters indicate significant differences among residues within the same PPL treatment and growth stage (*P*<0.05).

	Soil inorganic N, mg kg^{-1}		
PPL	Cereal rye	Mixture	Hairy vetch
Emergence			
No	3.26 cB	7.74 cA	9.31 cA
Brd	5.08 bB	12.05 bA	14.50 bA
SSB	3.40 cB	8.06 cA	9.70 cA
Inc	10.83 aB	25.71 aA	30.91 aA
Fifth-leaf			
No	5.28 bB	11.27 bA	19.43 bA
Brd	12.06 aB	21.82 aAB	24.80 abA
SSB	15.61 aB	22.64 aA	26.66 abA
Inc	9.51 abB	25.51 aA	35.95 aA
Silking			
No	2.99 aA	3.42 bA	3.99 bA
Brd	4.16 aA	4.58 bA	7.96 bA
SSB	4.34 aA	6.69 abA	9.56 bA
Inc	3.66 aB	15.41 aA	28.59 aA
Milk			
No	2.72 bA	3.13 bA	3.30 bA
SSB	4.36 aA	5.01 aA	5.29 aA
Maturity			
No	2.97 aA	2.73 aA	6.91 bA
Brd	4.73 aA	2.67 aA	6.79 bA
SSB	4.43 aA	7.44 aA	8.92 abA
Inc	2.21 aB	7.81 aAB	28.90 aA

Table 5.7 Profile soil inorganic nitrogen (IN) concentrations by growth stage, cover crop residue type, and pelletized poultry litter (PPL) treatment in 2013. Estimates were calculated using the mean soil profile IN concentration predictions of three replicates for each treatment. Different lowercase letters indicate significant differences among PPL treatments within the same cover crop residue and growth stage (*P*<0.05). Different uppercase letters indicate significant differences among residues within the same PPL treatment and growth stage (*P*<0.05).

	Soil inorganic N, mg kg^{-1}		
PPL	Cereal rye	Mixture	Hairy vetch
Emergence			
No	3.53 cB	4.22 cB	12.66 cA
Brd	5.16 bB	6.27 bB	18.51 bA
SSB	3.60 cB	4.31 cB	12.92 cA
Inc	7.57 aB	9.05 aB	27.13 aA
Fifth-leaf			
No	4.39 bA	4.48 bA	6.75 cA
Brd	4.73 bB	6.46 abAB	8.33 bcA
SSB	12.05 aA	9.56 aA	14.38 aA
Inc	4.56 bB	4.87 bB	11.11 abA
Silking			
No	2.90 bA	2.29 bA	3.13 bA
Brd	3.16 bA	2.48 bA	3.40 bA
SSB	5.57 aA	5.10 aA	6.98 aA
Inc	3.81 bA	3.00 bA	4.11 aA
Milk			
No	3.22 aA	3.60 aA	2.89 bA
SSB	4.48 aA	3.85 aA	5.28 aA
Maturity			
No	5.66 aA	5.59 aA	5.92 aA
Brd	5.18 aA	5.11 aA	5.41 aA
SSB	6.18 aA	6.10 aA	6.46 aA
Inc	5.11 aA	5.05 aA	5.34 aA

Table 5.8 The NO_3^--N proportion (NP) of total inorganic nitrogen (IN) by growth stage, cover crop residue type, pelletized poultry litter (PPL) treatment, and depth class in 2012. Means of three interactions within each growth stage are presented: residue type x PPL treatment, PPL treatment x depth class, and residue type x depth class. Different lowercase letters indicate significant differences among values in the same column within each of these interactions ($P<0.05$). Different uppercase letters indicate significant differences among values in the same row within each of these interactions ($P<0.05$). For the subsurface band treatment, the NP was often significantly different in the band than away from the band, so values from within the band (rows labeled "In") are presented separately from NP means for the entire profile (rows labeled "SSB"), and "In" values are bolded where the mean in the band differs from the mean of the overall profile (listed directly above).

		----------- Cover crop residue ------------			------------------------------ Depth class ------------------------------		
PPL	Residue	Cereal rye	Mixture	Hairy vetch	Surface (0-10 cm)	Mid (10-20 cm)	Deep (20-30 cm)
				Emergence			
No		0.14 bC	0.40 cB	0.71 bA	0.52 bA	0.41 cA	0.26 cB
Brd		0.59 aB	0.69 bAB	0.78 bA	0.80 aA	0.64 bB	0.61 bB
SSB		0.24 bB	0.59 bcA	0.69 bA	0.64 bA	0.51 bcB	0.35 cC
Inc		0.72 aB	0.88 aA	0.92 aA	0.86 aA	0.88 aA	0.82 aA
	Rye				0.45 cA	0.40 bAB	0.34 cB
	Mixture				0.78 bA	0.70 aA	0.49 bB
	Vetch				0.86 aA	0.77 aB	0.72 aB
				Fifth-leaf			
No		0.58 abB	0.77 bcA	0.82 bcA	0.79 bA	0.73 bcAB	0.67 aB
Brd		0.67 aB	0.85 aA	0.88 bA	0.90 aA	0.80 abB	0.71 aC
SSB		0.54 bB	0.75 cA	0.78 cA	0.74 bA	0.69 cAB	0.66 aB
In		**0.17**	**0.18**	**0.15**			
Inc		0.61 abC	0.84abB	0.92 aA	0.88 aA	0.83 aB	0.74 aC
	Rye				0.67 cA	0.59 cB	0.55 cB
	Mixture				0.87 bA	0.80 bB	0.73 bC
	Vetch				0.90 aA	0.86 aB	0.79 aC
				Silking			
No		0.26 aB	0.39 bcAB	0.54 abA	0.38 abA	0.38 abA	0.41 abA
Brd		0.16 abB	0.23 cB	0.52 bA	0.31 bA	0.28 bA	0.27 bA
SSB		0.35 aB	0.52 abAB	0.69 abA	0.50 aA	0.52 aA	0.55 aA

In	**0.66**	0.64	0.66			
Inc	0.08 bB	0.67 aA	0.77 aA	0.52 aA	0.53 aA	0.33 bB
Rye				0.23 cA	0.17 cB	0.17 cB
Mixture				0.45 bA	0.47 bA	0.42 bA
Vetch				0.62 aA	0.68 aA	0.61 aA
---------- Milk ----------						
No	0.45 aA	0.42 aA	0.48 aA	0.43 aB	0.43 aB	0.49 aA
SSB	0.47 aA	0.45 aA	0.51 aA	0.46 aB	0.45 aB	0.52 aA
In	**0.62**	**0.67**	**0.75**			
Rye				0.44 aB	0.44 aB	0.50 aA
Mixture				0.42 aB	0.41 aB	0.48 aA
Vetch				0.48 aB	0.47 aB	0.54 aA
---------- Maturity ----------						
No	0.22 bB	0.44 bA	0.39 bA	0.43 bA	0.31 bA	0.29 bA
Brd	0.26 bB	0.50 bA	0.44 bA	0.51 abA	0.37 bAB	0.31 bB
SSB	0.31 bB	0.55 bA	0.50 bA	0.51 abA	0.45 bA	0.39 bA
In	0.47	0.70	0.68			
Inc	0.63 aB	0.83 aA	0.79 aA	0.66 aB	0.82 aA	0.78 aAB
Rye				0.38 bA	0.36 bAB	0.31 bB
Mixture				0.63 aA	0.60 aAB	0.55 aB
Vetch				0.58 aA	0.55 aAB	0.50 aB

Table 5.9 The NO_3^--N proportion (NP) of total inorganic nitrogen (IN) by growth stage, cover crop residue type, pelletized poultry litter (PPL) treatment, and depth class in 2013. Means of three interactions within each growth stage are presented: residue type x PPL treatment, PPL treatment x depth class, and residue type x depth class. Different lowercase letters indicate significant differences among values in the same column within each of these interactions ($P<0.05$). Different uppercase letters indicate significant differences among values in the same row within each of these interactions ($P<0.05$). For the subsurface band treatment, the NP was often significantly different in the band than away from the band, so values from within the band (rows labeled "In") are presented separately from NP means for the entire profile (rows labeled "SSB"), and "In" values are bolded where the mean in the band differs from the mean of the overall profile (listed directly above).

		-------- Cover crop residue --------------			-------------------------- Depth class --------------------------		
PPL	Residue	Cereal rye	Mixture	Hairy vetch	Surface (0-10 cm)	Mid (10-20 cm)	Deep (20-30 cm)
Emergence							
No		0.43 bB	0.53 bB	0.73 bA	0.70 bA	0.63 bcA	0.37 aB
Brd		0.59 aB	0.69 aB	0.84 aA	0.85 aA	0.76 abA	0.49 aB
SSB		0.41 bB	0.52 bB	0.72 bA	0.70 bA	0.57 cA	0.38 aB
Inc		0.61 aB	0.71 aB	0.86 aA	0.88 aA	0.79 aB	0.45 aC
	Rye				0.69 bA	0.56 bB	0.29 bC
	Mixture				0.77 bA	0.66 bB	0.39 bC
	Vetch				0.89 aA	0.83 aB	0.60 aC
Fifth-leaf							
No		0.60 aA	0.61 aA	0.68 abA	0.63 abA	0.63 abA	0.63 abA
Brd		0.50 aB	0.58 aAB	0.75 abA	0.62 abA	0.62 abA	0.62 abA
SSB		0.56 aA	0.53 aA	0.59 bA	0.56 bA	0.56 bA	0.56 bA
In		**0.03**	**0.02**	**0.03**			
Inc		0.55 aB	0.62 aB	0.80 aA	0.66 aA	0.66 aA	0.66 aA
	Rye				0.59 aA	0.56 bA	0.50 bA
	Mixture				0.62 aA	0.57 bA	0.57 bA
	Vetch				0.65 aB	0.72 aAB	0.76 aA
Silking							
No		0.20 cB	0.25 cAB	0.32 cA	0.34 bA	0.21 bB	0.22 aB
Brd		0.24 bcB	0.29 bcAB	0.37 bcA	0.39 bA	0.30 abAB	0.22 aB
SSB		0.40 aB	0.47 aAB	0.56 aA	0.52 aA	0.42 aA	0.48 aA

In		**0.19**	**0.29**	**0.31**			
Inc		0.33 abB	0.39 abAB	0.47 abA	0.43 abA	0.44 aA	0.32 aA
	Rye				0.35 bA	0.27 bB	0.24 bB
	Mixture				0.42 abA	0.33 abB	0.30 abB
	Vetch				0.50 aA	0.41 aB	0.37 aB
---------- Milk ----------							
No		0.37 aA	0.38 aA	0.36 bA	0.40 bA	0.37 bAB	0.34 bB
SSB		0.40 aB	0.43 aB	0.59 aA	0.50 aA	0.47 aAB	0.45 aB
In		**0.21**	0.36	0.68			
	Rye				0.41 aA	0.38 aAB	0.36 aB
	Mixture				0.43 aA	0.40 aAB	0.38 aB
	Vetch				0.50 aA	0.47 aAB	0.45 aB
---------- Maturity ----------							
No		0.34 aA	0.50 aA	0.44 aA	0.57 aA	0.46 aA	0.26 aB
Brd		0.37 aA	0.53 aA	0.47 aA	0.61 aA	0.49 aA	0.27 aB
SSB		0.39 aA	0.55 aA	0.50 aA	0.63 aA	0.46 aB	0.35 aB
In		0.36	0.38	0.39			
Inc		0.40 aA	0.56 aA	0.50 aA	0.56 aA	0.58 aA	0.32 aB
	Rye				0.50 aA	0.42 aA	0.23 bB
	Mixture				0.63 aA	0.47 aAB	0.44 aB
	Vetch				0.65 aA	0.54 aB	0.25 bC

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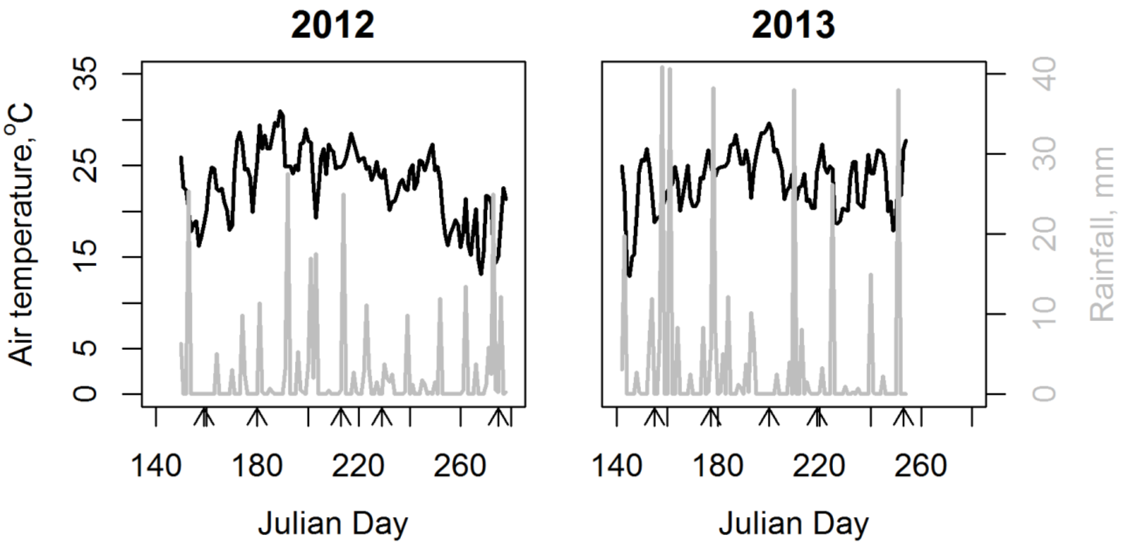


Figure 5.1 Average daily air temperature (black lines) and daily total rainfall (grey lines) in 2012 and 2013 corn growing seasons at Beltsville, MD. Arrows along the x axis indicate soil sampling dates.

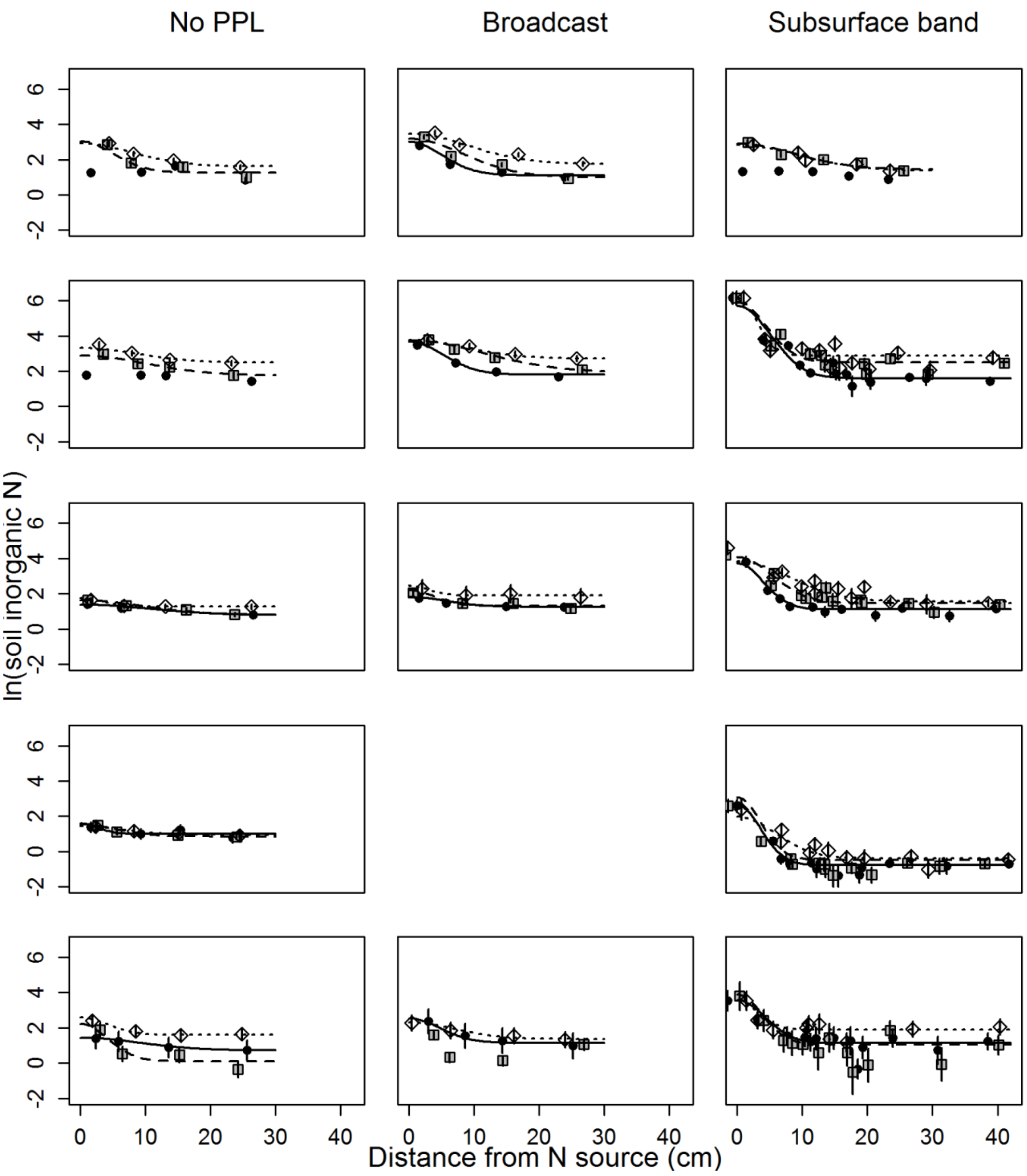


Figure 5.2 Natural log of soil inorganic nitrogen (IN) concentration as a function of Euclidean distance from IN source at five growth stages in 2012 (top to bottom: corn emergence, fifth-leaf, silking, milk, maturity). Inorganic N source is the soil surface for no pelletized poultry litter (PPL) and broadcast treatments, and PPL band for subsurface band treatments. Solid lines, dashed lines and dotted lines represent diffusion/dispersion equations fitted to cereal rye, mixture, and hairy vetch treatments, respectively. Black circles, grey squares and white diamonds represent the means of the natural logs of soil IN concentrations for the cereal rye, mixture and hairy vetch treatments, respectively. 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 distances between 25 and 27, and 38 and 42 were pooled in calculating plotted means and standard errors.

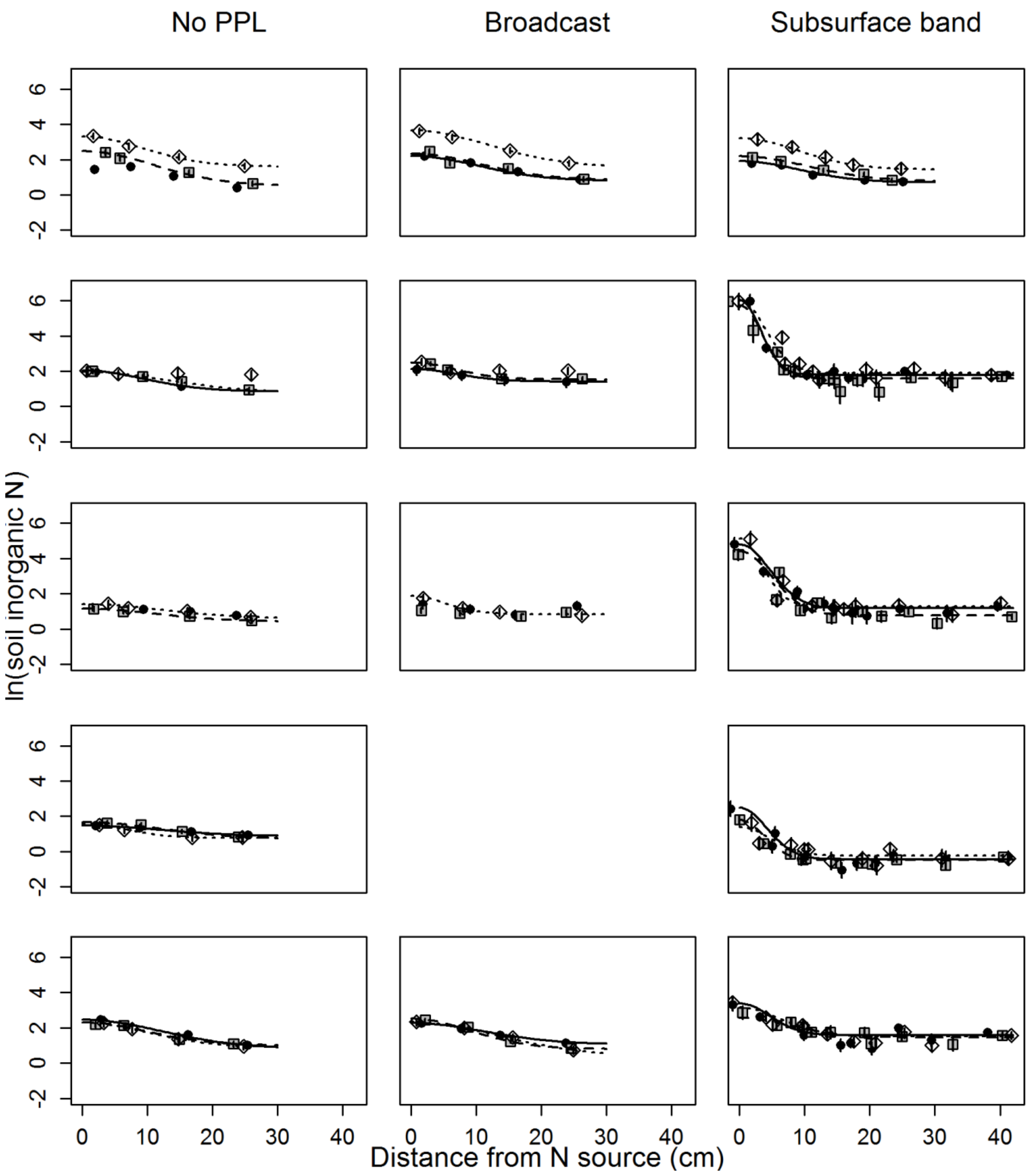


Figure 5.3 Natural log of soil inorganic nitrogen (IN) concentration as a function of Euclidean distance from IN source at five growth stages in 2013 (top to bottom: corn emergence, fifth-leaf, silking, milk, maturity). Inorganic N source is the soil surface for no pelletized poultry litter (PPL) and broadcast treatments, and PPL band for subsurface band treatments. Solid lines, dashed lines and dotted lines represent diffusion/dispersion equations fitted to cereal rye, mixture, and hairy vetch treatments, respectively. Black circles, grey squares and white diamonds represent the means of the natural logs of soil IN concentrations for the cereal rye, mixture and hairy vetch treatments, respectively. 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 distances between 25 and 27, and 38 and 42 were pooled in calculating plotted means and standard errors.

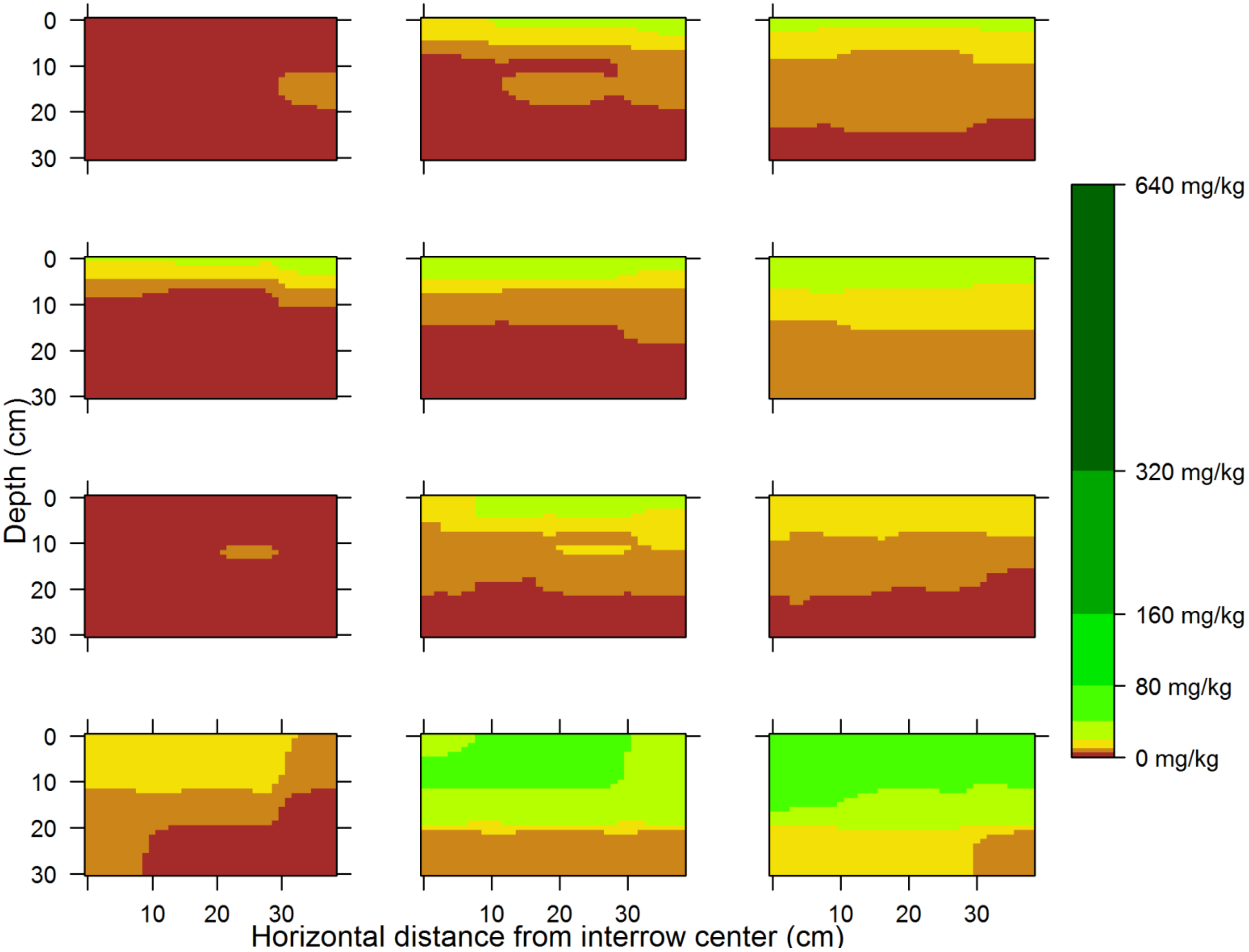


Figure 5.4 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn emergence in 2012 for four pelletized poultry litter (PPL) treatments (top to bottom: no PPL, broadcast PPL, subsurface band, incorporated PPL) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

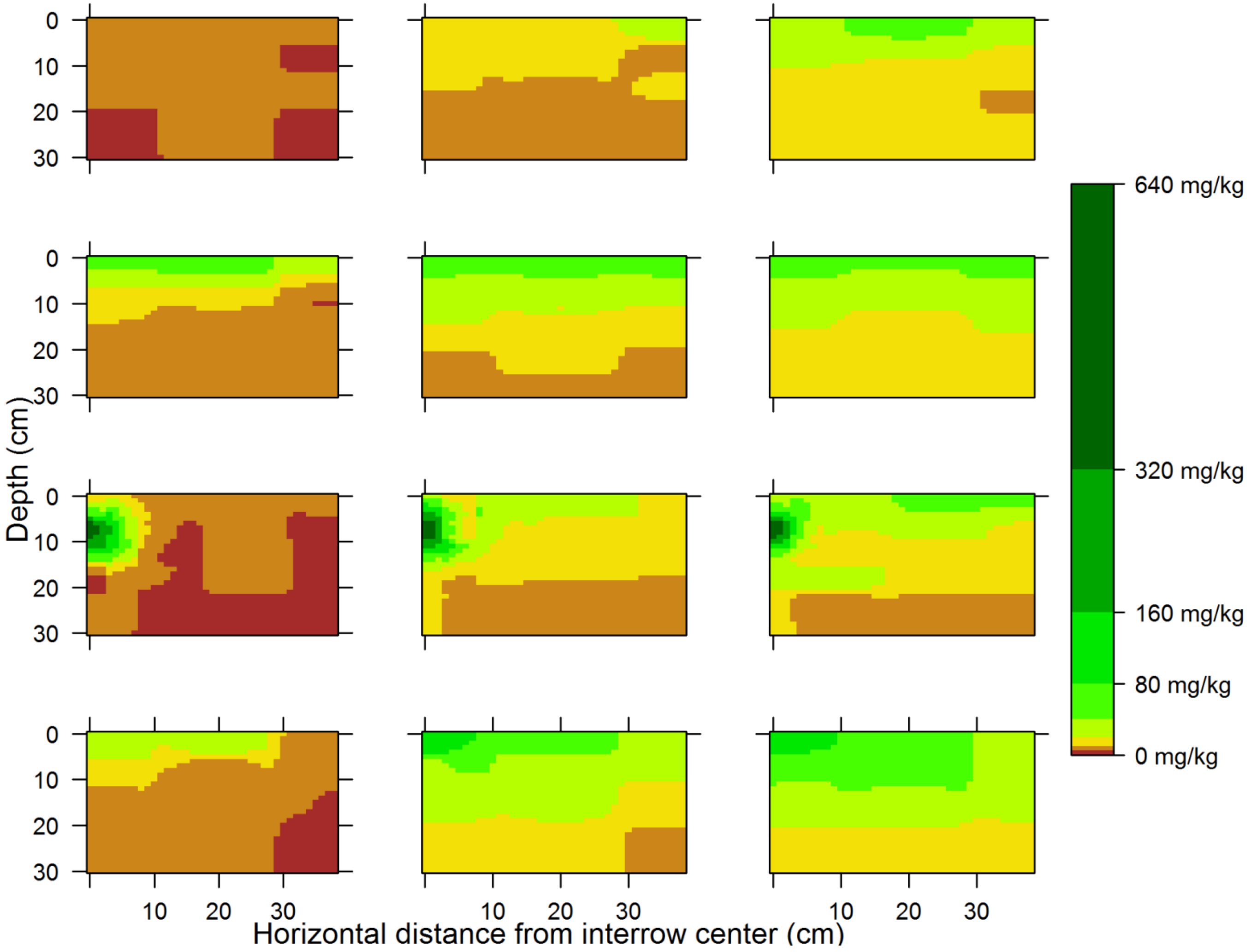


Figure 5.5 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn fifth-leaf stage in 2012 for four pelletized poultry litter (PPL) treatments (top to bottom: no PPL, broadcast PPL, subsurface band, incorporated PPL) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

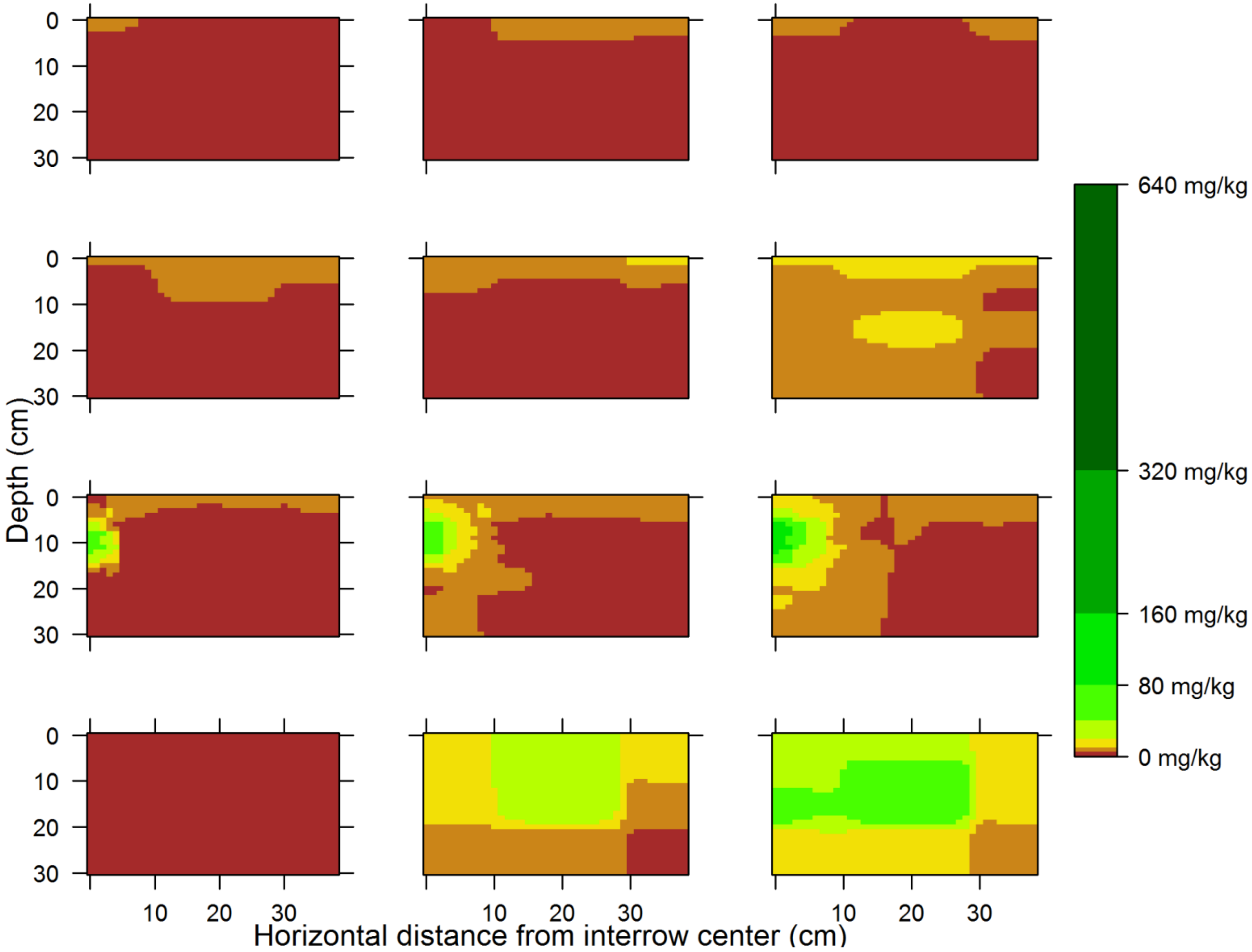


Figure 5.6 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn silking stage in 2012 for four pelletized poultry litter (PPL) treatments (top to bottom: no PPL, broadcast PPL, subsurface band, incorporated PPL) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

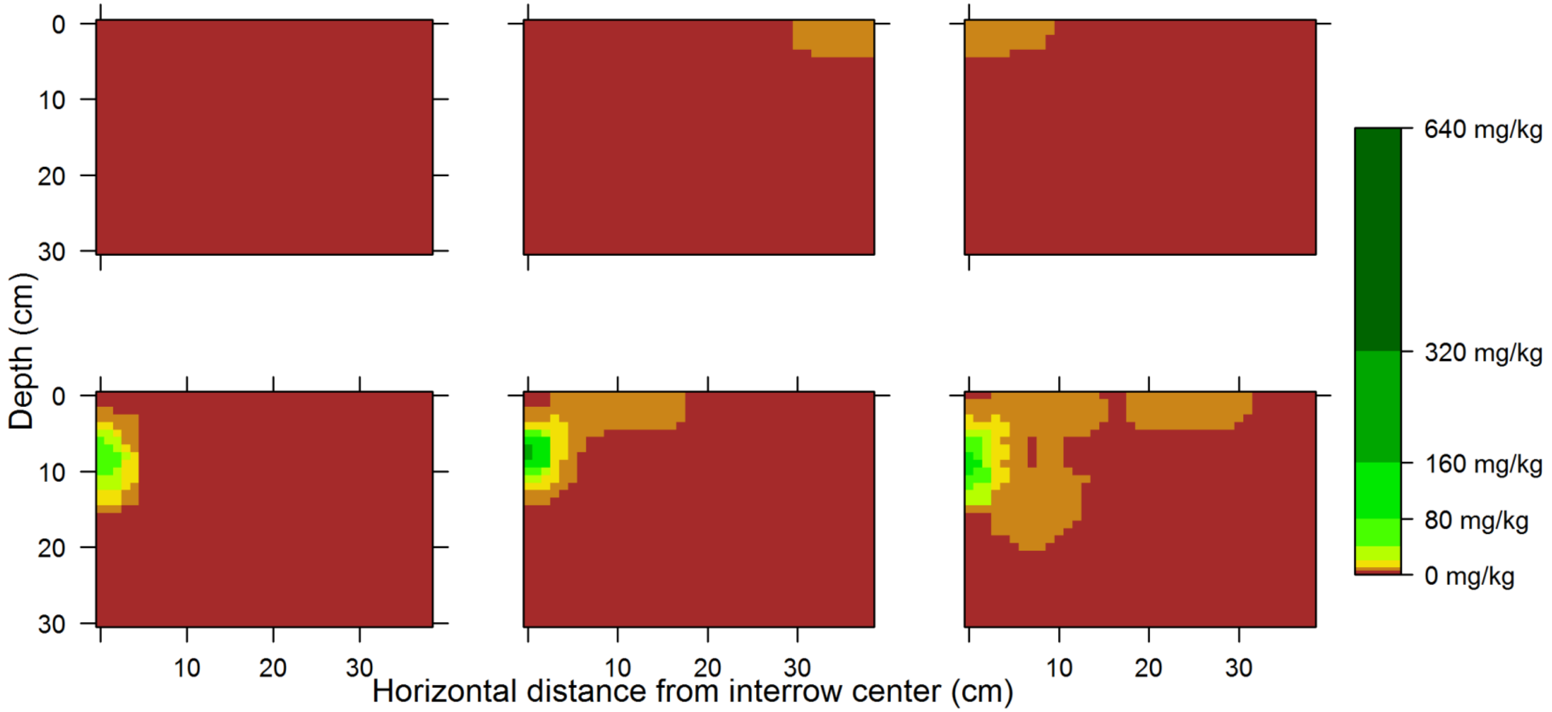


Figure 5.7 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn milk stage in 2012 for two pelletized poultry litter (PPL) treatments (top: no PPL; bottom: subsurface band) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

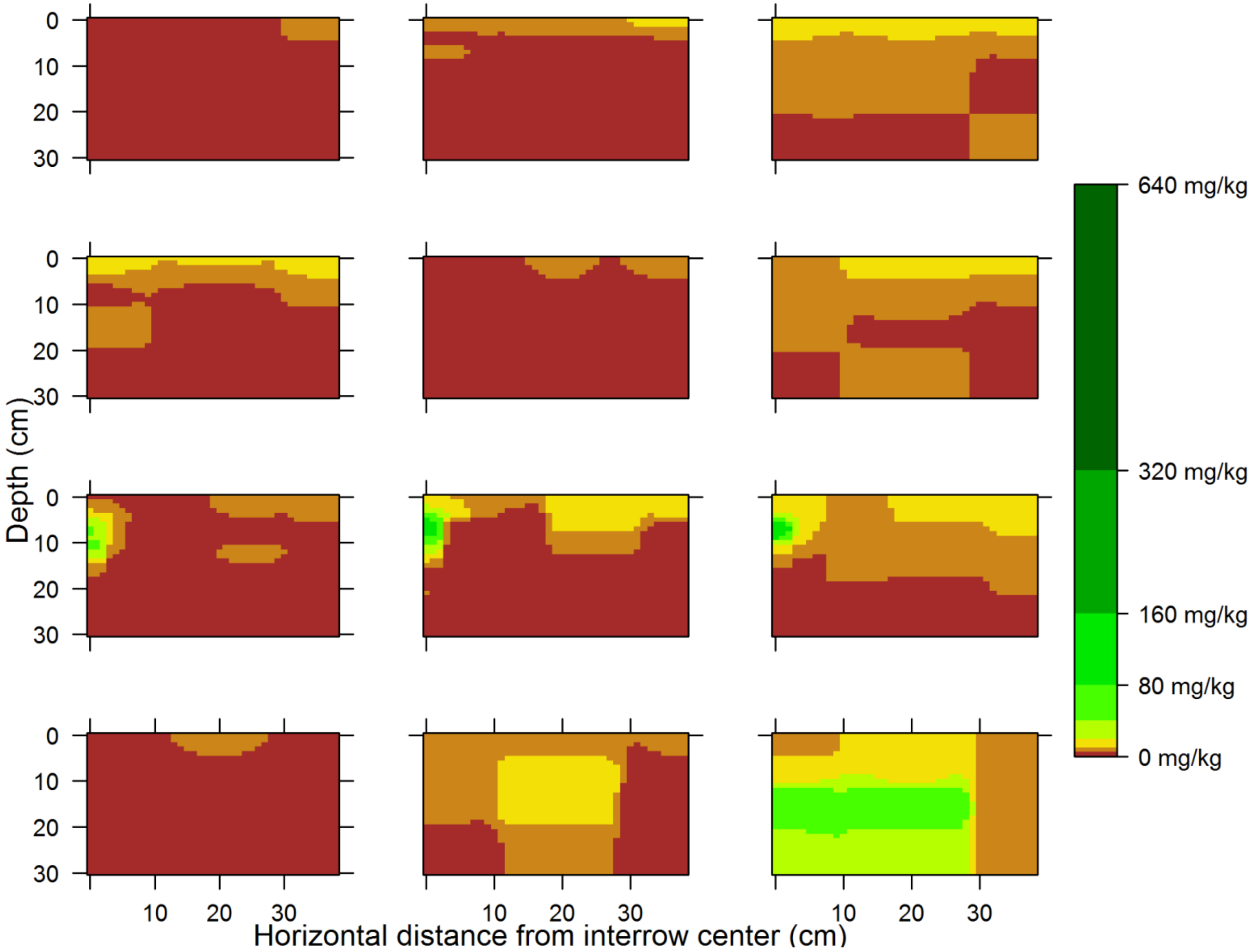


Figure 5.8 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn maturity in 2012 for four pelletized poultry litter (PPL) treatments (top to bottom: no PPL, broadcast PPL, subsurface band, incorporated PPL) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

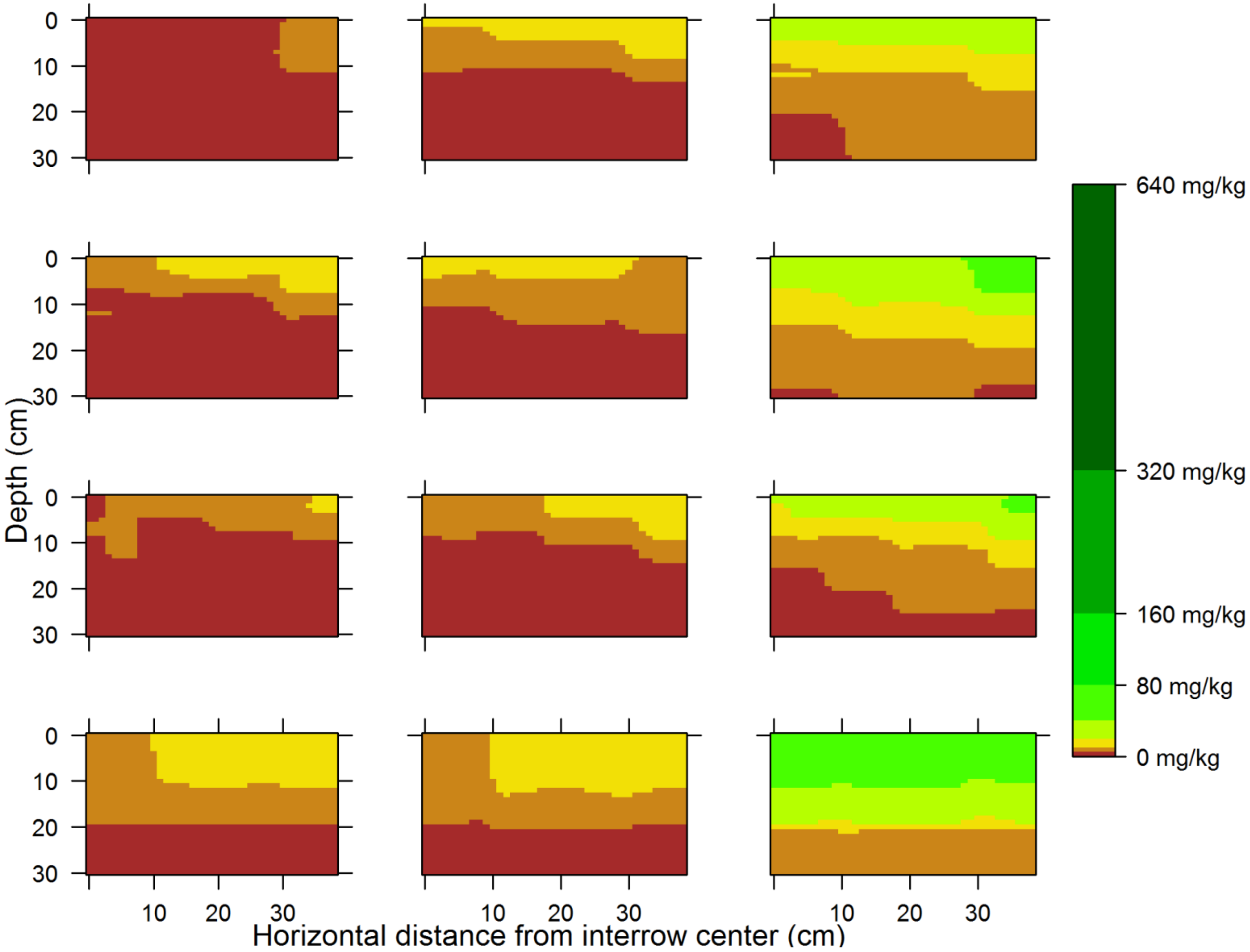


Figure 5.9 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn emergence in 2013 for four pelletized poultry litter (PPL) treatments (top to bottom: no PPL, broadcast PPL, subsurface band, incorporated PPL) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

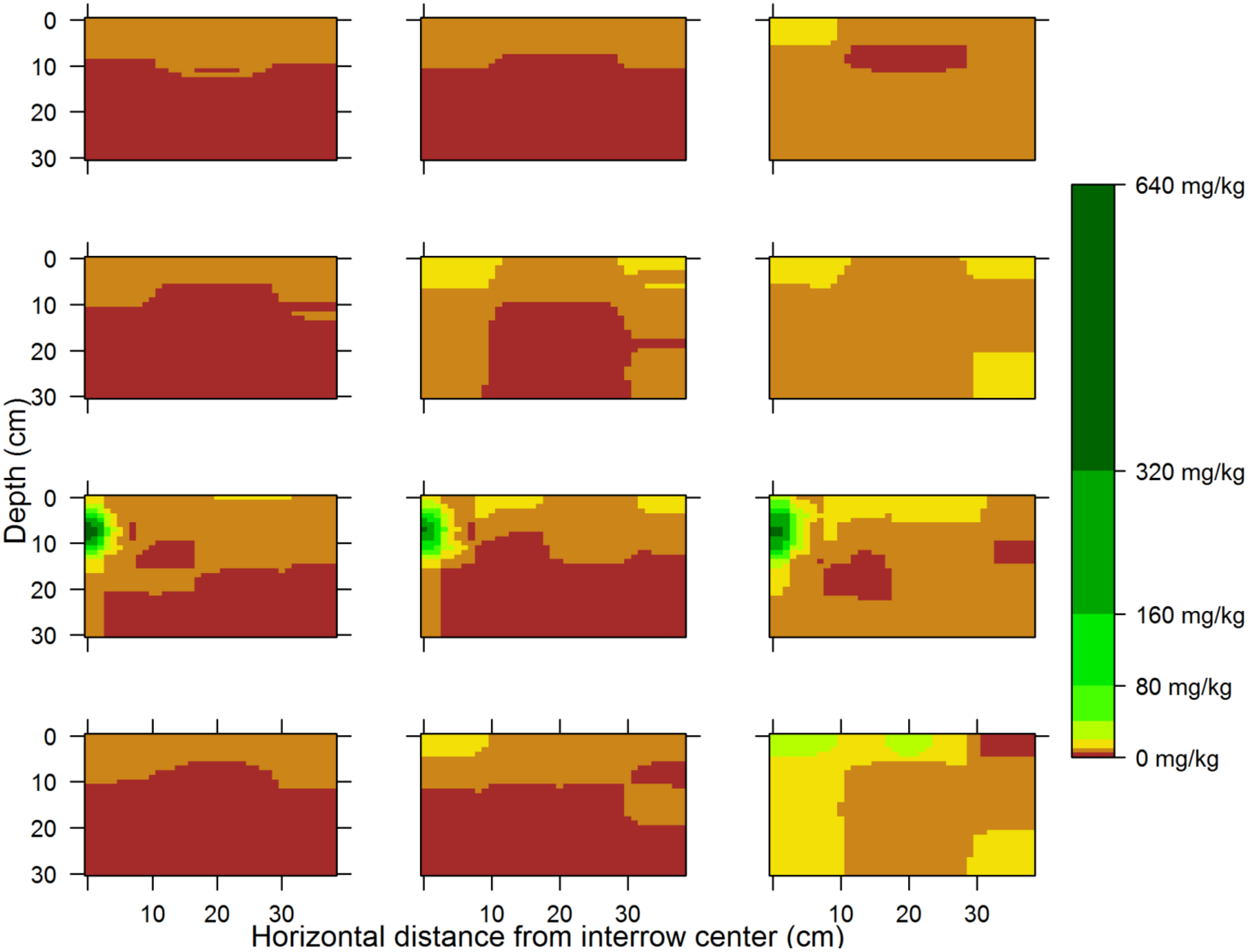


Figure 5.10 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn fifth-leaf stage in 2013 for four pelletized poultry litter (PPL) treatments (top to bottom: no PPL, broadcast PPL, subsurface band, incorporated PPL) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

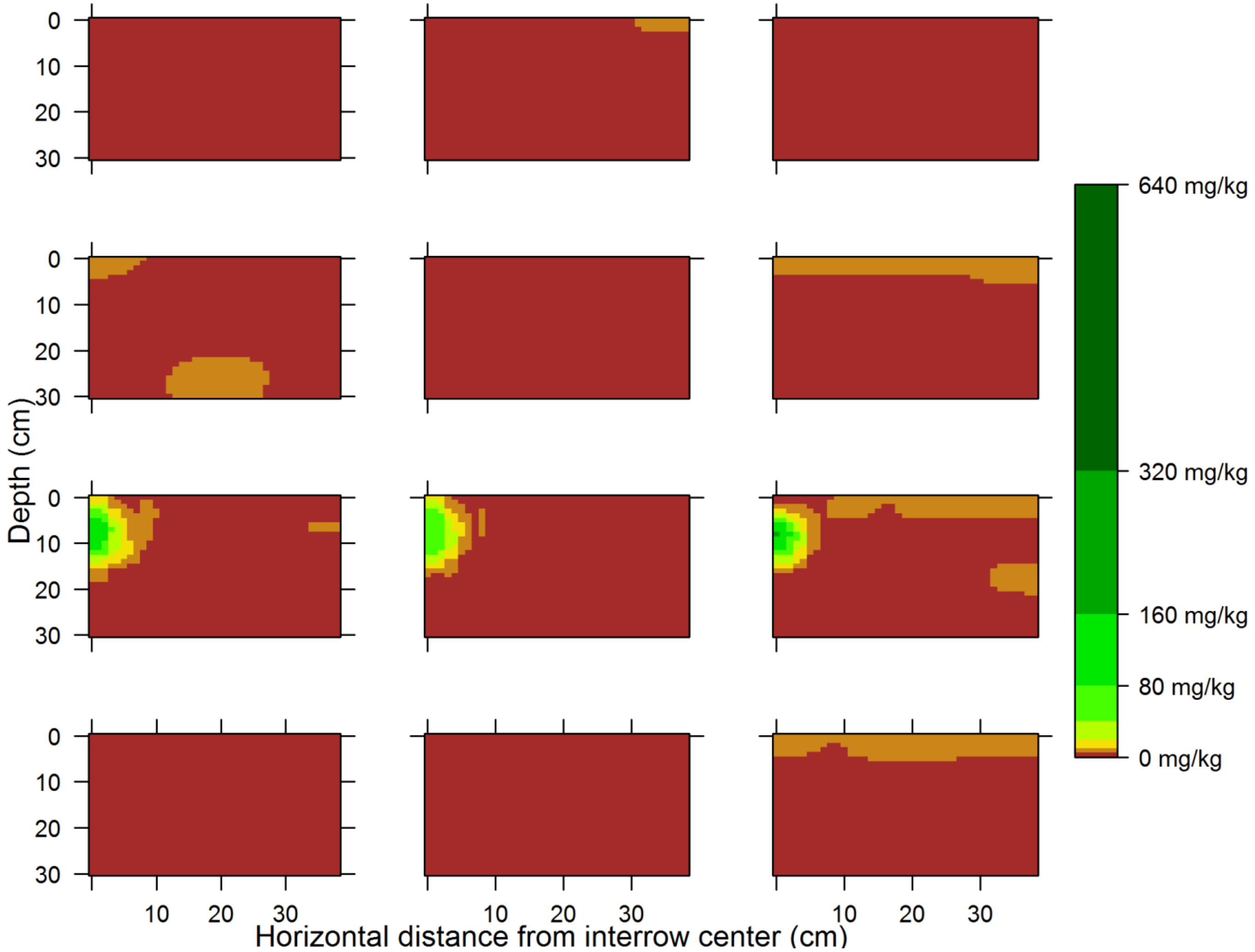


Figure 5.11 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn silking stage in 2013 for four pelletized poultry litter (PPL) treatments (top to bottom: no PPL, broadcast PPL, subsurface band, incorporated PPL) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

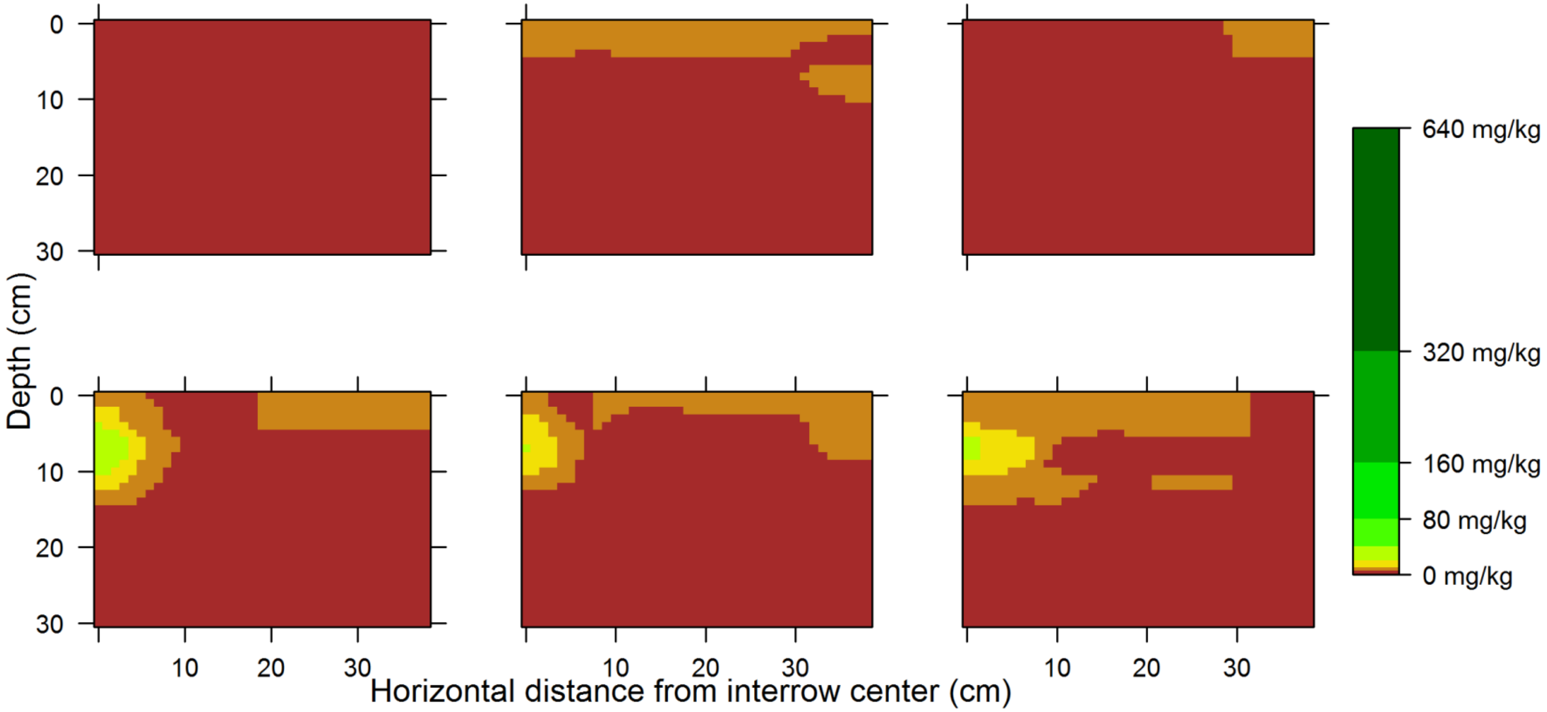


Figure 5.12 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn milk stage in 2013 for two pelletized poultry litter (PPL) treatments (top: no PPL; bottom: subsurface band) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

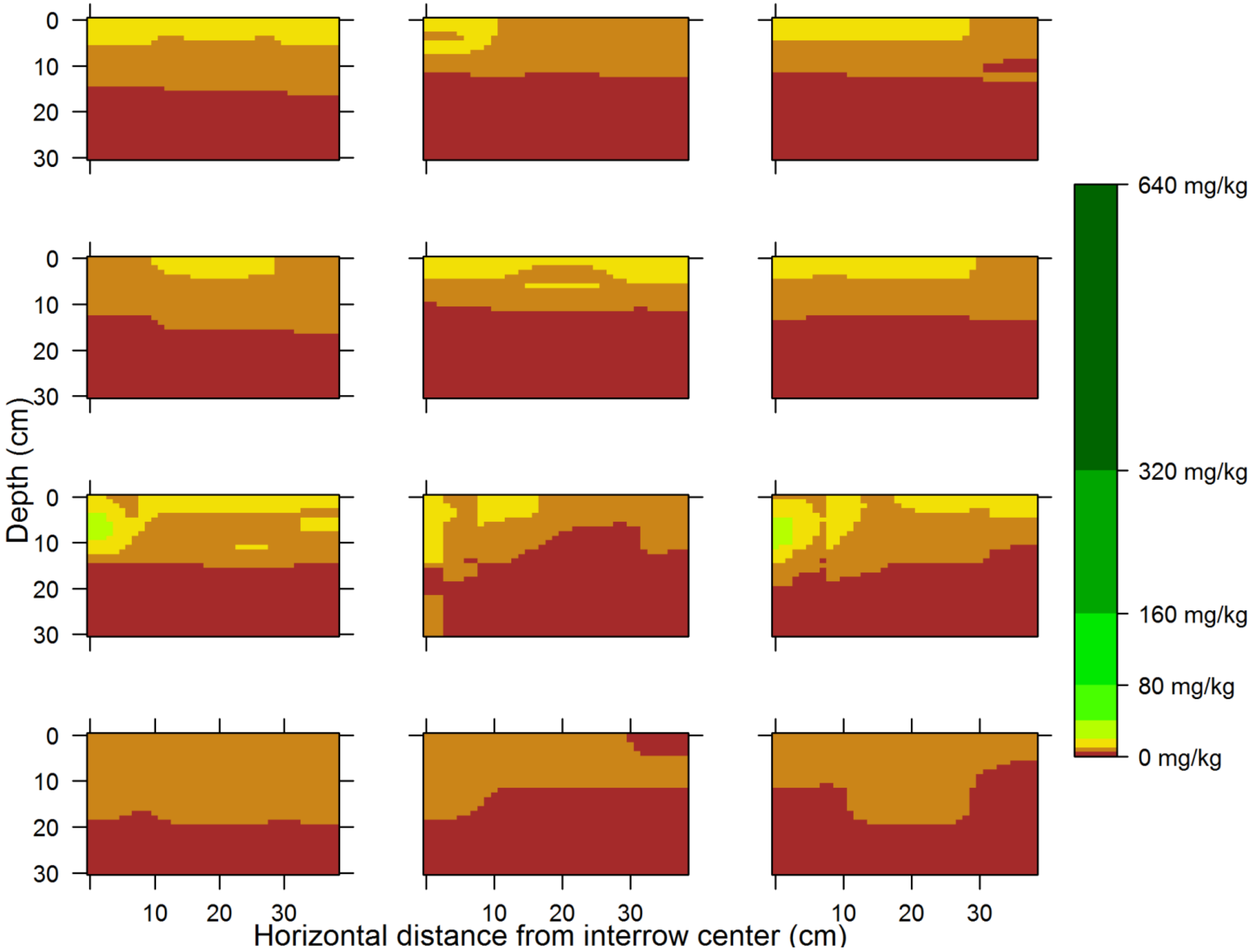


Figure 5.13 Spatial distribution of soil inorganic nitrogen (IN) concentration at corn maturity in 2013 for four pelletized poultry litter (PPL) treatments (top to bottom: no PPL, broadcast PPL, subsurface band, incorporated PPL) and three cover crop treatments (left: cereal rye; middle: hairy vetch/cereal rye mixture; right: hairy vetch).

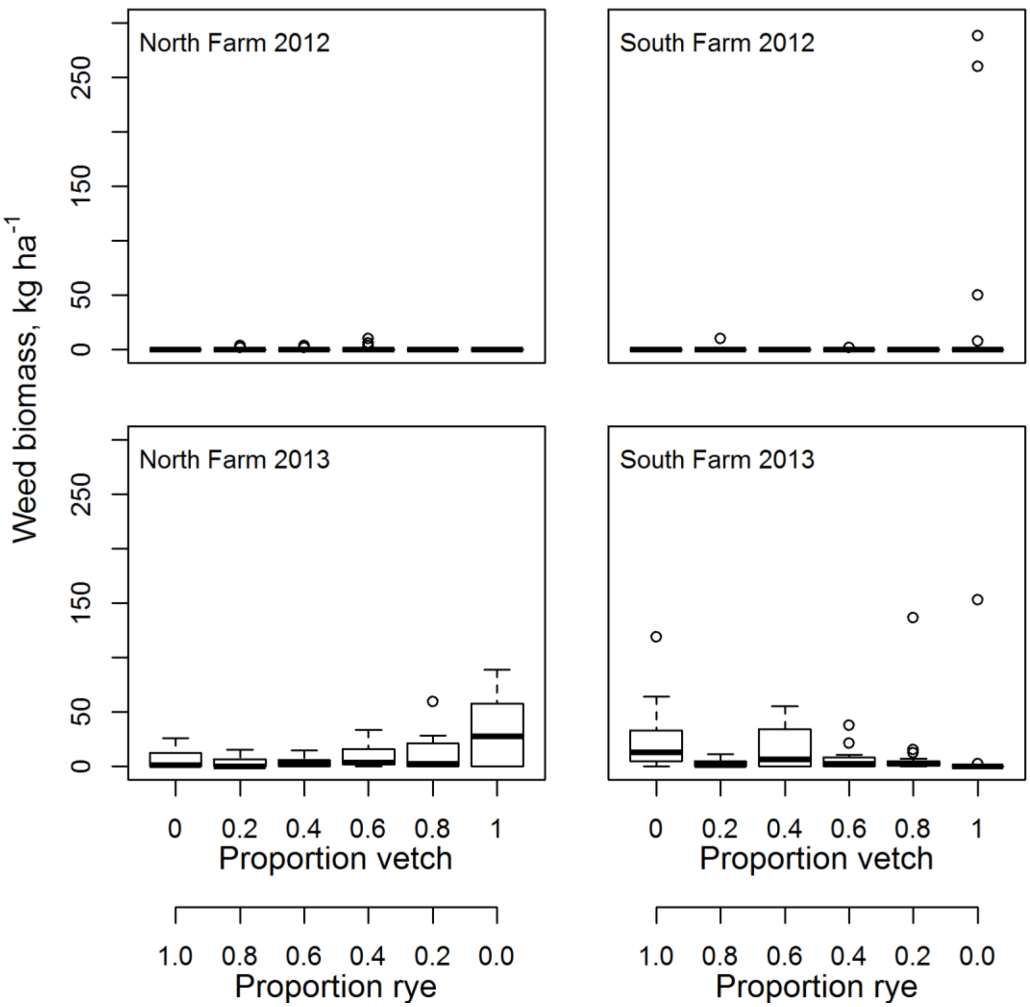
Chapter 6 Conclusions and recommendations

The overarching goal of this study was to improve nitrogen (N) use efficiency in cover crop-based no-till corn production. I evaluated two approaches: hairy vetch/cereal rye cover crop mixtures and sidedress subsurface band pelletized poultry litter (PPL) application. Cover crop mixtures were generally more efficient in biomass production and N accumulation than monocultures. The high biomass production and moderate decomposition rates of mixtures make them an excellent tool to balance ecological weed management and N release relative to monocultures in no-till corn. In most years, a relatively low cereal rye seeding rate (34 kg ha^{-1}) was required to achieve > 8 Mg ha^{-1}, but optimal N accumulation required a relatively high hairy vetch seeding rate (27 kg ha^{-1}). However, substantial variability in proportional compositions among site-years suggests that the proportions of each species in mixture cannot be consistently predicted by cover crop seeding rate. Thus, I recommend that, at least for now, producers growing hairy vetch/cereal rye mixtures obtain an estimate of cover crop biomass and proportional composition in the spring prior to planting to inform management decisions. These data can inform weed suppression potential, total N content and the proportion of N that will be released by the mixture using models developed in this thesis and by other researchers.

The decomposition study revealed several key findings related to residue persistence and N release. First, despite large differences in moisture conditions between the two years, cumulative proportional mass and N losses at each cover crop species proportion were, for practical purposes, very similar. Based on the cumulative proportional mass loss estimates between years, it seems reasonable to assume that greater than 50% of cereal rye biomass and greater than 20% of hairy vetch biomass will persist as a mulch during the corn growing season. However, the proportion remaining at any given time during the growing season was largely dependent on conditions each year. A small proportion of hairy vetch mixed with cereal rye residue increased the cumulative proportional N loss dramatically, and our findings suggest that a mixture with only 20% hairy vetch residue by weight can release up to 50% of its N during a corn growing season. A residue with greater than 50% hairy vetch can be expected to release 75-85% of its N. Regardless of species proportions, the majority of the cumulative proportional N losses occurred before the sixth-leaf growth stage in corn. Soil inorganic N data from 2013 suggest that, in a wet year, the N lost from cover crop residues was susceptible to losses.

Based on the two site-years of soil inorganic N data collected, the subsurface band PPL application at sidedress appears to be an efficient N delivery method relative to broadcast application and incorporation. The broadcast application method is known to cause N losses through NH_3 volatilization. We also found evidence of early-season N losses in the broadcast PPL treatment, particularly with the hairy vetch cover crop. Incorporating hairy vetch residues and PPL facilitated rapid N mineralization, and this inorganic N was susceptible to early-season losses in a wet year, and post-harvest losses in a dry year. Delaying PPL application until sidedress avoided the early-season losses that occurred prior to corn uptake. The combination of cereal rye + sidedress subsurface band PPL application seems to be the most efficient for N delivery to corn and maintains the most persistent mulch cover. However, this treatment would require a greater PPL rate, and possibly additional starter PPL, to meet corn N needs. Increasing the PPL application rate would increase P loading and increase the amount of denitrification losses from the PPL band. Thus, I recommend using a cover crop mixture with sidedress subsurface band PPL application. For best results, PPL rates should be based on estimates of cover crop N release using measured properties.

Appendices



Appendix 1: Weed biomass in hairy vetch/cereal rye cover crops
Weed biomass in response to sown proportions of hairy vetch and cereal rye for four site-years in Beltsville, MD. The top and bottom of each box represents the upper and lower quartile; the line within each box represents the median. The ends of the whiskers represent the lowest datum still within 1.5x the interquartile range of the lower quartile, and the highest datum still within 1.5x the interquartile range of the upper quartile.

Appendix 2: Exponential decay parameter estimates and half lives

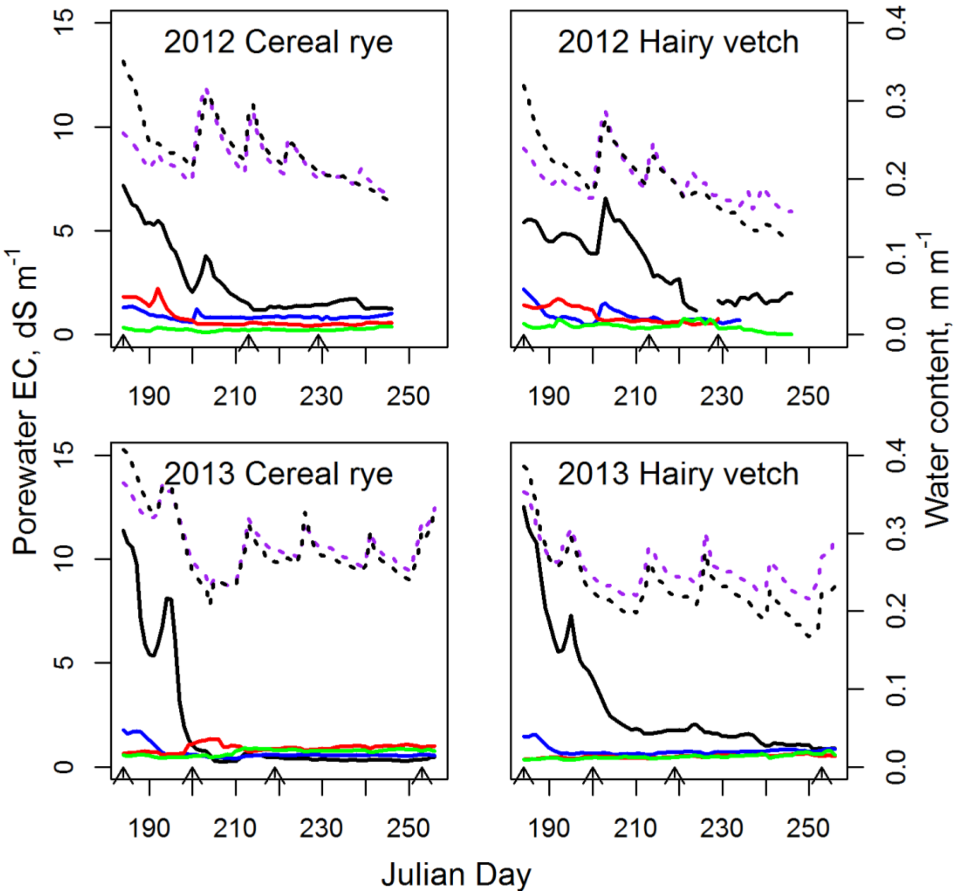
Table A2.1 Exponential decay parameter estimates, half-lives and coefficients of determination for each hairy vetch/cereal rye (HV/CR) cover crop proportion and pelletized poultry litter (PPL) treatment in 2012. Predicted proportional loss estimates presented below were made by fitting the asymptotic exponential function to each cover crop proportion x PPL treatment x year subset. All parameter estimates are significantly different than zero (P<0.05) unless indicated with italicized font.

HV/CR	Proportional mass loss	Mass decay constant, soil GDD^{-1} (x 10^{-3})	Mass $t_{1/2}$, soil GDD	Mass decay R^2	Proportional N loss	N decay constant soil GDD^{-1} (x 10^{-3})	N $t_{1/2}$, soil GDD	N decay R^2
---------- No PPL ----------								
0/1	*0.89(0.514)*	*0.18(0.13)*	4563	0.93				
0.21/0.79	0.75(0.204)	0.39(0.16)	2838	0.91	0.42(0.054)	1.23(0.43)		0.74
0.43/0.57	0.68(0.060)	0.72(0.13)	1837	0.96	0.62(0.021)	2.72(0.37)	604	0.95
0.67/0.33	0.72(0.053)	0.89(0.15)	1335	0.95	0.72(0.034)	1.63(0.24)	727	0.93
1/0	0.77(0.032)	1.17(0.13)	893	0.97	0.78(0.026)	2.18(0.25)	470	0.96
---------- Subsurface band ----------								
0/1	*1.00†*	0.14(0.01)	4933	0.96				
0.21/0.79	0.79(0.263)	0.29(0.13)	3454	0.93	0.55(0.042)	1.15(0.43)	2085	0.90
0.43/0.57	0.84(0.152)	0.45(0.13)	2006	0.94	0.62(0.034)	2.36(0.52)	696	0.88
0.67/0.33	0.65(0.029)	1.17(0.14)	1250	0.97	0.70(0.024)	2.69(0.33)	466	0.95
1/0	0.75(0.047)	1.22(0.20)	900	0.93	0.77(0.026)	3.09(0.43)	339	0.94
---------- Broadcast ----------								
0/1	*1.00†*	0.23(0.01)	3072	0.95	0.46(0.050)	1.51(0.50)		0.75
0.21/0.79	0.62(0.092)	0.70(0.21)	2356	0.88	0.54(0.032)	4.48(1.40)	581	0.82
0.43/0.57	0.79(0.072)	0.75(0.15)	1344	0.95	0.57(0.036)	2.42(0.56)	867	0.84
0.67/0.33	0.77(0.074)	0.84(0.20)	1243	0.92	0.65(0.026)	3.19(0.53)	460	0.92
1/0	0.76(0.017)	1.38(0.09)	780	0.99	0.74(0.019)	2.26(0.21)	498	0.97
---------- Incorporated ----------								
0/1	0.80(0.207)	0.42(0.18)	2348	0.90				
0.22/0.78	0.71(0.059)	1.23(0.29)	993	0.90	0.45(0.023)	2.67(0.55)		0.91
0.39/0.61	0.75(0.047)	1.22(0.21)	901	0.93	0.62(0.026)	5.07(1.09)	324	0.90
0.64/0.36	0.73(0.021)	2.52(0.27)	458	0.97	0.73(0.019)	5.40(0.75)	214	0.96
1/0	0.75(0.028)	4.15(0.72)	265	0.92	0.83(0.023)	6.16(0.93)	150	0.96

†Proportional mass loss of 1 was added as a constant to achieve model convergence.

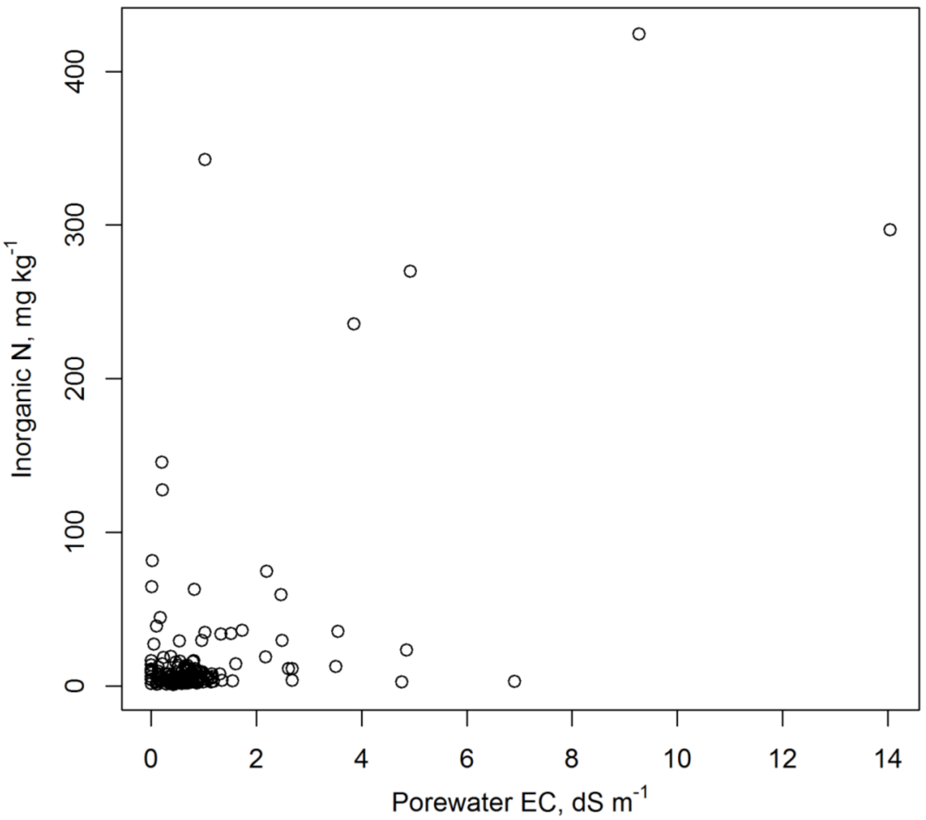
Table A2.2 Exponential decay parameter estimates, half-lives and coefficients of determination for each hairy vetch/cereal rye (HV/CR) cover crop proportion and pelletized poultry litter (PPL) treatment in 2013. Predicted proportional loss estimates presented below were made by fitting the asymptotic exponential function to each cover crop proportion x PPL treatment x year subset. All parameter estimates are significantly different than zero (*P*<0.05) unless indicated with italicized font.

HV/CR	Proportional mass loss	Mass decay constant, soil GDD^{-1} (x 10^{-3})	Mass $t_{1/2}$, soil GDD	Mass decay R^2	Proportional N loss	N decay constant soil GDD^{-1} (x 10^{-3})	N $t_{1/2}$, soil GDD	N decayR^2
No PPL								
0/1	0.45(0.022)	1.29(0.17)		0.98				
0.25/0.75	0.57(0.021)	1.56(0.17)	1346	0.97	0.59(0.022)	3.73(1.08)	504	0.80
0.50/0.50	0.64(0.026)	1.74(0.22)	872	0.96	0.71(0.021)	4.37(0.68)	279	0.96
0.75/0.25	0.72(0.025)	1.82(0.20)	652	0.97	0.78(0.016)	3.61(0.32)	284	0.98
1/0	0.76(0.016)	2.92(0.24)	367	0.98	0.80(0.013)	4.29(0.31)	229	0.99
Subsurface band								
0/1	0.55(0.045)	0.97(0.20)	2478	0.95				
0.25/0.75	0.59(0.030)	1.63(0.27)	1153	0.95	0.58(0.023)	4.51(0.83)	439	0.92
0.50/0.50	0.62(0.027)	2.08(0.31)	790	0.94	0.68(0.028)	4.25(0.78)	313	0.91
0.75/0.25	0.73(0.020)	2.40(0.23)	481	0.97	0.77(0.018)	3.70(0.37)	283	0.97
1/0	0.76(0.031)	3.12(0.51)	344	0.93	0.82(0.026)	3.50(0.45)	269	0.95
Broadcast								
0/1	0.58(0.022)	1.41(0.15)	1403	0.97	0.39(0.042)	3.65(1.67)		0.64
0.25/0.75	0.70(0.028)	1.61(0.19)	778	0.96	0.62(0.024)	3.50(0.57)	469	0.93
0.50/0.50	0.73(0.026	1.89(0.22)	612	0.96	0.69(0.032)	3.33(0.63)	387	0.90
0.75/0.25	0.73(0.019)	2.74(0.27)	421	0.97	0.71(0.024)	3.86(0.57)	316	0.94
1/0	0.73(0.017)	3.09(0.29)	373	0.98	0.75(0.015)	4.47(0.41)	246	0.98
Incorporated								
0/1	0.93(0.128)	0.43(0.10)	1782	0.97				
0.23/0.77	0.70(0.031)	1.54(0.20)	814	0.96	0.44(0.023)	6.29(1.85)		0.84
0.47/0.53	0.73(0.022)	1.67(0.15)	691	0.98	0.60(0.025)	4.90(1.03)	366	0.90
0.72/0.28	0.78(0.021)	2.48(0.25)	413	0.97	0.77(0.020)	4.81(0.63)	218	0.96
1/0	0.79(0.022)	3.65(0.59)	274	0.96	0.84(0.018)	4.87(0.52)	186	0.98



Appendix 3: Soil porewater EC and water content surrounding pelletized poultry litter band

Daily soil porewater electrical conductivity (EC) and volumetric water content surrounding a subsurface pelletized poultry litter (PPL) band during the 2012 and 2013 corn growing seasons under cereal rye and hairy vetch surface residues. The solid lines represent porewater EC at different soil profile locations (mean of two replicates per location; black = subsurface band, blue = 10 cm below band, red = 10 cm horizontal from band at 10 cm depth in 2012 or 5 cm depth in 2013, green = 25 cm horizontal from band at 5 cm depth). Locations in which EC trends over time varied greatly between replicates are not presented. The purple dashed lines represent soil water content averaged over the locations for which EC data are presented; the black dashed lines represent soil water content within the PPL band. Arrows along the x axis indicate soil sampling dates.



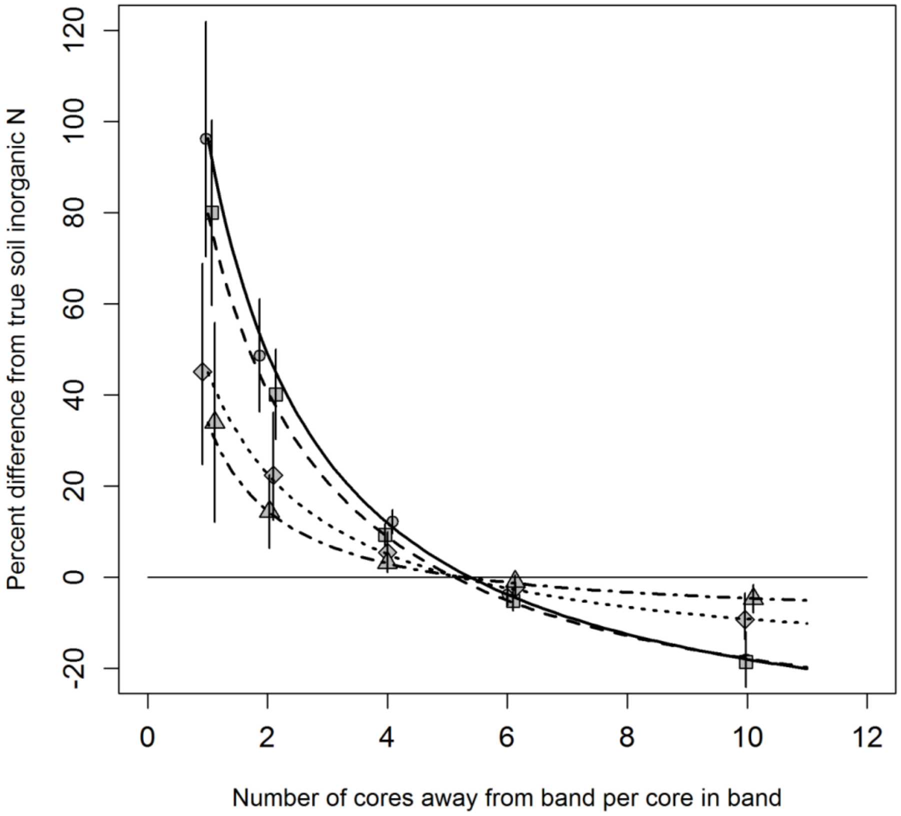
Appendix 4: Relationship between EC and soil inorganic nitrogen concentration
Relationship between electrical conductivity (EC) measured in the field and soil inorganic nitrogen (N) concentration measured on soil samples collected at corresponding locations and time points as EC measurements

Appendix 5: Additional NO_3^--N proportion results

The NO_3^--N proportion (NP) of total inorganic nitrogen (IN) as affected by interrow location class within each pelletized poultry litter (PPL) treatment at four growth stages in 2012; and pooled across PPL treatments at two growth stages in 2013. Means are presented only for growth stages in which interrow location significantly affected NP. Different lowercase letters indicate significant differences among PPL treatments within the same interrow location class (*P*<0.05). Different uppercase letters indicate significant differences among interrow location classes within the same PPL treatment (*P*<0.05).

	Interrow center (0-13 cm)†	-------- Mid (13-26 cm) --------	----- Corn row (26-38 cm) -----
2012 Fifth-leaf			
None	0.77 bA	0.74 bA	0.69 bA
Brd	0.84 abA	0.80 abA	0.79 aA
Band	0.62 cB	0.75 abA	0.72 abA
Inc	0.88 aA	0.82 aB	0.74 abC
2012 Silking			
None	0.37 abA	0.42 abA	0.39 abA
Brd	0.33 bA	0.31 bA	0.22 bA
Band	0.64 aA	0.48 abB	0.45 aAB
Inc	0.52 abA	0.57 aA	0.28 abB
2012 Milk			
None	0.40 bA	0.49 aA	0.46 aA
Band	0.57 aA	0.42 aB	0.43 aB
2012 Maturity			
None	0.38 bA	0.32 bA	0.33 bA
Brd	0.37 bA	0.51 bA	0.32 bA
Band	0.52 bA	0.42 bA	0.41 bA
Inc	0.76 aAB	0.83 aA	0.67 aB
2013 Emergence			
	0.60 B	0.65 AB	0.70 A
2013 Maturity			
	0.40 B	0.48 A	0.49 A

†Data from soil cores collected between 0-13, 13-26 and 26-38 cm intervals from the interrow center were pooled to produce the interrow location classes.



Appendix 6: Soil sampling protocol for sampling with a subsurface band

The effect of systematic soil sampling scheme on the accuracy of measured soil inorganic nitrogen (IN) concentration in plots that received subsurface band pelletized poultry litter (PPL) application. Different symbols and lines represent different sampling times (circles and solid line = fifth-leaf, squares and dashed line = silking, diamonds and dotted line = milk, triangles and dashed-dotted line = maturity). Soil IN concentration predictions at 1 cm increments (30 cm deep x 38 cm horizontal from interrow center to corn row) were averaged to generate true soil IN concentrations for each cover crop treatment at each sampling time ("profile"). Sampling scheme estimates for each profile were determined by averaging the mean of soil IN for 5 cm horizontally from PPL band (30 cm depth) with means soil IN concentrations from 2-cm wide "cores" (30 cm depth) taken randomly from at least 10 cm horizontally from the PPL band. Percent differences between sampling scheme estimates and true means were calculated as the difference relative to the true soil IN concentration. The lines are hyperbolic equations fit to each growth stage subset (fifth-leaf: $y = 100 - (75.6(x - 0.95))/(1 + 0.53(x - 0.95))$; silking: $y = 100 - (78.7(x - 0.70))/(1 + 0.56(x - 0.70))$; milk: $y = 100-(113.7(x-0.11))/(1+0.94(x-0.11))$; maturity: $y = 100 - (217.9(x - 0.24))/(1 + 1.98(x - 0.24))$. Error bars represent ± one standard deviation.

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