

Winter legume cover-crop root decomposition and N release dynamics under disking and roller-crimping termination approaches

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Abstract

Several approaches can be used to terminate legume cover crops in the spring prior to planting summer crops, but the effect that these methods have on decomposition and nitrogen (N) release dynamics of legume cover-crop roots is poorly understood. The main objectives of this study were to: (i) quantify decomposition and N release of roots from pea (*Pisum sativum*), clover (*Trifolium incarnatum*) and vetch (*Vicia villosa* Roth); (ii) determine if roots decompose and release N faster when cover crops are terminated by disking compared with roller-crimping; and (iii) determine if roots decompose and release N faster under higher soil inorganic N levels. Two field experiments were conducted in Goldsboro and Kinston, North Carolina in the summer of 2012. Cover crops at these sites were terminated in spring by disking or roller-crimping and planted to unirrigated corn. Air-dried roots placed in litterbags were buried in their corresponding cover-crop plots and in plots where cover crops had not been grown that had either synthetic N fertilizer added at burial or had no fertilizer addition. Root litterbags were collected over 16 weeks at both sites. Cover-crop plots terminated by disking had up to 117 and 49% higher soil inorganic N than roller-crimped plots in Goldsboro and Kinston, respectively. However, roots did not appear to contribute significantly to these increases, as measured root decomposition and N release was not affected by termination approach at either site. Roots decomposed rapidly at both sites, losing up to 65% of their original biomass within 4 weeks after burial. Root N release was also rapid at both sites, with vetch generally releasing N fastest and clover slowest. It was estimated that cover-crop roots supplied 47–62 and 19–33 kg N ha⁻¹ during the corn cycle in Goldsboro and Kinston, respectively. Our results indicate that under the warm, humid summer conditions of the Southeastern USA, legume cover-crop roots decompose and release N rapidly.

Key words: legume cover crops, roots, roller-crimping, disking, decomposition, soil nitrogen

Introduction

Winter legume cover crops furnish essential plant nutrients, particularly nitrogen (N), to subsequent summer crops (Ranells, 1992; Waggoner et al., 1998), but estimates of this N contribution have traditionally been based solely on the decomposition and N release dynamics of shoot residues (Wilson and Hargrove, 1986; Utomo et al., 1990; Stute and Posner, 1995), while N contributions of roots have largely been ignored. Legume cover-crop shoots decompose and release N rapidly following spring termination, in large part because their biochemical composition (low C/N ratio and percent lignin) is

conducive to fast rates of decomposition and N release (Buchanan and King, 1993; Sainju et al., 2005). In contrast, legume cover-crop roots have higher C/N ratios, elevated lignin content, and are often physically protected from microbial decomposition within soil aggregates (Buchanan and King, 1993; Puget and Drinkwater, 2001; Schmidt et al., 2011; Dungait et al., 2012), all of which lead to slower rates of legume cover-crop root decomposition and N release relative to shoots. Although legume cover-crop root decomposition and N release is relatively slow, roots can account for nearly 30% of total legume cover-crop biomass (Sainju et al., 2005), and it is, therefore, important to include root-derived N in

estimates of legume cover-crop contributions to soil inorganic N pools.

Several authors have found that in legume pasture systems where shoots are removed from cover crops such as alfalfa (*Medicago sativa* L.) and subterranean clover (*Trifolium subterraneum* L.), roots play an important role in providing N for subsequent crops (Rasse et al., 1999; Bolger et al., 2003). However, the quantity of N released from decomposing roots of spring-terminated winter legume cover crops during subsequent summer crop growth, as well as the temporal dynamics of this release, have not been thoroughly investigated. The effect that a spring termination approach, which varies in its level of soil disturbance and placement of N-rich winter legume cover-crop shoot residues, may have on root decomposition and N release is of interest to growers utilizing cover crops for nutrient management, and is also poorly understood.

In the Southeastern USA, winter legume cover crops are terminated in the spring using both traditional and novel approaches. Termination with a tractor-mounted mechanical disk that incorporates legume cover-crop shoots into the soil is a traditional spring termination approach. Disking results in rapid shoot decomposition and nutrient release, compared to termination approaches that leave surface mulch, due to greater shoot–soil contact and elevated levels of soil oxygen in disked systems, both of which stimulate microbial decomposition (Buchanan and King, 1993; Coppens et al., 2007; Paul and Clark, 2007). These faster rates of shoot decomposition and nutrient release under disking result in higher soil inorganic N levels at an earlier date compared with traditional herbicide-based no-till termination approaches (Wilson and Hargrove, 1986; Sarrantonio and Scott, 1988). Additions of soil inorganic N are known to have a positive effect on shoot decomposition (Fog, 1988; Mary et al., 1996), but the effect of added N on legume cover-crop root decomposition is poorly understood and may be positively impacted by the addition of N-rich disked legume cover-crop shoot biomass.

Terminating cover crops with a roller-crimper is a novel approach that has been gaining popularity in the Southeastern USA due to its proven effectiveness in weed suppression and soil moisture conservation (Ashford and Reeves, 2003; Kornecki et al., 2009; Mirsky et al., 2011). This tractor-mounted cylindrical drum implement with chevron-shaped blades rolls over and crimps cover-crop stems when the crop is in full bloom, leaving plants flattened on the soil surface as protective mulch (Davis, 2010; Parr et al., 2011). When cover-crop biomass production is sufficiently high, resulting in a thick surface layer of mulch, roller-crimping can reduce or eliminate herbicide usage (Mirsky et al., 2009, 2011) offering the possibility of no-till organic farming systems. Roller-crimping also leaves cover-crop root systems intact and soil undisturbed, which is in stark contrast to disking where soil disturbance can lead to relocation of cover-crop biomass and enhanced decomposition

through increased soil respiration (Paul and Clark, 2007; Yaduvanshi and Sharma, 2008; Soriano et al., 2012). Research in North Carolina (NC) indicates that roller-crimped legume cover crops can furnish 10–217 kg N ha⁻¹ depending on species and termination date (Parr et al., 2011), and that peak soil inorganic N occurs 4–6 weeks after roller-crimping (Parr et al., 2014). However, comparisons of legume cover-crop N release dynamics under disking and roller-crimping termination at the same field site and during the same season are lacking.

In the present study, we investigated the effect of a spring termination approach on decomposition and N release dynamics of roots from pea (*Pisum sativum*), clover (*Trifolium incarnatum*) and vetch (*Vicia villosa* Roth). These species were selected because they are well-adapted to the moderately acid soils of the Southeastern USA, are among the most common winter legume cover crops grown by farmers in the region, and are compatible with roller-crimper termination (Wilson and Hargrove, 1986; Ranells, 1992; Parr et al., 2011). Field studies at separate sites in the NC Coastal Plain were conducted in the summer of 2012. Our main objectives were to: (i) quantify decomposition and N release dynamics of pea, clover and vetch roots; (ii) determine if roots decompose and release N faster when terminated by disking than roller-crimping; and (iii) determine if roots decompose and release N faster under higher soil inorganic N levels. We hypothesized that the most rapid decomposition and N release would occur in roots from species with favorable biochemical composition, and in disked plots over rolled plots.

Materials and Methods

Field sites and experimental setup

Legume cover-crop root decomposition and N release were investigated in Goldsboro (35.39°N, 78.03°W) and Kinston (35°26'N, 77°65'W), NC, during the summer of 2012. In Goldsboro, the study was conducted at the Center for Environmental Farming Systems on Wickham loamy sand (fine loamy, mixed, thermic, Typic Hapludult), while in Kinston the study took place at the NC Department of Agriculture & Consumer Services Caswell Research Farm on Portsmouth loam (fine loamy fluviomarine deposits over sandy skeletal fluviomarine, mixed, thermic Typic Umbraquult). These sites are located in the NC Coastal Plain, an important agricultural production area of the state characterized by mild winters and hot, humid summers. Long-term state weather data (1971–2011) indicates that these sites have similar air temperatures (~23°C) during the growing season (April–September), but Kinston has higher average rainfall during this period (750 versus 650 mm) (State Climate Office of North Carolina, NC State University, 2014). These sites allowed us to test our hypothesis on different soil types and in locations

Table 1. Field activities schedule at Goldsboro and Kinston, NC study sites.

	Goldsboro	Kinston
Previous crop	Corn	Corn
Cover crop planting	Sept 30, 2011	Sept 29, 2011
Shoot biomass collection	May 10, 2012	Apr 19, 2012
Root collection for litterbags	Apr 20–30, 2012	Apr 1–10, 2012
Cover crop termination	May 10, 2012	Apr 19, 2012
Fertilizer added to N150 plots ¹		Apr 30, 2012
Corn planting	May 25, 2012	May 2, 2012
Root litterbag burial	May 25, 2012	May 2, 2012
Root litterbag collection	June 8, 22; July 6, 20; Aug 17; Sept 13	May 16, 30; June 13, 27; July 25; Aug 23

¹ In Kinston, 150 kg N ha⁻¹ as urea and ammonium nitrate solution was added to half of plots where cover crops were not grown.

likely to experience some climatic variability over the course of the experiment. Pea, clover and vetch were planted at both sites in September 2011 (Table 1) in a randomized complete block split-plot design. Main plots (termination method) were 324 m² in Goldsboro and 549 m² in Kinston, while subplots (legume cover-crop species) measured 84 m² in Goldsboro and 90 m² in Kinston. Each treatment plot was replicated four times. Within each main plot, one (Goldsboro) and two (Kinston) subplots were not planted to legume cover crops and were left bare over the winter and early spring. Cover crops were terminated by disking and roller-crimping on April 19 and May 10, 2012 in Kinston and Goldsboro, respectively (Table 1). At spring termination, plots not planted to cover crops were also subject to disking and roller-crimping, which terminated the small amount of natural vegetation that had grown in these cover crop-free bare plots during winter and early spring. In Goldsboro, cover crop-free bare plots received no N addition (N00), while in Kinston in addition to the N00 plots there were also cover-crop-free bare plots that received 150 kg N ha⁻¹ (N150) as urea and ammonium nitrate solution approximately 2 weeks after termination (Table 1). There were no N150 plots established in Goldsboro because the land is certified-organic, which prohibits use of synthetic fertilizers. These N00 and N150 plots served the purpose of allowing us to follow root decomposition and N release under natural and elevated soil N conditions without the history of a legume cover crop which would add large amounts of N-rich biomass and likely increase soil microbial activity (Paul and Clark, 2007). Pea, clover, vetch, N00 and N150 plots are collectively referred to as 'cover-crop treatment plots'. All cover-crop treatment plots were planted to unirrigated corn (cv. AgVenture AV8262) approximately 2 weeks after cover-crop termination at both sites.

Cover-crop biomass determination

A 0.5 m² quadrat was used to collect legume shoot biomass from pea, clover and vetch plots just prior to termination (Table 1). One sample was taken from a

representative location within each plot. Biomass samples were transported to North Carolina State University (NCSU), dried at 65°C until constant weight was achieved, and final dry weights were recorded. Root biomass of pea, clover and vetch remaining in the field was estimated using root:shoot ratios for these species previously determined in a greenhouse study (unpublished data). Briefly, in this greenhouse study pea, vetch, and clover were grown in replicates of six in a completely randomized design for 16 weeks in transparent plastic sleeves placed in 75 cm tall, 10 cm diameter polyvinyl chloride cylinders. The greenhouse temperature range was 10–30°C. One plant was grown per cylinder in a sand (90%) and top soil (10%) medium. Plants were irrigated and fertilized daily using 200 ml N-free Hoagland solution per cylinder (Hoagland and Arnon, 1950). At harvest, sleeves were removed from cylinders, cut open along their length, and the medium was washed off with a gentle hose spray. Plants were cut with scissors at the soil line to separate shoots and roots, which were then oven-dried at 65°C until constant weight was achieved. Oven-dried root and shoot weights were used to determine root:shoot ratios. The range of root:shoot ratios determined in the greenhouse (0.27–0.3) was slightly higher than the values reported for these species in field studies (0.21–0.28) (Puget and Drinkwater, 2001; Williams *et al.*, 2006; Kong and Six, 2010; Vasileva, 2015). These small differences likely relate to greater root production in the greenhouse compared with the field due to optimal greenhouse growing conditions, our ability to more easily capture fine roots (<2 mm diameter) using this greenhouse method compared with field methods (Puget and Drinkwater, 2001; Kong and Six, 2010), and the deeper root excavation depth (75 cm) we used compared with field studies (15–40 cm) (Puget and Drinkwater, 2001; Williams *et al.*, 2006; Kong and Six, 2010; Vasileva, 2015). Since these greenhouse-derived root:shoot ratios were relatively close in value to those reported for these species under field conditions, we used these ratios to estimate standing pea, clover and vetch root biomass at termination.

Cover-crop root litter collection and burial

The litterbag method (Bocock and Gilbert, 1957) was used to determine the effect of termination approach on root decomposition and N release. In April 2012, prior to legume cover-crop termination in Goldsboro and Kinston, root litter from flowering pea, clover and vetch was collected to 15 cm soil depth at both sites (Table 1) and processed separately. To collect root litter, we identified the base of legume cover-crop plants and used a shovel to dig up plants carefully removing weed roots manually. Roots were soaked and washed thoroughly using tap water, air-dried at room temperature on greenhouse benches until constant weight was achieved, and cut into 3–5 cm pieces (Berg et al., 1987). Root litter was placed in nylon bags ($9 \times 9 \text{ cm}^2$, 1 mm mesh) in the following quantities: 0.8 g bag^{-1} for pea and clover, 0.7 g bag^{-1} for vetch. Root litterbags were buried approximately 2 weeks after cover-crop termination on the same day as corn planting, and were placed between corn rows to 15 cm depth in all plots. Treatment combinations are summarized as follows: cover-crop treatment (pea, clover, vetch, N00 and N150) \times termination (disking and roller-crimping) \times time (0, 2, 4, 6, 8, 12 and 16 weeks after root litterbag burial) whereas pea, clover and vetch roots were buried in pea, clover and vetch plots, respectively, and roots from all species were buried in N00 and N150 plots. When inserting litterbags into soil precautions were taken to minimize soil disturbance, which was especially important for roller-crimped treatments since undisturbed soil is a defining characteristic of this termination approach. A high level of soil disturbance in roller-crimped plots at litterbag burial would have made them indistinguishable from disked plots thereby weakening the termination component of this study. To bury litterbags, a spade (20 cm width) was pressed vertically into moist soil to 15 cm depth creating approximately a $20 \text{ cm} \times 2 \text{ cm}$ slot just wide enough for vertical placement of litterbags. Slots were gently closed in by pressing soil down and slightly inward. This method of litterbag placement minimized the area and level of soil disturbance compared to digging with a shovel. The presence of surface mulch, another defining characteristic of roller-crimping termination that differentiates it from disking, was not affected by this insertion method. Litterbags were retrieved 2, 4, 6, 8, 12 and 16 weeks after burial and were oven-dried at 70°C for 48 h. Oven-dried roots were removed from litterbags and a brush and forceps were used to gently remove adhering soil (Wang et al., 2010). Oven-dried root weight was recorded.

Soil collection and N analysis

Soil samples were collected at litterbag burial and at each litterbag retrieval date from all plots to 15 cm depth using a 2.54 cm diameter soil probe. Ten subsamples were taken per plot in a 'W' pattern, homogenized manually, and bulked. Soils were dried at 40°C to constant mass,

then ground to pass 2 mm mesh screen. Samples were extracted with 1 mol l^{-1} KCl with shaking for 1 h, and allowed them to settle for 20 min before filtering. Extracts were refrigerated at 4°C until analysis for NH_4^+ and NO_3^- on a QuikChem 2000 injection auto analyzer (Lachat Instruments, Loveland, CO). Separate samples were also taken to determine percent total soil N using a Perkin Elmer 2400 CHNS/O Elemental Analyzer (Norwalk, CT) in the Environmental and Analytical Testing Service facility at NCSU (Raleigh, NC).

Root litter chemical analysis, root mass loss and root N release

Root litter subsamples were collected prior to placement in litterbags, ground to pass a 1 mm mesh screen, and analyzed for initial C, N and lignin content. Carbon and N were determined using the Perkin Elmer 2400 CHNS/O Elemental Analyzer described previously. Lignin was measured by Dairy One (Ithaca, NY) using 72% w/w sulfuric acid digestion followed by near infrared reflectance spectroscopy. Due to insufficient root biomass at both locations, only single composite samples from each species were analyzed for lignin, and multiple comparisons to determine differences in lignin content between species were not possible. At each litterbag retrieval date, litterbag content oven-dried weight was determined, and was followed by taking subsamples of litterbag content to determine C, N and ash concentration. For ash determination, litterbag contents were combusted in a muffle furnace at 550°C for 16–18 h. Remaining ash represented the soil mineral contaminant in litterbags. To determine root mass loss at each collection date, subsample weight used for ash determination was recorded before and after combustion. We assumed that differences in weight resulting from combustion were due to root C loss as CO_2 . The proportion root in subsamples is equal to the root subsample weight before combustion minus root subsample weight after combustion divided by the root subsample weight before combustion. The proportion of originally buried root mass remaining in retrieved litterbags at time (t) is equal to the collected oven-dried litterbag content weight multiplied by the percent root mass of the subsample and divided by the original weight of the buried root mass. Litterbag root N mass remaining at each collection was determined by subtracting litterbag soil-derived N mass, which was calculated by multiplying litterbag ash content by percent total soil N, from litterbag content N mass. Percent original root N mass remaining in litterbags was determined by dividing litterbag root N mass remaining at each collection by original litterbag root N mass at burial multiplied by 100.

Statistical analyses

Analysis of variance with the PROC MIXED procedure (SAS Institute Inc., Cary, NC) was used to analyze the

following variables: shoot and root biomass, percent root mass remaining, percent root C and N, root N mass remaining, percent total soil N and soil inorganic N content. Termination approach, cover-crop treatment plots and time were fixed effects, while block was treated as a random effect. Multiple comparisons between treatment means were made with Tukey–Kramer's HSD ($P < 0.05$) on least-squared means.

Plant litter decomposition and nutrient release are best described by first-order decomposition kinetics characterized by initial rapid mass loss or nutrient release and followed by a slower rate of mass loss or nutrient release (Wilson and Hargrove, 1986; Buchanan and King, 1993; Luna-Orea *et al.*, 1996; Paul and Clark, 2007). Percent root mass and root N mass remaining for each litterbag retrieval date were regressed with time from all plots using nonlinear regression procedures of SigmaPlot 12.5 (Systat Software, Inc., San Jose, CA) to find the most suitable exponential model to describe root decomposition and N release. The following exponential models were tested:

$$f = ae^{-kx} + \varepsilon \quad (1)$$

$$f = a + be^{-kx} + \varepsilon \quad (2)$$

$$f = ae^{-k_1x} + be^{-k_2x} + \varepsilon \quad (3)$$

where f is the percent root or N mass remaining at time x (week), a and b represent the percent root or N mass at week 0, k is the decomposition or N release rate constant, and ε is the random error term.

The single exponential, two-parameter model (1) assumes an equal rate of residue decomposition throughout the experiment, while the single exponential, three-parameter model (2) assumes a portion of litter does not decompose during the experiment. The double exponential, four-parameter model (3) assumes that litter decomposes at two different rates during the experiment (Lopp and Guillard, 2004; Soto *et al.*, 2005). Model selection to best describe decomposition and N release was based on adjusted coefficient of determination values produced using nonlinear regression.

Results and Discussion

Soil inorganic N dynamics

In Goldsboro, soil inorganic N content in plots was significantly affected by the higher order interaction of cover-crop treatment \times termination \times time ($P = 0.0001$). Pea, clover and vetch plots terminated by disking had higher soil inorganic N levels than their corresponding plots terminated by roller-creasing until week 12 for pea and clover, and through week 16 for vetch (Fig. 1). In Goldsboro, disked vetch plots had higher soil inorganic N levels than disked pea or clover plots for several sampling dates through week 8 of the study, while roller-creasing vetch plots also had higher soil inorganic N

levels than roller-creasing pea and clover, but for a much shorter duration (Fig. 1). Parr *et al.* (2014) similarly reported higher soil inorganic N levels in roller-creasing vetch plots than in roller-creasing clover plots at sites in the NC Coastal Plain. Not surprisingly, N00 plots had lower soil inorganic N levels than pea, clover and vetch plots under both termination approaches for several sampling dates (Fig. 1). In Goldsboro, peak soil inorganic N occurred in disked pea and vetch plots 4 weeks after litterbag burial (~6 weeks after cover-crop termination), which is in agreement with earlier findings by Varco *et al.* (1989). However, disked clover plots peaked in soil inorganic N 8 weeks after litterbag burial (~10 weeks after cover-crop termination). In roller-creasing plots, peak soil inorganic N was reached for all species 4 weeks after litterbag burial (Fig. 1), which falls within the general time frame of peak soil inorganic N following legume cover-crop spring termination by roller-creasing in the NC Coastal Plain (Parr *et al.*, 2014). At its peak in Goldsboro, soil inorganic N in disked plots was 73–117% higher than in roller-creasing plots, depending on cover-crop species (Fig. 1).

In Kinston plots, the higher order interaction of cover-crop treatment \times termination \times time also had a significant effect ($P < 0.0001$) on soil inorganic N levels (Fig. 1). However, soil inorganic N fluctuation over the course of the study was drastically different in Kinston compared with Goldsboro as differences in soil inorganic N levels between plots were only observed at litterbag burial (~2 weeks after termination). Not surprisingly, N150 plots had the highest levels of soil inorganic N under both disking and roller-creasing at litterbag burial, while N00 plots had the lowest soil inorganic N levels (Fig. 1). Disked pea plots also had approximately 49% higher soil inorganic N content than roller-creasing pea plots (Fig. 1) at litterbag burial. Unlike in Goldsboro, roller-creasing pea, clover and vetch plots had similar soil inorganic N levels throughout the study in Kinston. The highest recorded measurements of soil inorganic N in Kinston occurred at litterbag burial in both disked and roller-creasing plots, 4 weeks earlier than in Goldsboro.

There were substantial differences in soil inorganic N levels in pea, clover and vetch plots between sites, with soil inorganic N levels generally being higher in Goldsboro than in Kinston (Fig. 1). Clover and vetch biomass production was considerably higher in Goldsboro than in Kinston (Table 2), and there was a larger quantity of standing cover-crop N (shoots plus roots) for all species in Goldsboro (258–359 kg N ha⁻¹) compared with Kinston (137–222 kg N ha⁻¹) at termination. However, our data also indicate that N00 plots in Goldsboro had a higher range of soil inorganic N (2.2–14.7 mg N kg soil⁻¹) than N00 plots in Kinston (1.9–5.6 mg N kg soil⁻¹), which may relate to differences in rainfall distribution between sites. Rainfall was approximately three times higher in Kinston than in Goldsboro during the month following cover-crop termination (Table 3). We speculate that this higher rainfall may have accelerated

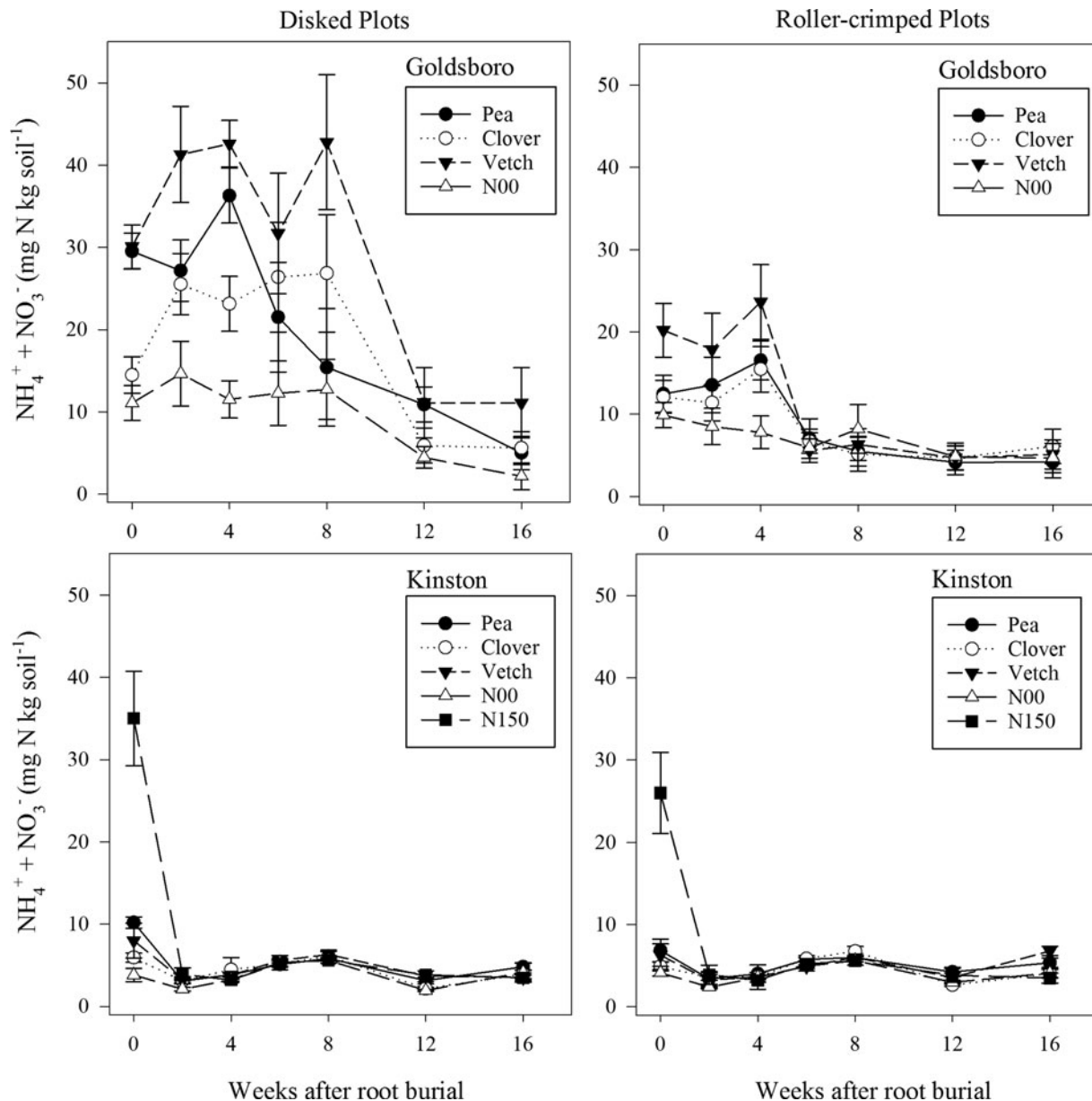


Figure 1. Soil inorganic N (mg N kg soil^{-1}) fluctuation in disked and roller-crimped pea (*Pisum sativum*), clover (*Trifolium incarnatum*) and vetch (*Vicia villosa* Roth) plots and in cover crop-free bare plots with no N addition (N00) or with 150 kg N ha^{-1} (N150) added as urea and ammonium nitrate solution at Goldsboro and Kinston, NC study sites.

cover-crop N release and subsequent N losses in Kinston plots. High rates of NO_3^- leaching from legume cover-crop residues have been observed in both disked and surface mulched systems where soil moisture content exceeds soil water-holding capacity (Moller and Reents, 2009; Campiglia et al., 2011). The very sharp decline in soil inorganic N in Kinston N150 plots within 2 weeks of litterbag burial and fertilizer application provides additional evidence in support of leaching-related N losses (Table 1; Fig. 1). The Portsmouth loam soil at the Kinston site also does not drain as rapidly as the Wickham loamy sand of Goldsboro, and excessive rainfall in Kinston may have generated soil moisture conditions conducive to denitrification

(Mosier et al., 2002), which may have also contributed to soil inorganic N losses in Kinston. In Goldsboro, total rainfall was relatively low compared with Kinston, and N losses through leaching or denitrification likely were not major events. These results suggest that in high rainfall environments N released from decomposing legume cover-crop residues may have a relatively low soil residence time.

Cover-crop root decomposition dynamics

Although disked and roller-crimping generated different levels of soil inorganic N over a prolonged period in Goldsboro, root decomposition rate was not affected

Table 2. Shoot and root biomass and N yields for pea (*Pisum sativum*), clover (*Trifolium incarnatum*) and vetch (*Vicia villosa* Roth) at Goldsboro and Kinston, NC study sites.

Cover crop ¹	R:S ²	Goldsboro				Kinston			
		Biomass Mg ha ⁻¹		Nitrogen kg ha ⁻¹		Biomass Mg ha ⁻¹		Nitrogen kg ha ⁻¹	
		Shoots	Roots	Shoots	Roots	Shoots	Roots	Shoots	Roots
Pea	0.27a	6.5a	1.7a	205a	53a	6.1a	1.6a	170a	36a
Clover	0.3a	9.6b	2.8b	256b	66b	6.4a	1.9a	110b	27b
Vetch	0.29a	8.7b	2.5b	288b	71b	6.5a	1.8a	175a	47c

¹ Values within a column followed by the same letter are not significantly different (Tukey–Kramer's HSD; $P < 0.05$).

² Root:Shoot ratios (R:S) were determined from 16-week-old greenhouse-grown plants in replicates of six for each species.

Table 3. Monthly means of daily maximum air temperature (°C) and total precipitation (mm) at Goldsboro and Kinston, NC study sites.

Climatic factor ¹	Goldsboro				Kinston			
	June	July	August	September	May	June	July	August
Precipitation (mm)	56	120	103	42	178	53	157	229
Temperature (°C)	23	27	24	21	22	23	27	25

¹ Data collected until the last litterbag collection date at Goldsboro (September 13) and Kinston (August 23) sites.

($P = 0.79$) by termination approach at this site (Fig. 2). There also was not a higher-order interaction among termination, cover-crop treatment and time ($P = 0.07$). Only the cover-crop treatment \times time interaction was significant ($P = 0.04$) in Goldsboro. When averaged across termination approaches, pea and vetch roots buried in respective pea and vetch plots decomposed faster than when buried in N00 plots at week 8 (Fig. 3). In Kinston, termination approach also did not affect ($P = 0.82$) root decomposition (Fig. 2). The cover-crop treatment \times termination \times time interaction also was not significant ($P = 0.31$), but like in Goldsboro, there was a significant cover-crop treatment \times time interaction ($P < 0.001$). When averaged across termination approaches, clover roots buried in clover plots decomposed faster than all pea and vetch treatments at weeks 8 and 12 (Fig. 4). At week 16, clover roots buried in clover plots decomposed faster than clover roots buried in N00 and N150 plots, pea roots buried in N150 plots and vetch roots buried in vetch plots (Fig. 4).

In Goldsboro, there was large variability in model selection to best describe root decomposition, while in Kinston model 3, and in one case model 2, best described root decomposition, suggesting that in all but one case, root litter decomposed at two different rates in Kinston (Table 4). The decomposition rate constants (k) produced by models 1 and 3 reflect the faster rates of decomposition for clover roots buried in clover plots compared with other treatments during the latter portion of the study in Kinston (Table 4). The exponential models used to describe root decomposition at both sites have also been

selected by other authors to best describe legume cover-crop decomposition using litterbag methods (Buchanan and King, 1993; Luna-Orea *et al.*, 1996).

Averaged over termination approach, pea, clover and vetch roots buried in plots of their respective species lost 56–65% of their initial root mass within 4 weeks of burial in Goldsboro (Fig. 3). Taking into account our estimates of standing root biomass for each of these species immediately before termination (Table 2), this rate of decomposition indicates that approximately 1037, 1568 and 1625 kg ha⁻¹ of pea, clover and vetch root biomass, respectively, was lost within 1 month of root burial. After 16 weeks, it is estimated that these species lost 87–90% of their original root biomass, which is equivalent to 1479, 2520 and 2200 kg ha⁻¹ for pea, vetch and clover, respectively. Root decomposition was also rapid immediately following termination in Kinston, but slowed considerably during the second half of the study in comparison with Goldsboro. Averaged over termination approach, pea, clover and vetch roots buried in plots of their respective species lost 60–65% of their original mass within 4 weeks of burial in Kinston (Fig. 4), which is equivalent to 960, 1235 and 1100 kg ha⁻¹ of pea, clover and vetch root biomass, respectively. After 16 weeks, 73–85% of roots had decomposed, and 1232, 1615 and 1314 kg ha⁻¹ of pea, clover and vetch root biomass, respectively, was lost.

The rates of clover and vetch root decomposition observed in both Goldsboro and Kinston resembled rates of shoot decomposition reported for these species in the Southeastern USA. For example, clover shoots

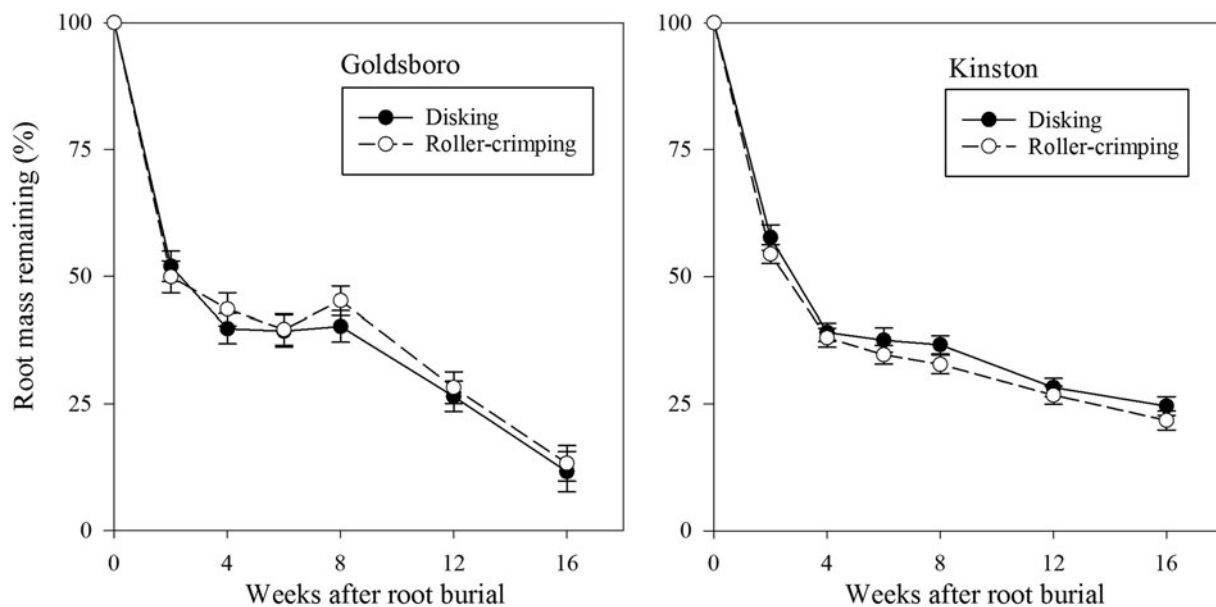


Figure 2. Percentage of original root mass remaining over time averaged across cover crop treatments as a function of termination approach at Goldsboro and Kinston, NC study sites.

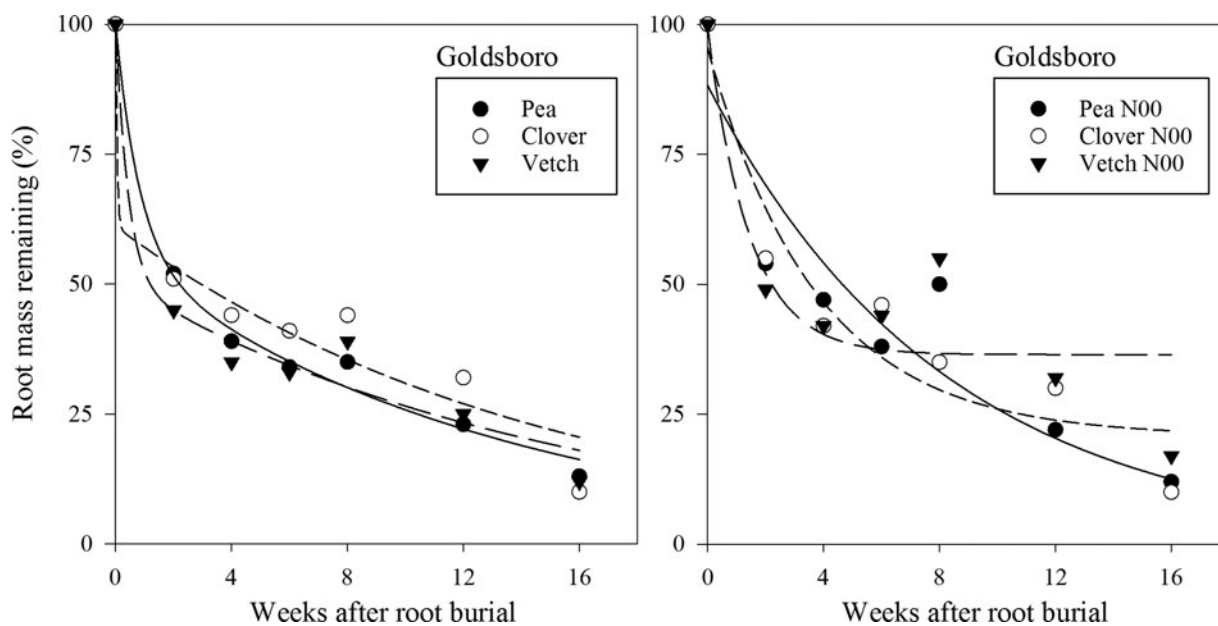


Figure 3. Percentage of original pea (*Pisum sativum*), clover (*Trifolium incarnatum*) and vetch (*Vicia villosa* Roth) root mass remaining over time in cover crop treatment plots averaged across termination approaches at the Goldsboro, NC study site. Equations for these curves are given in Table 4.

lost 70% of their biomass within 4 weeks under conventional tillage in a study in the nearby Piedmont region of NC (Buchanan and King, 1993), while clover roots in our study, averaged across sites and termination approaches, lost 61% of their initial biomass during this same time period (Figs. 3 and 4). After 16 weeks, approximately 90% of original clover shoot biomass was lost in the Piedmont region study (Buchanan and King, 1993), which closely mirrors the 87% of clover roots lost

during this time frame averaged across sites and termination approaches in our study. In a Mississippi field study, Varco et al. (1993) reported that 44 and 76% of vetch shoot biomass was lost from no-tillage and conventional tillage plots, respectively, within 4 weeks, while approximately 58 and 78% of shoot biomass was lost from no-tillage and conventional tillage plots, respectively, after 16 weeks. In our study, averaged across sites and termination approaches, 63% of vetch roots decomposed

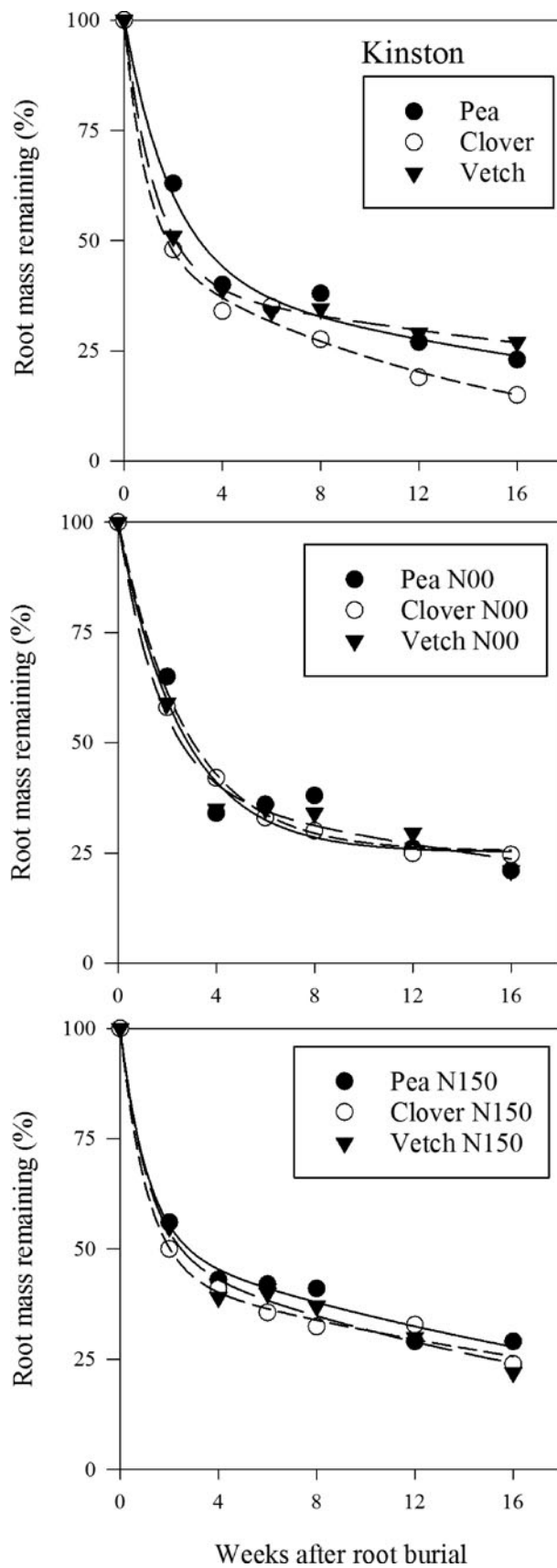


Figure 4. Percentage of original pea (*Pisum sativum*), clover (*Trifolium incarnatum*) and vetch (*Vicia villosa* Roth) root mass remaining over time in cover crop treatment plots averaged across termination approaches at the Kinston, NC study site. Equations for these curves are given in Table 4.

Table 4. Coefficients for the single exponential two-parameter model (1), single exponential three-parameter model (2) and double exponential four-parameter model (3) used to describe pea, clover and vetch root decomposition averaged over termination in pea, clover, vetch, N00 and N150 plots. Model selection was based on the highest adjusted R^2 values.

Treatments ¹	Model 1			Model 2				Model 3				
	Coefficients ²			Coefficients				Coefficients				
	<i>a</i>	<i>k</i>	Adj. R^2	<i>a</i>	<i>b</i>	<i>k</i>	Adj. R^2	<i>a</i>	<i>b</i>	<i>k</i> ₁	<i>k</i> ₂	Adj. R^2
Goldsboro												
Pea	89.3	0.15a	0.86	22.2	76.4	0.37a	0.93	44	56	1.25a	0.08	0.99
Pea00	88.3	0.12a	0.81	18.2	75.4	0.22a	0.8	Not valid ³				
Clover	80.3	0.11a	0.82	26.1	71.2	0.33a	0.79	Not valid				
Clover00	88.4	0.12a	0.85	20.7	74.8	0.27a	0.86	Not valid				
Vetch	85.3	0.15a	0.75	26.7	73.7	0.56a	0.88	48.9	51.1	2.25a	0.07	0.95
Vetch00	82.3	0.09a	0.64	36.4	63	0.69a	0.71	Not valid				
Kinston												
Pea	89.3	0.13ab	0.83	26.7	73.2	0.36a	0.96	58.9	41.6	0.58ab	0.03a	0.97
Pea00	90	0.13ab	0.82	25.4	74.9	0.36a	0.94	59.5	41.3	0.51b	0.04a	0.93
Pea150	84.3	0.1a	0.74	33.1	66	0.46ab	0.95	48.5	51.5	0.93ab	0.04a	0.98
Clover	88.9	0.18b	0.84	21.4	77.3	0.45ab	0.95	51.5	48.6	1.13a	0.07a	0.99
Clover00	89.3	0.14ab	0.83	25.2	74.4	0.39ab	0.98	67.9	32	0.45b	0.02a	0.99
Clover150	83.6	0.12a	0.7	30.5	68.9	0.55ab	0.97	49.9	50.2	0.91ab	0.05a	0.98
Vetch	83.5	0.11a	0.69	30.6	69.1	0.57b	0.98	60	40	0.77ab	0.02a	0.99
Vetch00	87.8	0.14ab	0.79	26.9	73.1	0.43ab	0.96	60.5	39.9	0.59ab	0.03a	0.97
Vetch150	85.4	0.11a	0.77	30.5	68.9	0.56ab	0.97	49.9	50.2	0.91ab	0.05a	0.98

¹ Values within a column (separated by site) followed by the same letter are not significantly different (Tukey–Kramer’s HSD; $P < 0.05$).

² Model 1: $f = ae^{-kx} + \epsilon$. Model 2: $f = a + be^{-kx} + \epsilon$. Model 3: $f = ae^{-k_1x} + be^{-k_2x} + \epsilon$. In models, f is the percent of original root mass remaining at time x (week); a and b represent the percent root mass at week 0; k is the decomposition rate constant, and ϵ is the random error term.

³ ‘Not valid’ indicates data exceeded maximum number of iterations and did not converge. Thus, model coefficients could not be validated.

within 4 weeks, while 80% of vetch roots decomposed by week 16 (Figs. 3 and 4). The rate of root decomposition observed in our study was substantially faster than rates of legume cover-crop root decomposition observed in field studies in the Northern and Western USA (Puget and Drinkwater, 2001; Kong and Six, 2010). However, Buchanan and King (1993) also found that clover roots decomposed more slowly than shoots in a NC field study, but differences between root and shoot decomposition rates were smaller compared with differences under more temperate conditions (Puget and Drinkwater, 2001). Climatic factors, particularly temperature and soil moisture, are a major determinant of plant residue decomposition (Gijsman et al., 1997; Berg and McLaugherty, 2008), and may help explain these regional variations in legume cover-crop root decomposition.

The initial rapid rates of root decomposition observed at both sites in this study have also been observed for clover root decomposition in the Southeastern USA (Buchanan and King, 1993). These initial faster rates of plant litter decomposition are most often attributed to microbial consumption of easily decomposable materials such as simple carbohydrates, hemicelluloses and proteins (Berg et al., 1987; Gunnarsson and Marstorp, 2002).

After this initial rapid rate of root mass loss, decomposition slowed considerably for the remainder of the study in Kinston, while in Goldsboro root decomposition unexpectedly increased during the final 8 weeks of the study after having slowed during weeks 4–8 (Fig. 2). From weeks 8–16 of the study, 21–27% of initial pea, clover and vetch roots buried in plots of their corresponding species were lost in Goldsboro (Fig. 3) compared with only 7–15% of root mass loss for these species in Kinston (Fig. 4) averaged across termination methods. Our findings are unusual in investigations of plant litter decomposition as initial rapid rates of decomposition are normally followed by slower rates as microbial decomposers consume less palatable materials (Paul and Clark, 2007; Berg and McLaugherty, 2008).

The faster rate of root decomposition in Goldsboro observed during the latter part of this study may relate to greater soil microbial activity in Goldsboro compared with Kinston during this period. Liang et al. (2014) measured several soil microbial properties in disked plots over the course of this study, and reported higher soil enzyme activity (β -glucosidase and β -glucosaminidase) in disked Goldsboro plots than in disked Kinston plots during the latter portion of this study. The increase in rainfall in

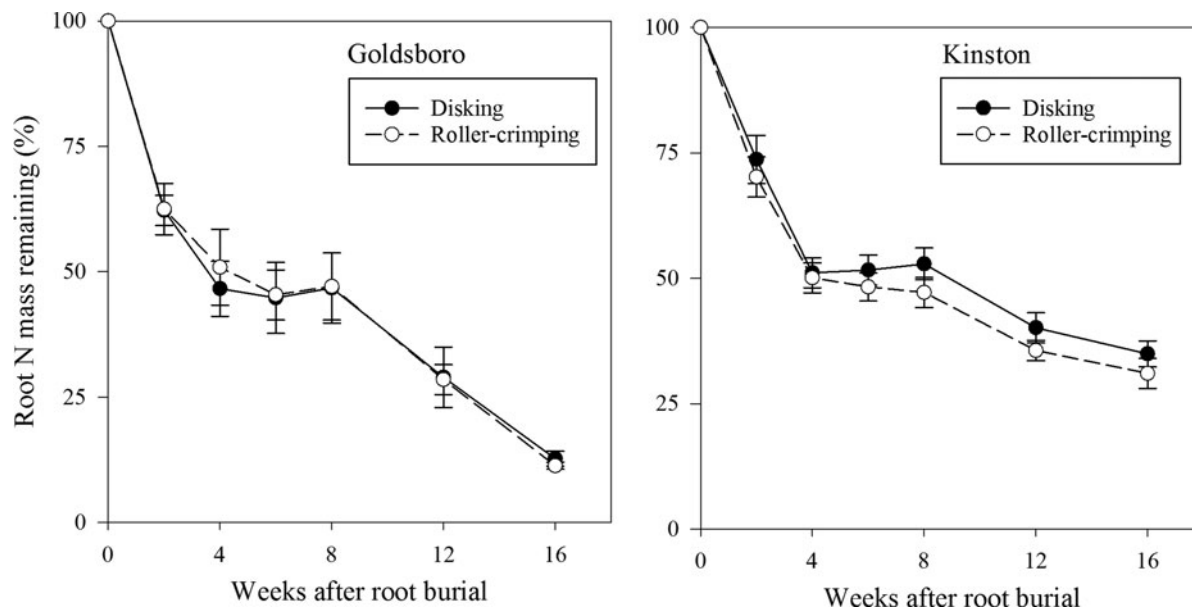


Figure 5. Percentage of original root N mass remaining over time averaged across cover crop treatments as a function of termination approach at Goldsboro and Kinston, NC study sites.

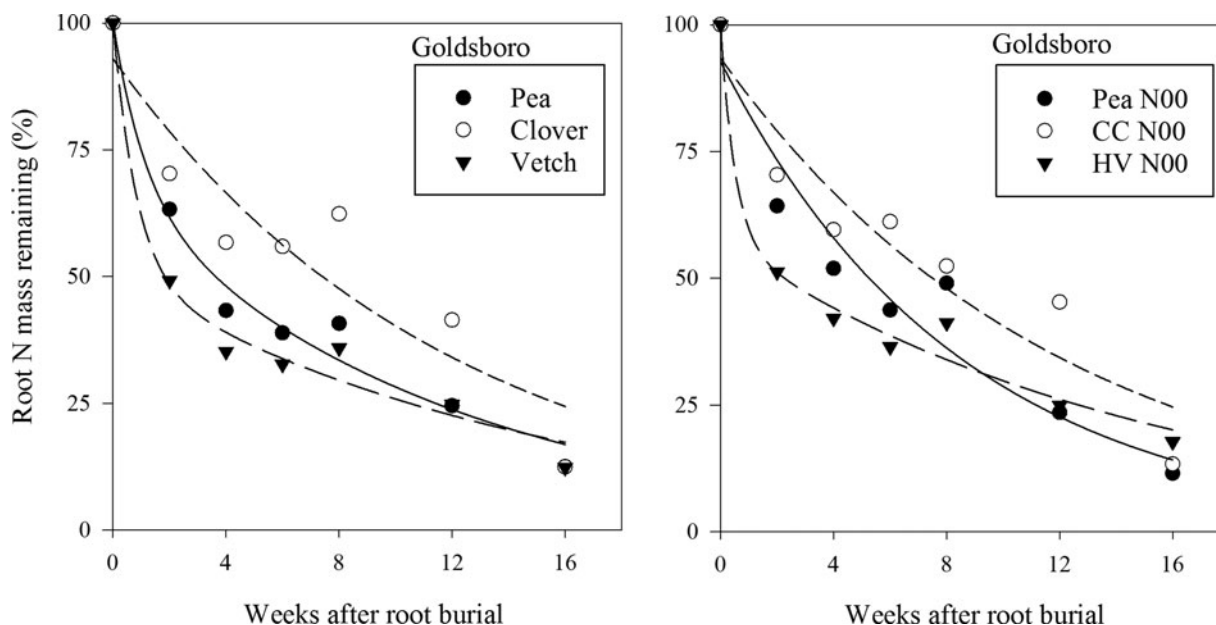


Figure 6. Percentage of original pea (*Pisum sativum*), clover (*Trifolium incarnatum*) and vetch (*Vicia villosa* Roth) root N mass remaining over time in cover crop treatment plots averaged across termination approaches at the Goldsboro, NC study site. Equations for these curves are given in [Table 6](#).

Goldsboro ([Table 3](#)) 1 month after litterbag burial, while still lower than in Kinston, likely played an important role in sustaining soil microbial activity during the later stages of the study in Goldsboro. Although Liang *et al.* (2014) did not measure soil microbial properties in roller-crimped plots, it is conceivable that soil enzyme activity may have also been greater in Goldsboro roller-crimped plots later in the study leading to faster root decomposition in Goldsboro compared with Kinston.

One of our main objectives in this study was to determine if root litter would decompose faster under elevated soil inorganic N levels. While disking cover crops generated higher levels of soil inorganic N than roller-crimping for varying lengths of time at both sites, the lack of termination effect at either site indicates that factors other than soil inorganic N played a more pivotal role in driving root decomposition in disked and roller-crimped plots. Soil inorganic N levels were also higher in pea,

vetch and clover plots than in N00 plots for multiple sampling dates in Goldsboro and at litterbag burial in Kinston disked plots (Fig. 1), but faster root decomposition in these higher N plots was limited to week 8 where vetch roots in vetch plots decomposed faster than vetch roots in N00 plots (Fig. 3). Higher soil microbial activity in vetch plots than in N00 plots is a possible explanation for this finding (Liang et al., 2014).

Legume cover-crop root N release dynamics

Legume cover-crop termination approach did not affect root N release ($P=0.71$) in Goldsboro (Fig. 5). There also was not a significant higher-order interaction among termination, cover-crop treatment and time ($P=0.87$) on root N release at this site. However, the cover-crop treatment \times time interaction did have a significant effect on root N release ($P=0.008$) in Goldsboro. Vetch roots buried in vetch plots released N at a faster rate than clover roots buried in clover plots through week 12 in Goldsboro (Fig. 6), whereas in N00 plots in Goldsboro vetch roots released N at a faster rate than clover roots at all but two sampling dates (weeks 8 and 16).

Termination approach also did not affect root N release ($P=0.56$) in Kinston (Fig. 5). Neither was there a significant higher-order interaction among termination, cover-crop treatment and time ($P=0.97$). However, like in Goldsboro, the cover-crop treatment \times time interaction was significant ($P=0.005$) with vetch roots buried in vetch plots releasing N faster than clover roots buried in clover plots until week 12 (Fig. 7). In N00 and N150 plots, vetch roots released N faster than clover roots through the entire study (Fig. 7). Clover roots never released N at a faster rate than pea or vetch roots at either site, which was likely due to the lower initial N content in clover roots compared with pea and vetch roots (Table 5) (Luna-Orea et al., 1996; Lawson et al., 2012). In Goldsboro, pea and vetch roots buried in their respective pea and vetch plots as well as in N00 plots released N at similar rates (Fig. 6), while vetch roots buried in vetch plots released N faster than pea roots buried in pea plots during the 2nd and 8th week of the study in Kinston (Fig. 7).

Root N release was best described in most cases by model 3 in Goldsboro, while in Kinston there was greater variability in model selection (Table 6). Only N released from vetch roots in cover-crop treatment, N00 and N150 plots was best described using the same model at both sites. The faster rate of vetch root N release from vetch, N00 and N150 plots compared with several other treatments in the study is in some, but not all, instances reflected by the higher N release rate constants associated with vetch treatments that were produced by these models (Table 6).

In legume cover-crop-based production systems in the Southeastern USA, corn can be planted at cover-crop termination in roller-crimped systems (Parr et al., 2011, 2014), or immediately after seed bed establishment in

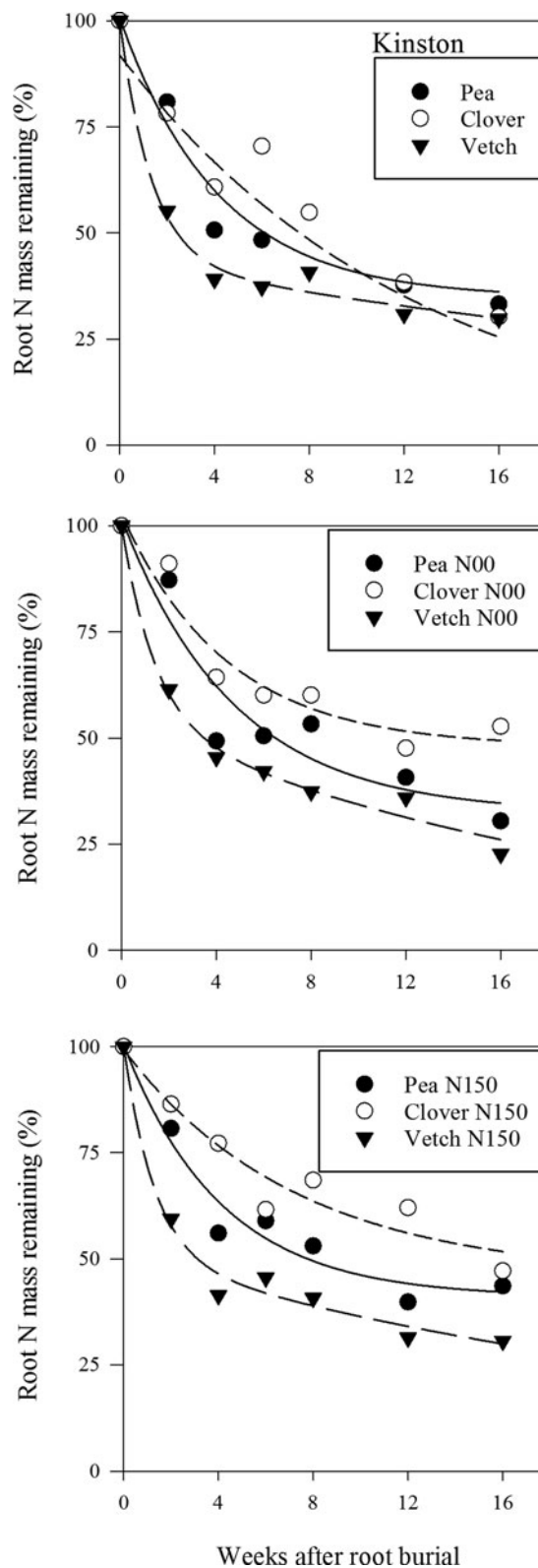


Figure 7. Percentage of original pea (*Pisum sativum*), clover (*Trifolium incarnatum*) and vetch (*Vicia villosa* Roth) root N mass remaining over time in cover crop treatment plots averaged across termination approaches at the Kinston, NC study site. Equations for these curves are given in Table 6.

Table 5. Initial root chemical characteristics and root N mass (mg) at the beginning (N_0) and end (N_{16}) of the study for pea, clover and vetch at Goldsboro and Kinston, NC study sites.

Cover crop ¹	% C	% N	C/N	Lignin ²	Lignin/N	N ₀ (mg)	N ₁₆ (mg)
Goldsboro							
Pea	41.9a	3.0a	14.0a	13.0	4.3	19.6a	2.6a
Clover	40.6a	2.3b	17.7b	10.9	4.7	15.5b	2.0a
Vetch	38.9a	2.8a	13.9a	15.4	5.5	17.3a	2.2a
Kinston							
Pea	29.7a	2.2a	13.8a	13.7	6.4	12.8a	4.3a
Clover	39.9b	1.4b	28.1b	11.2	7.9	10.5b	3.2a
Vetch	36.5b	2.5a	14.6a	15.0	6.0	15.1a	4.3a

¹ Values within a column (separated by site) followed by the same letter are not significantly different (Tukey–Kramer's HSD; $P < 0.05$).

² Only single composite samples from pea, clover and vetch were analyzed for lignin and multiple comparisons were not possible.

Table 6. Coefficients for the single exponential two-parameter model (1), single exponential three-parameter model (2), and double exponential four-parameter model (3) used to describe pea, clover and vetch root N release averaged over termination in pea, clover, vetch, N00 and N150 (Kinston only) plots at Goldsboro and Kinston, NC study sites. Model selection was based on the highest adjusted R^2 values.

Treatments ¹	Model 1			Model 2				Model 3				
	Coefficients ²			Coefficients				Coefficients				
	<i>a</i>	<i>k</i>	Adj. R^2	<i>a</i>	<i>b</i>	<i>k</i>	Adj. R^2	<i>a</i>	<i>b</i>	<i>k</i> ₁	<i>k</i> ₂	Adj. R^2
Goldsboro												
Pea	93.7	0.1ab	0.84	17.8	79.3	0.23ab	0.93	33.8	66.3	0.88a	0.09a	0.96
Pea00	93.7	0.12ab	0.92	6.8	87.2	0.14a	0.9	Not valid ³				
Clover	93	0.08a	0.82	Not valid				36.5	63.7	0.84a	0.08a	0.96
Clover00	93.9	0.09a	0.87	Not valid				Not valid				
Vetch	87.3	0.15b	0.81	23.9	74.9	0.46b	0.91	50.4	49.7	1.11a	0.06a	0.96
Vetch00	86.1	0.13ab	0.8	27	71	0.41b	.9	42.1	57.9	1.7a	0.07a	0.97
Kinston												
Pea	92	0.08ab	0.83	35.2	65.7	0.25ac	0.89	47.2	54.2	0.36ab	0.03a	0.87
Pea00	94.4	0.08ab	0.83	32.3	69.4	0.21ac	0.86	45.7	56.7	0.33ab	0.03a	0.83
Pea150	91	0.06ab	0.81	41	59.4	0.24ab	0.94	57.2	43.2	0.25ab	0.003a	0.92
Clover	94.3	0.07ab	0.91	11.2	80	0.09ac	0.78	Not valid				
Clover00	93.7	0.05a	0.77	47.9	54.7	0.22ac	0.9	54.7	47.9	0.22a	0.01a	0.87
Clover150	94.7	0.04a	0.87	45.8	53.4	0.14a	0.89	19.1	81.3	0.42ab	0.03a	0.87
Vetch	82.8	0.1b	0.67	33.5	66.4	0.55b	0.97	57.1	43.1	0.75b	0.02a	0.98
Vetch00	87.3	0.11b	0.82	30.4	68.5	0.35ab	0.95	45.7	54.4	0.72b	0.05a	0.98
Vetch150	84.5	0.1b	0.73	34.4	65	0.45bc	0.95	49.8	50.4	0.77b	0.03a	0.97

¹ Values within a column (separated by site) followed by the same letter are not significantly different (Tukey–Kramer's HSD; $P < 0.05$).

² Model 1: $f = ae^{-kx} + \epsilon$. Model 2: $f = a + be^{-kx} + \epsilon$. Model 3: $f = ae^{-k_1x} + be^{-k_2x} + \epsilon$. In models, f is the percent of original root N mass remaining at time x (week); a and b represent the percent root N mass at week 0; k is the N release rate constant, and ϵ is the random error term.

³ 'Not valid' indicates data exceeded maximum number of iterations and did not converge. Thus, model coefficients could not be validated.

disked systems. From a nutrient management perspective, it is most critical that the legume cover crop releases a large enough portion of its N to meet corn demands during its period of rapid N consumption, beginning at the six-leaf stage (Magdoff, 1991) and continuing until

tasseling and silking (Jones, 1985), which begins approximately 70 days after planting for the corn cultivar planted in this study. Clover and vetch shoots have been reported to release approximately 60% of their N within 1 month of being disked, and N released at this rate has been found to

satisfactorily meet the demands of corn during its period of peak N demand (Wilson and Hargrove, 1986; Stute and Posner, 1995). In this study, clover and vetch root N release rates closely mirrored the rates of clover and vetch shoot N release described in the previous studies, which was unexpected since legume cover-crop shoots generally release nutrients faster than roots (Buchanan and King, 1993; Puget and Drinkwater, 2001). Within 2 weeks after root burial, vetch roots buried in vetch plots released 45–50% of their N at both sites, while pea and clover roots buried in plots of their respective species released 19–37 and 24–29.5% of their N, respectively (Figs. 6 and 7). After 4 weeks, these figures rose to 62–65, 49–57 and 39% for vetch, pea and clover, respectively. While it is clearly evident that roots released N rapidly, it is important that root-derived N be quantified to determine if its reservoir is large enough to play an important role in furnishing N for subsequent summer crops.

Our estimates of root biomass production for pea, clover and vetch indicated that just prior to termination, these species contained 53–71 and 36–47 kg N ha⁻¹ in Goldsboro and Kinston, respectively (Table 2). Taking into account the rate at which these roots released N, within 1 month after termination, pea, clover and vetch roots would have released approximately 30, 26 and 46 kg N ha⁻¹, respectively, in Goldsboro, and 18, 11 and 29 kg N ha⁻¹, respectively, in Kinston. The availability of this N would coincide with the beginning of the period of rapid N uptake for corn (Magdoff, 1991). By corn silking, pea, clover and vetch roots in Goldsboro would have released 38, 39 and 52 kg N ha⁻¹, respectively, whereas in Kinston, 21, 14 and 30 kg N ha⁻¹, respectively, would have been released. In the NC Coastal Plain, Parr et al. (2011) found application of 168 kg N ha⁻¹ to produce the highest corn yields for this cultivar. Our N release data suggest that roots from these species could potentially contribute 28–37 and 14–20% of this N recommendation in Goldsboro and Kinston, respectively.

Conclusions

This study suggests that in the humid Southeastern USA pea, clover and vetch roots decompose and release N rapidly and that termination by disking or roller-crimping does not affect these processes. Root decomposition and N release were driven primarily by favorable root biochemistry rather than available soil inorganic N. This study also highlighted large regional differences in root decomposition for these species, with roots in this study decomposing at a much faster rate than roots reported in studies from more temperate climates. Cover-crop roots released N rapidly in this study supplying subsequent corn with a small, but notable, quantity of N during its phase of peak N demand.

From a production standpoint, it is essential that farmers utilizing legume cover crops have an understanding

of their total N contributions (shoots plus roots) that can be used by subsequent crops. This information can allow producers to better gauge yield expectations of summer crops and plan for additional fertilization, if needed. Our results indicate that vetch, in particular, may be an especially appealing option to farmers in the Southeastern USA, due to its large biomass production and relatively large contribution to soil inorganic N pools in the weeks following spring termination.

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