

Fertilizer Management for a Rye Cover Crop to Enhance Biomass Production

Kipling S. Balkcom,* Leah M. Duzy, Francisco J. Arriaga, Dennis P. Delaney, and Dexter B. Watts

ABSTRACT

Winter cereal cover crops are necessary to achieve maximum benefits of conservation tillage in the southeastern United States. These benefits generally increase as cover crop biomass increases; therefore, we conducted a study to evaluate N application times, sources, and optimal rates to maximize cover crop biomass production at Headland, AL, on a Fuquay sand (loamy, kaolinitic, thermic Arenic Plinthic Kandiodults) during the 2006–2008 growing seasons. Treatments were arranged in a split-split plot treatment restriction in a randomized complete block design with four replications. Main plots were time of fertilizer application (fall and spring), subplots were N source (commercial fertilizer and poultry [*Gallus gallus domesticus*] litter), and sub-subplots were N rate (0, 34, 67, and 101 kg N ha⁻¹ as commercial fertilizer and 0, 2.2, 4.5, and 6.7 Mg ha⁻¹ as poultry litter [as-sampled basis]) for a cereal rye (*Secale cereale* L.) cover crop. Commercial fertilizer produced 13% greater biomass compared to poultry litter across all rates and application times. Lower biomass production and higher costs for poultry litter reduced the feasibility of poultry litter as an N source compared with commercial N. Higher C/N ratios were measured for fall-applied N compared to spring-applied N, while N fertilizer recovery efficiency (RE_N) averaged 37% across the experiment. Results indicated fall application of commercial fertilizer N produced superior results across cover crop responses examined in this study, while providing general information about N fertilizer requirements to increase surface residue associated with cover crops across the southeastern United States.

Core Ideas

- Additional N can enhance cereal cover crop biomass production and maximize benefits.
- Cover crop N fertilizer recovery efficiency averaged 37% across all treatments.
- Commercial N fertilizer increased biomass for less money compared to poultry litter.

LONG-TERM EXPERIMENTS across the world have consistently documented soil quality benefits associated with soil C increases (Reeves, 1997). The hot-humid climate of the southeastern United States, aggravated by conventional tillage operations, does not allow surface residues to persist that has contributed to the degraded condition of soils in the region (Causarano et al., 2006; Novak et al., 2009; Franzluebbers, 2010). Conservation tillage has been promoted in the southeastern United States to increase soil C sequestration and enhance crop productivity (Brown et al., 1985; Schwab et al., 2002; Causarano et al., 2006; Balkcom et al., 2013). Conservation tillage systems combined with winter cover crops can offset degraded soil conditions of the region because they minimize surface soil disturbance and provide additional residue that increases C inputs to the soil (Causarano et al., 2006). This additional residue from cover crops also protects against soil erosion, improves water infiltration, protects against short-term drought stress, and provides a surface mulch layer that promotes suppression of many small-seeded weeds (Williams and Weil, 2004; Price et al., 2006, 2007; Faircloth et al., 2012). All these factors contribute to enhancing soil physical, chemical, and biological functions, which promote improved soil health and subsequent increased productivity for degraded soils typical of the southeastern United States.

Planting a cereal cover crop does not guarantee that an adequate level of biomass can be achieved that will be beneficial. Low fertility levels of degraded soils in the southeastern United States typically require some N fertilizer to maximize biomass production and realize subsequent benefits associated with cover crops (Reiter et al., 2008). Numerous agronomic experiments have documented forages responding to N (Ball et al., 1991), and many species grown as forages could also be grown as cover crops. Nitrogen fertilizer for forage production also affects forage quality by increasing protein content, particularly of grasses (Ball et al., 1991). However, current N fertilizer strategies and economic thresholds specific to a forage grown as an animal feed will likely not coincide with cover crop N fertilizer strategies.

No recommendations exist on the level of N required for cereal cover crops, but to enhance cover crop benefits, biomass

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Abbreviations: LSD, least significant difference; LSR, least significant ratio; NH₄NO₃, ammonium nitrate; RE_N, nitrogen fertilizer recovery efficiency.

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production should be maximized (Balkcom et al., 2007b). However, applying N to a crop that by definition will not be harvested causes concern for many growers (Balkcom et al., 2007b). Despite the ability of supplemental N fertilization to increase cover crop biomass production, the cost of N fertilizer persuades most growers to eliminate this expense to reduce total N production costs, although benefits of greater biomass production exist.

Nitrogen fertilization research for winter cereal cover crops in southeastern US cropping systems examined summer legumes to supply N and maximize biomass production for the cover crop. One legume evaluated in Alabama as a potential N source for winter cereal cover crops was peanut (*Arachis hypogaea* L.), a summer cash crop grown in rotation across the southeastern United States (Balkcom et al., 2007b). Despite measuring an N content of 39 kg ha⁻¹ in the peanut residue, no significant N response was measured in the following rye cover crop (Balkcom et al., 2007b). Sunn hemp (*Crotalaria juncea* L.), a summer tropical legume was also examined as a potential N source for a subsequent winter cereal cover crop. Sunn hemp was planted following winter wheat (*Triticum aestivum* L.) in early summer and corn (*Zea mays* L.) in late summer (Balkcom et al., 2011). The sunn hemp treatment produced 43 and 33% greater rye biomass as compared with rye following fallow, averaged over two planting dates for both years of the study following winter wheat. Rye biomass production following sunn hemp after corn was equivalent to the fallow treatment. Sunn hemp seeding rate following wheat or corn had no effect on rye biomass production (Balkcom et al., 2011). Although sunn hemp following wheat improved rye biomass production, the added complexity of cropping sequence management must be considered for this to be a viable option.

In many areas of the southeastern United States, poultry litter is a readily available N source typically land-applied to both pastures and row crops (Feng et al., 2015). Poultry litter contains both mineral and organic N (Tewolde et al., 2015), which, due to its slow N release that occurs over a long period, raises environmental concerns for fall and winter applications to bare soil (Feng et al., 2015; Tewolde et al., 2015). Above freezing soil temperatures following application allow a higher portion of the organic N to convert to mineral N forms, which becomes susceptible to leaching and volatilization losses (Feng et al., 2015; Tewolde et al., 2015). Winter cover crops can alleviate concerns associated with potential N leaching losses, regardless of N source. Cereals, such as rye, are considered the best choice due to their winter hardiness and ability to scavenge N (Dabney et al., 2001; Kaspar et al., 2007; Lacey and Armstrong, 2015; Tewolde et al., 2015).

Poultry litter offers an advantage as an N source in a cover crop–cash crop system because the mineral N fraction would be readily available to the cover crop, while the organic fraction that mineralizes slowly over time could contribute to the N requirements of the subsequent summer crop. Previous research examining N applications to cover crops typically have focused on how N applied to the cover crop affects subsequent crop N requirements, particularly for an organic N source like poultry litter (Endale et al., 2008; Tewolde et al., 2015). Minimal research has been conducted focusing primarily on cover crop biomass production following fertilizer or poultry litter applications. Ryan et al. (2011) examined how rye seeding rate and poultry litter rate affected biomass production and subsequent weed suppression associated with biomass levels. Despite

multiple benefits associated with increased biomass production in the southeastern United States, information regarding N application times, sources, and optimal rates to maximize cereal cover crop biomass production is limited. Therefore, our objective was to compare N fertilizer sources, application times, and rates to determine biomass production, N content, C/N ratio, RE_N, and costs for a rye winter cover crop.

MATERIALS AND METHODS

A 3-yr field study was conducted at the Wiregrass Research and Extension Center, Auburn University, in Headland, AL (31°21.4' N, 85°19.4' W; 113 m above sea level), on a Fuquay sand (loamy, kaolinitic, thermic Arenic Plinthic Kandiudults) during the 2006, 2007, and 2008 growing seasons. This experiment was initiated in the fall of 2005 and contained a cereal rye ('Wrens Abruzzi') cover crop followed by strip-tillage cotton (*Gossypium hirsutum* L.) that remained in the same location each year with no re-randomization of treatments.

The experimental design consisted of a split-split plot treatment restriction in a randomized complete block design with four replications. Main plots (14.7 × 48.8 m) consisted of time of application (fall and spring), subplots were N source (commercial fertilizer and poultry litter), and sub-subplots (7.3 × 12.2 m) were N rates defined as a control, low, medium, and high rates. These categories correspond to the four N rates for each N source (0, 34, 67, and 101 kg N ha⁻¹ as ammonium nitrate [NH₄NO₃] commercial fertilizer and 0, 2.2, 4.5, and 6.7 Mg ha⁻¹ poultry litter on an as-sampled basis). Mineral N supplied by commercial fertilizer was consistent across years and application times, but mineral N supplied by poultry litter was not consistent across years and application times. Poultry litter sources are typically not consistent with variability attributed to differences in ratios of litter to wood shavings, time of house clean out, feed conversion, and length of time and temperature conditions for stacking (Gascho et al., 2001). Table 1 shows the estimated mineral N from poultry litter compared with commercial fertilizer rates based on 50% mineralization of the total N contained in poultry litter becoming available the first year of application (Endale et al., 2008; Reddy et al., 2008).

The rye cover crop was established at 101 kg ha⁻¹ across the experimental area each fall (19 Nov. 2005, 9 Nov. 2006, 2 Nov. 2007) with a no-till drill (Great Plains Mfg., Salina, KS) on 19-cm rows. Routine composite soil samples were collected randomly across blocks with a 2.54-cm soil probe to 30 cm each year to evaluate soil test ratings for P, K, and lime, which were considered "high" based on Alabama Experiment Station recommendations for cotton (Adams et al., 1994). Fall cover crop fertilization was applied on 12 Dec. 2005, 4 Dec. 2006, and 19 Nov. 2007 after cover crop stand establishment, whereas spring cover crop fertilization was applied on 8 Feb. 2006, 7 Feb. 2007, and 14 Feb. 2008. Commercial fertilizer and poultry litter were surface-applied by hand at each application time.

Biomass yield was determined, prior to chemical termination, by cutting aboveground tissue from two random 0.25 m² areas within each sub-subplot, drying at 55°C for 72 h, and weighing. Cover crop termination occurred on 20 Apr. 2006, 16 Apr. 2007, and 21 Apr. 2008 and was not based on growth stage. However, rye termination was delayed as long as possible

Table 1. Estimated poultry litter (PL) available N based on 50% mineralization of the total N contained in poultry litter becoming available the first year of application compared to commercial fertilizer rates across fall and spring application times during the 2006–2008 growing seasons at the Wiregrass Research and Extension Center, Auburn University, Headland, AL.

Crop year	Time of application	N rate					
		Low		Medium		High	
		Fertilizer	PL	Fertilizer	PL	Fertilizer	PL
kg ha ⁻¹							
2005–2006	Fall	34	38	67	76	101	115
	Spring	34	37	67	73	101	110
2006–2007	Fall	34	27	67	53	101	80
	Spring	34	35	67	69	101	104
2007–2008	Fall	34	32	67	64	101	96
	Spring	34	33	67	66	101	100

to maximize biomass production and subsequent benefits for each treatment and respective growing conditions observed each year (Balkcom et al., 2015). Cover crop termination dates corresponded to approximately 3 wk before the anticipated cotton planting date. After chemical termination with glyphosate [*N*-(phosphonomethyl)glycine] (Monsanto Company, St. Louis, MO) sprayed at 0.84 kg a.e. ha⁻¹, all plots were rolled (Ashford and Reeves, 2003) to form a cover crop mat on the soil surface by laying the cover crop residue down parallel to the direction of planting.

All collected cover crop tissue was ground to pass through a 2-mm screen with a Wiley mill (Thomas Scientific, Swedesboro, NJ), then ground further to pass through a 1-mm screen with a Cyclone grinder (Thomas Scientific, Swedesboro, NJ). Subsamples were analyzed for total C and N by dry combustion on a LECO TruSpec-CN analyzer (Leco Corp., St Joseph, MI). Nitrogen content present in the cover crop tissue was determined by multiplying total N concentration by the corresponding cover crop biomass yield. The C/N ratio was determined by dividing total C concentration by total N concentration. Nitrogen uptake efficiency, defined as RE_N by Cassman et al. (2002), was calculated using the difference method.

Economic Analysis

An economic analysis was conducted to compare differences in biomass production costs associated with N source and rate. Variable costs related to cover crop planting, fertilization, and termination were included in the analysis. Cost was assumed not to vary across application timing (fall vs. spring). Total cost for cover crop seed, planting, and termination was estimated at US\$98.72 ha⁻¹ (Shurley and Smith, 2017), regardless of treatment. Total cost for NH₄NO₃ was estimated at US\$0 ha⁻¹ (zero rate), US\$54.51 ha⁻¹ (low rate), US\$93.02 ha⁻¹ (medium rate), and US\$132.70 ha⁻¹ (high rate), including commercial fertilizer (US\$1.17 kg⁻¹; USDA, 2017) and custom field application (US\$14.83 ha⁻¹). Total cost of poultry litter was estimated at US\$0 ha⁻¹ (zero rate), US\$106.70 ha⁻¹ (low rate), US\$218.25 ha⁻¹ (medium rate), and US\$324.95 ha⁻¹ (high rate), including poultry litter and custom field application (US\$48.50 Mg⁻¹; Shurley and Smith, 2017). The cost of producing 100 kg of biomass was calculated as the total cost of cover crop establishment and termination plus either commercial fertilizer or poultry litter (US\$ ha⁻¹) divided by biomass

(100 kg ha⁻¹). As biomass production increases, cost of production decreases for a given N source and rate.

Statistical Analysis

All dependent variables (biomass, N content, C/N ratio, RE_N, and US\$ 100 kg⁻¹ biomass) were analyzed using linear mixed models procedures within SAS PROC GLIMMIX (SAS Institute, 2013). Fixed effects for the previously described experimental design included timing, source, rate, and interactions among these factors. Random terms included year block(year), timing × block(year), and source × block(year timing). During the analyses, normal distributions were used to describe residuals for RE_N, while the lognormal distribution was required to produce normally distributed residuals for the remaining variables. The lognormal distribution requires values to be back transformed to the original scale so values can be easily distinguished among treatment levels using meaningful values. During the analysis, the difference between any two means on a log_e scale (log_e of y1 – log_e of y2) is defined also as the log_e of the ratio between means on the original scale (log_e of y1/y2). Therefore, back transforming the difference (*e*^{difference}) is defined as the mean ratio. The corresponding least significant difference (LSD), calculated from the ANOVA of the log_e transformed data is also back transformed using *e*^{LSD} and denoted as the least significant ratio (LSR). The LSR defines the point where two means can be considered different from each other at a given significance level. Both ratios represent the percentage difference between means. The SLICE option for the LSMEANS command was used to partition significant interactions among fixed effects. If single degree of freedom contrasts indicated a significant linear or quadratic response, the specified regression model was fit with the PROC REG procedure of SAS using the corresponding numerical N rate values for the fertilizer N source. Previously defined, descriptive class variables were used to graphically represent inorganic N rates (Table 1) across both N sources. Treatment differences were considered significant if *P* > *F* was ≤ 0.10.

RESULTS AND DISCUSSION

Growing Conditions

Rainfall received during all three cover crop growing seasons differed from a 30-yr normal period (Fig. 1A). The 2006 and 2007 growing seasons received less rainfall, while the 2008 growing season received more rainfall compared with the 30-yr normal. Cumulative total rainfall measured during the 2006 and 2007 growing seasons were 37 and 11% lower than the 30-yr normal. Rainfall measured for the 30-yr normal, 2006, and 2007 growing seasons were similar, except for March and April (Fig. 1A). In 2006, minimal rainfall was received during March and April. In 2007, March was also dry, whereas April was wet. Cumulative total rainfall measured during the 2008 growing season was 18% greater than the 30-yr normal with rainfall measured during all months, except November, exceeding the 30-yr normal (Fig. 1A). Growing degree days were similar between cover crop growing seasons and the 30-yr normal period, except for the cooler 2006 growing season (Fig. 1B). Although 2006 was cooler, cumulative growing degree days were similar among growing seasons and the 30-yr normal with a range of 162 growing degree days.

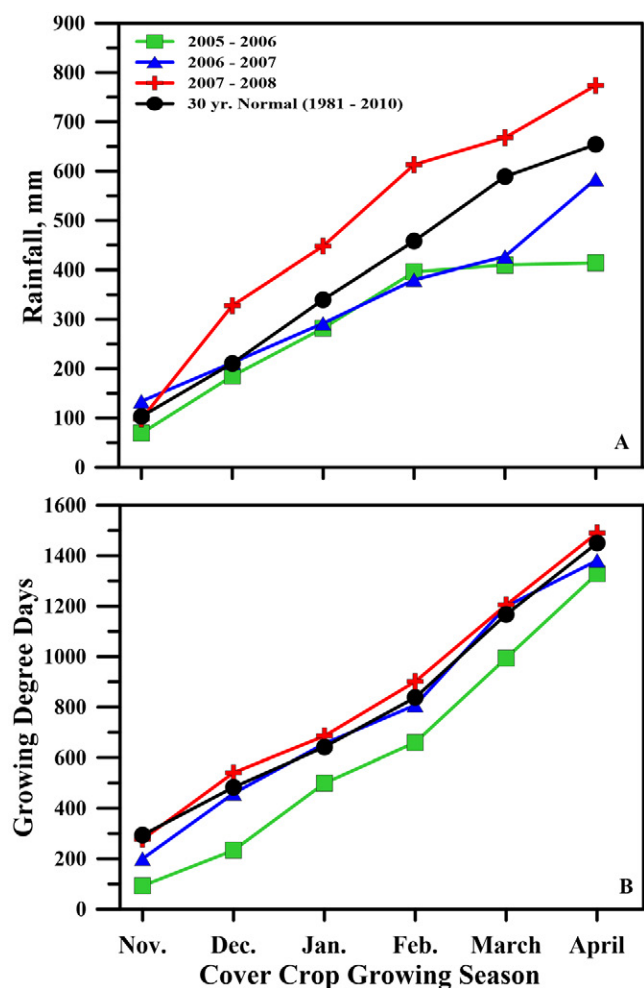


Fig. 1. Monthly rainfall (A) and growing degree day (B) calculations (4.4°C) recorded for the 2006–2008 cover crop growing seasons compared with a 30-yr normal at the Wiregrass Research and Extension Center, Auburn University, Headland, AL. The 30-yr normal period corresponds to 2 Nov. 1981 to 21 April 2011.

Biomass Production

Source ($P = 0.0333$) and rate ($P \leq 0.0001$) each affected rye biomass production with rate exhibiting the greatest effect (Table 2). Commercial fertilizer produced 13% more biomass than poultry litter (Table 3), which may have been due to the inconsistent composition (Gascho et al., 2001) of poultry litter and/or rapid release of N from the organic component of poultry litter associated with mild fall and winter temperatures attributing to leaching losses (Feng et al., 2015), particularly on the sand soil type used in this experiment. Because cover crops, such as rye, are known to scavenge mineral N and reduce N leaching, we expected a similar response between both N source treatments (Dabney et al., 2001; Kaspar et al., 2007; Lacey and Armstrong, 2015). However, variability in the composition of poultry litter also affects when N becomes available through mineralization. Although the southeastern United States has the potential to produce mild temperatures during the fall and winter that would favor mineralization, N availability could also have been limited by an incorrect mineralization estimate (50%) for this study.

As expected, rye biomass production responded to additional N, regardless of source (Fig. 2). Previous research has shown cereal cover crops to be responsive to supplemental N, particularly in the humid southeastern United States on sandy textured

soils containing limited residual N levels (Balkcom et al., 2007a, 2007b). The biomass response to inorganic N present in both sources (Table 1) was linear, but the equation only explained 41% of the variability (Fig. 2). The linear response for biomass indicates that additional N would have produced more biomass, but high rates are not likely to be applied by growers, despite potential benefits, due to N costs for a non-harvested crop (Balkcom et al., 2007b). Future research should focus on determining biomass levels necessary to achieve specific soil health benefits.

Reiter et al. (2008) reported 67 kg N ha⁻¹ maximized rye biomass production for soil erosion protection, soil C accumulation, and improved soil quality in northern Alabama; however, 67 kg N ha⁻¹ was the highest rate used in their study. Reiter et al. (2008) reported an average biomass production of ~5120 kg ha⁻¹ on a Decatur silt loam (fine, kaolinitic, thermic Rhodic Paleudult) in northern Alabama with 67 kg N ha⁻¹. Biomass production measured on the Fuquay sand produced an equivalent amount of biomass (5250 kg ha⁻¹) at the medium N rate (~67 kg N ha⁻¹), based on the linear equation (Fig. 2). However, Reiter et al. (2008) speculated high rainfall amounts for one growing season contributed to N losses, which lowered the overall average biomass production in northern Alabama.

Although rate exhibited the greatest effect on biomass production, interactions between rate and timing and rate and source were also observed (Table 2). The timing × rate interaction ($P = 0.0253$) indicated biomass production with fall-applied and spring-applied N both responded linearly, but fall-applied N produced more biomass than spring-applied N only at the medium and high N rates (Fig. 3A). Low N rates produced similar biomass levels, regardless of timing. The low N rate, which corresponds to a lower N management cost for the cover crop, indicates fall- or spring-applied N were equally effective (Fig. 3A), providing growers more flexibility with their cover crop N application. Timing appeared to be more important as N rates for the cover crop increase. An examination of the source × rate interaction ($P = 0.0656$) revealed biomass response to fertilizer was quadratic, whereas the response to poultry litter was linear (Fig. 3B). Fertilizer produced more biomass for a given N rate as compared with poultry litter, but final biomass production at the high N rate was similar between sources (Fig. 3B).

Nitrogen Content

Nitrogen content of the aboveground tissue was affected by source ($P = 0.0404$), rate ($P \leq 0.0001$), and a source × rate interaction ($P = 0.0457$) (Table 2). Nitrogen content for rye receiving fertilizer averaged approximately 16% higher than for rye receiving poultry litter (Table 3). Nitrogen content across cover crop N rates ranged from approximately 21 kg ha⁻¹ to 59 kg ha⁻¹ and responded linearly to the N applied (Fig. 4A). Reeves (1994) noted that N content of small grain cover crops can vary widely and reported values between 13 kg ha⁻¹ and 100 kg ha⁻¹ from various studies. The source × rate ($P = 0.0457$) interaction revealed a linear response to N for both sources, and a slight advantage for fertilizer N as compared to poultry litter N (Fig. 4B).

Carbon/Nitrogen Ratio

Timing ($P \leq 0.0001$), rate ($P \leq 0.0001$), and a timing × rate interaction ($P = 0.0028$) all affected the C/N ratio with timing

Table 2. Analysis of variance for rye biomass, N content, C/N ratio, N fertilizer recovery efficiency (RE_N), and US\$ per 100 kg of biomass for the 2006–2008 cover crop growing seasons at the Wiregrass Research and Extension Center, Auburn University, Headland, AL.

Effect	df	Biomass		N content		C/N ratio		RE _N		US\$ 100 kg ⁻¹	
		F ratio	Prob > F	F ratio	Prob > F	F ratio	Prob > F	F ratio	Prob > F	F ratio	Prob > F
Timing (T)	1	1.61	0.2301	0.82	0.3834	27.44	0.0003	0.34	0.5742	1.61	0.2301
Source (S)	1	5.16	0.0333	4.75	0.0404	0.40	0.5347	2.81	0.1078	76.53	<0.0001
T × S	1	0.38	0.5452	0.01	0.9229	2.15	0.1566	3.40	0.0789	0.38	0.5452
Rate (R)	3	91.70	<0.0001	82.79	<0.0001	14.92	<0.0001	0.92	0.4034	4.40	0.0055
T × R	3	3.21	0.0253	0.60	0.6188	4.94	0.0028	0.20	0.8151	3.21	0.0253
S × R	3	2.46	0.0656	2.74	0.0457	1.25	0.2952	1.27	0.2871	17.19	<0.0001
T × S × R	3	1.61	0.1897	1.46	0.2279	2.04	0.1112	2.85	0.0635	1.61	0.1897

Table 3. Means for timing and source comparisons across rye biomass, N content, C/N ratio, N fertilizer recovery efficiency (RE_N), and US\$ per 100 kg of biomass averaged across the 2006–2008 cover crop growing seasons at the Wiregrass Research and Extension Center, Auburn University, Headland, AL.

Timing and source main effect comparisons	LS-Means		Mean ratio†	LSR‡	Mean ratio > LSR§
	Fall	Spring			
Timing					
Biomass from fall vs. biomass from spring, kg ha ⁻¹	4211	3911	1.077	1.137	
Rye N content from fall vs. rye N content from spring, kg ha ⁻¹	34.5	37.2	1.079	1.161	
C/N ratio from fall vs. C/N ratio from spring	56.1	48.2	1.164	1.053	TRUE
RE _N for fall vs. RE _N for spring	39.2	34.3	¶		
US\$ 100 kg ⁻¹ from fall vs. US\$ 100 kg ⁻¹ from spring	4.55	4.90	1.077	1.110	
Source	Fertilizer	Poultry litter			
Biomass from fertilizer vs. biomass from poultry litter, kg ha ⁻¹	4315	3817	1.131	1.119	TRUE
Rye N content from fertilizer vs. rye N content from poultry litter, kg ha ⁻¹	38.5	33.3	1.154	1.120	TRUE
C/N ratio from fertilizer vs. C/N ratio from poultry litter	51.5	52.5	1.019	1.050	
RE _N for fertilizer vs. RE _N for poultry litter	43.7	29.9	¶		
US\$ 100 kg ⁻¹ from fertilizer vs. US\$ 100 kg ⁻¹ from poultry litter	3.73	5.99	1.605	1.097	TRUE

† Mean ratio = largest mean/smallest mean within a row.

‡ LSR = least significant ratio at $P = 0.10$.

§ If true, indicates a significant difference between means within a row.

¶ No mean ratio calculated because RE_N means were not back-transformed from a lognormal distribution.

exhibiting the greatest effect (Table 2). All C/N ratios were considered “high” and greater than the 25:1 to 30:1 threshold established to distinguish mineralization/immobilization of N (Tisdale et al., 1993; Reeves, 1994; Clark et al., 1997). Rye N concentration was greater for spring vs. fall application timing (data not shown). Consequently, the C/N ratio was lower for spring-fertilized rye compared with fall-fertilized rye (Table 3). This likely resulted from the overall greater biomass accumulation for fall-fertilized rye (Fig. 3B). Although rate affected the C/N ratio, a quadratic equation through the data only explained <10% of the variability (data not shown). The range of C/N ratios across N rates was small with values between 50:1 and 60:1 (data not shown).

Rye was grown to maximize biomass production by delaying termination as late as possible before planting the cash crop (Balkcom et al., 2015); therefore, the C/N ratio was also expected to be maximized for the growing conditions observed. Previous research has documented C/N ratio increases as cover crop termination dates increase from early to late (Wagger, 1989; Clark et al., 1994). The C/N ratio across all sources, application times, and rates for the three growing seasons ($n = 192$) ranged from 28:1 to 93:1 with a median value of 51:1 (data not shown). Although differences were observed among these factors (Table 2), the C/N ratio was not reduced to a level that would promote N mineralization and/or rapid decomposition. These differences were indicative of differences in maturity of the rye at termination. The differences in maturity

are most likely a result of the greater N availability to the fall fertilized rye enhancing the rate of rye development (phenological development, larger leaves, attaining reproductive stage earlier). Significant N loss can also occur during pollen shed when the rye is heading. Rumburg and Sneva (1970) estimated that 16 kg N ha⁻¹ could be lost via this mechanism.

Reiter et al. (2008) hypothesized that adding N to a rye cover crop would increase biomass and lower the C/N ratio, which would promote N mineralization for a subsequent crop. Reiter et al. (2008) applied up to 67 kg N ha⁻¹ as NH₄NO₃ to a rye (“Elbon”) cover crop in early spring. The subsequent N concentration in the rye at termination was 21.8 g N kg⁻¹ with a C/N ratio of 21:1 averaged across years (Reiter et al., 2008). These values contrasted with values from our study on the sandier soil in southern Alabama. The rye C/N ratio and N concentration reported by Reiter et al. (2008) was less than half our median C/N ratio (51:1) and more than two times (21.8 g N kg⁻¹ vs. 10.7 g N kg⁻¹) our highest measured rye N concentration (data not shown), despite more N applied at the “high” N rate (Table 1).

Balkcom and Burmester (2015) reported the high potential for residual N to be present in soils in northern Alabama following cotton, which may explain the discrepancy between the results Reiter et al. (2008) found in northern Alabama compared with our results in southern Alabama for N concentrations and subsequent C/N ratios. In addition, Reiter et al. (2008) applied all cover crop N, in northern Alabama, during

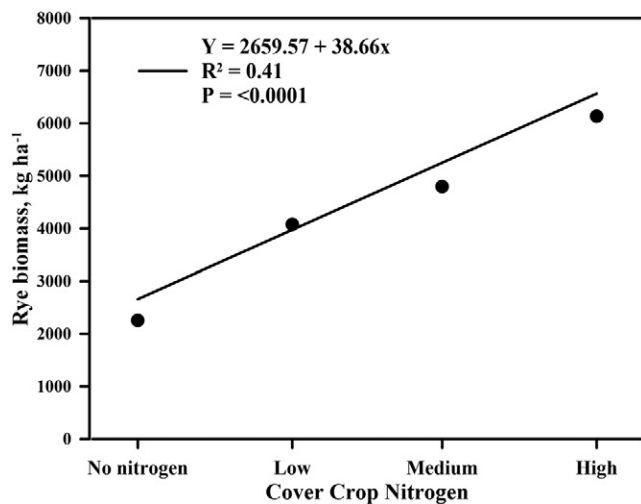


Fig. 2. Rye biomass measured across N rates during the 2006–2008 cover crop growing seasons at the Wiregrass Research and Extension Center, Auburn University, Headland, AL. Symbols represent means, while the line represents all data points. Class variables were used to define inorganic N rates (Table I) across each N source.

early spring, after a major portion of winter rainfall occurred, likely reducing potential for N loss. On the other hand, White et al. (2016) noted cover crop species, mixtures, environment, and management practices (Cherr et al., 2006; Poffenbarger et al., 2015; Finney et al., 2016) contribute to cover crop residue N content and C/N ratio variability.

The C/N ratio is a popular metric used to determine how quickly N will be released from plant residues (Wagger, 1989; Dabney et al., 2001), but the ratio can also simultaneously indicate how quickly plant residues can be expected to decompose. In general, legumes decompose faster than cereals (Schomberg and Endale, 2004; Starovoytov et al., 2010). As a result, plant residues that release N quickly, like legumes, reduce longevity of some benefits associated with surface residue, such as erosion control or weed suppression. For soils of the southeastern United States, residues, like rye, that are resistant to decomposition are beneficial for degraded soils. Burgess et al. (2002) suggested changes to surface residue management to increase soil organic C levels by retaining more row crop residue with higher C/N ratios. This principle also applies to the use of high-residue cereal cover crops. Cereals tend to produce residues that persist longer and provide erosion control or weed suppression benefits for a sustained period.

In contrast, a winter cereal, like rye, terminated early will produce low residue amounts with a low C/N ratio that will not persist on the soil surface to maximize residue benefits (Huntington et al., 1985; Reeves, 1994; Reiter et al., 2008). Although beyond the scope of this investigation, previous research has focused on using mixtures of cereals and legumes to manipulate C/N ratios (Clark et al., 1994; Blanco-Canqui et al., 2015; Poffenbarger et al., 2015). The goal of these mixtures was to produce a residue that allowed better synchronization of N release with subsequent plant uptake, while producing biomass levels that also promote erosion control and weed suppression.

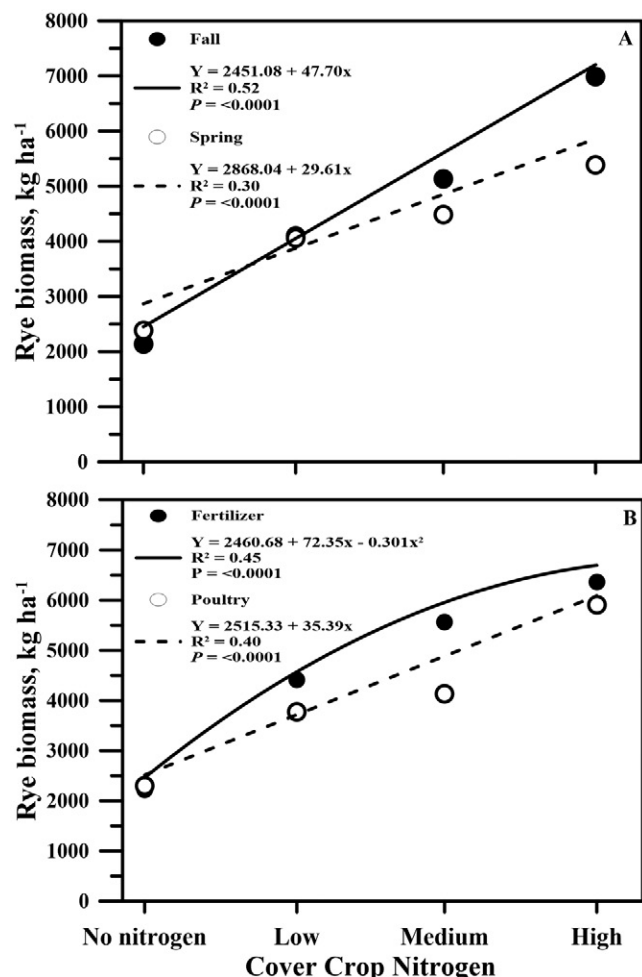


Fig. 3. Rye biomass measured across application time \times N rate (A) and N source \times N rate (B) interactions during the 2006–2008 cover crop growing seasons at the Wiregrass Research and Extension Center, Auburn University, Headland, AL. Symbols represent means, while the lines represents all data points. Class variables were used to define inorganic N rates (Table I) across each N source.

Nitrogen Fertilizer Recovery Efficiency

Cover crop RE_N calculated by the difference method was least affected by fixed effects examined in this study compared with other dependent variables (Table 2). Nitrogen fertilizer recovery efficiency across all effects averaged 37% (data not shown). This value corresponds to the 33% nutrient use efficiency value for worldwide cereal production estimated by Raun and Johnson (1999). A source \times timing ($P = 0.0789$) interaction indicated similar RE_N values ($\sim 40\%$) across sources for fall applications, but spring applications produced 145% higher RE_N for fertilizer compared with poultry litter (Fig. 5). This discrepancy between fall and spring applications for RE_N may be attributed to reduced initial availability of mineral N supplied by spring-applied poultry litter. Total N contained in poultry litter is the sum of the organic and mineral fractions, but, as previously discussed, the composition of poultry litter is highly variable. An estimate of the available N from poultry litter was based on 50% mineralization of the total N contained in poultry litter becoming available the first year of application. However, it was possible that the mineralization estimate overestimated N mineralization from spring-applied poultry litter during the period between

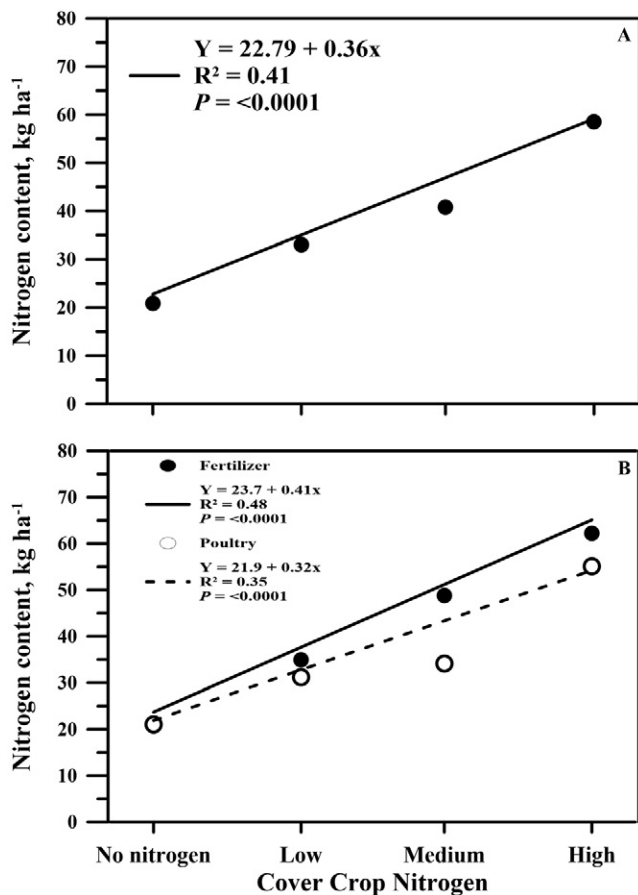


Fig. 4. Nitrogen contents for rye biomass measured across N rates (A) and the source \times rate interaction (B) during the 2006–2008 cover crop growing seasons at the Wiregrass Research and Extension Center, Auburn University, Headland, AL. Symbols represent means, while the lines represent all data points. Class variables were used to define inorganic N rates (Table 1) across each N source.

application and cover crop termination. For example, spring poultry litter applications occurred in early February with a late April cover crop termination date, which minimized the mineralization period and cover crop uptake period.

The RE_N analysis also indicated a timing \times source \times rate ($P = 0.0635$) interaction, although the agronomic significance associated with this interaction was minimal. The interaction consisted of small differences for RE_N between application times and N sources, primarily with RE_N decreasing from low N rates to high N rates (data not shown).

Monitoring N fertilizer recovery for cover crops is generally not practiced. However, in the southeastern United States where cereal cover crops are responsive to N fertilizer, examining N efficiencies is just as prudent for N management as maximizing N efficiencies for cash crops. Reiter et al. (2008) reported N efficiencies of 134, 35, and 97% using the difference method for rye fertilized with NH_4NO_3 in early spring (February–March) during the 2000–2002 growing seasons. The 2000 and 2002 cover crop growing seasons were generally drier and warmer compared with the 2001 cover crop growing season (Reiter et al., 2008). Reiter et al. (2008) speculated that high rainfall during the winter of 2001 likely increased N losses associated with denitrification and leaching compared with other growing

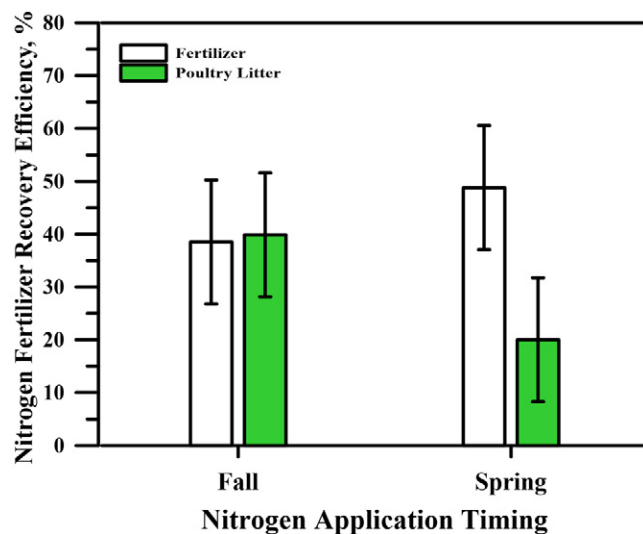


Fig. 5. Calculated N fertilizer recovery efficiencies using the difference method across the N source \times timing interaction during the 2006–2008 cover crop growing seasons at the Wiregrass Research and Extension Center, Auburn University, Headland, AL. Bars represent 90% confidence intervals around the means.

seasons, which combined with a slightly shorter growing season also subsequently reduced cover crop biomass levels.

Although all data were analyzed and presented across years, growing conditions varied among years (Fig. 1). Nitrogen management strategies to offset year-to-year weather variability should be considered. For example, a wet fall would likely promote some leaching of fall-applied N on these coarse-textured soils, despite the scavenging abilities of a winter cereal like rye, because there is limited growth of rye during this period. Delaying cover crop N applications until the spring could minimize N loss potential during a wet winter and improve N fertilizer recoveries. Accurate weather forecasting to predict general patterns of wet vs. dry and cool vs. hot for a 3- to 4-mo period, such as El Niño or La Niña weather oscillations, could also guide optimal application times. Split N applications were not examined in this study, but this practice could also be used to improve fertilizer recoveries. However, the question remains as to whether growers would have an economic incentive to make two trips across the field to fertilize a cover crop.

Biomass Economics

In the southeastern United States, the need to apply N to a cereal cover crop to enhance biomass production adds additional costs to cover crop production beyond seeding, planting, and termination costs that should be accounted for in cover crop budgets. Source ($P \leq 0.0001$) and rate ($P = 0.0055$) affected cost required to produce 100 kg biomass with source exhibiting the greatest effect (Table 2). We assumed the cost of N from fertilizer and poultry litter, respectively, was held constant across years and application times. As a result, observed cost differences to produce 100 kg biomass were correlated to biomass production across treatments (Table 2). Although various two-way interactions were observed among timing, source, and rate (Table 2), the agronomic and economic significance coincide with and can be summarized through the main effects (Table 3).

The greatest cost difference was observed between sources resulting from less biomass produced from poultry litter and

higher cost of poultry litter (Table 3). The cost of poultry litter depends on the proximity to the litter and procurement method. Analyses performed with poultry litter at half the reported cost (Shurley and Smith, 2017) indicated cost per 100 kg biomass was reduced, but remained greater than commercial fertilizer (data not shown). However, poultry litter contains other nutrients, which may benefit a cover crop and subsequent cash crop, and N mineralization from poultry litter may also promote subsequent crop growth comparable to commercial fertilizer N (Gascho et al., 2001; Reddy et al., 2004; Mitchell and Tu, 2005; Endale et al., 2008; Tewolde et al., 2016).

Rate increased cost required to produce 100 kg biomass when moving from the zero rate (US\$4.37 kg⁻¹) and low rate (US\$4.35 kg⁻¹) to the medium (US\$5.13 100 kg⁻¹) and high rate (US\$5.10 100 kg⁻¹). The linear equation through the four rates explained 38% of the variability (data not shown). As expected, the highest N rate produced the most biomass (Fig. 2); however, the cost to produce 100 kg biomass at the highest N rate was not statistically different from the medium rate. This finding only focuses on the cost to produce biomass and does not take into account any benefits associated with biomass production, such as reduced soil erosion and improved weed control. Although the cost for the low rate was US\$0.78 100 kg⁻¹ less than the cost for the medium N rate, benefits associated with a higher level of biomass for the following cash crop were not identified in this analysis since the focus was on the cover crop. In general, cover crop benefits associated with a single species increase as biomass levels increase, which are attributed to increased C inputs from the surface residue (Follett, 2001). However, Finney et al. (2016) reported that in addition to increasing biomass, functional traits such as C/N ratio may also enhance cover crop benefits, particularly for cover crop mixtures.

SUMMARY AND CONCLUSIONS

Commercial fertilizer produced 13% more biomass compared to poultry litter. Differences between sources were more pronounced when costs required to produce the biomass were considered based on assumed prices of commercial fertilizer and poultry litter. Lower biomass production and higher costs for poultry litter reduced the feasibility of poultry litter as an N source strictly for cover crop biomass production. However, these factors ignore potential residual N effects for the subsequent crop, soil quality benefits related to carbon additions, as well as benefits associated with other nutrients contained in poultry litter.

Nitrogen contents generally corresponded to biomass production. Nitrogen contents were 16% greater when fertilizer was applied compared with poultry litter applications. All C/N ratios were considered high and indicative of N immobilization and resistance to decomposition. Higher C/N ratios were measured for rye receiving fall-applied N compared with rye receiving spring-applied N. Subsequently, expected resistance to decomposition would be greater for rye receiving fall-applied N. Nitrogen fertilizer recovery efficiency averaged 37% across the experiment with fall applications producing consistent RE_N values across sources. Nitrogen recovery for fertilizer-applied in spring was 145% higher compared with poultry litter applied in spring.

Based on the conditions and location of this experiment, fall applications of commercial fertilizer N produced superior

results across the cover crop metrics examined in this study. Results also confirm that N applied to the cover crop was imperative for increased biomass production. An N rate recommendation for the cover crop is more difficult to quantify because biomass produced should be quantified into a benefit or group of benefits. The ideal N rate likely corresponds to grower comfort level associated with cost required to produce the biomass and expected positive impact on the subsequent cash crop. In this experiment, biomass produced was greatest for the highest N rate, but this was also the most expensive; however, associated benefits to the subsequent crop were not quantified. Ultisols, prevalent across the southeastern United States, should benefit in multiple ways from increased levels of surface residue associated with fertilized cover crops.

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