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Influence of cover crops on potential nitrogen availability to succeeding crops in a Southern Piedmont soil

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Abstract Winter cover crops are essential in conservation tillage systems to protect soils from erosion and for improving soil productivity. Black oat (*Avena strigosa* Schreb) and oilseed radish (*Raphanus sativus* L.) could be useful cover crops in the southeastern USA, but successful adoption requires understanding their influence on N availability in conservation tillage systems. Black oat and oilseed radish were compared to crimson clover (*Trifolium incarnatum* L.) and rye (*Secale cereale* L.) for biomass production and effects on N mineralization during the summer crop growing season from fall 1998 through summer 2002 near Watkinsville, GA. Rye produced 40 to 60% more biomass, although N contents were less than the other cover crops. Oilseed radish and black oat N contents were similar to crimson clover. Black oat, oilseed radish, and crimson clover C/N ratios were less than 30, whereas rye averaged 39. Amount of N mineralized in 90 days (N_{min90}) measured with in situ soil cores was 1.3 to 2.2 times greater following black oat, crimson clover, and oilseed radish than following rye. No differences in N_{min90} were found between black oats, crimson clover, and oilseed radish in 1999 and 2000. The amount of potentially mineralizable N (N_0) was not different due to cover crop, but was 1.5 times greater in 2000 and 2002 than in 1999. The rate of N mineralization (k) was 20 to 50% slower following rye than the other three cover crops. Black oat and oilseed radish biomass production and soil N mineralization dynamics were more similar to crimson clover than to rye, which indicates that they could be used as cover crops in the southeast without significant changes in N recommendations for most crops.

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Introduction

Conservation tillage is used on nearly 40% of the cropped acreage in the southeastern USA (CTIC 2004), and winter cover crops are essential in these systems to protect soils from erosion and for improving soil productivity (Bruce et al. 1995). Availability of C and N in decomposing residues and soil organic matter influences the mineralization–immobilization process and the amount of N available to subsequent crops (Hadas et al. 2004). Because surface residues accumulate in conservation systems and decompose more slowly, the impacts on N mineralization–immobilization processes and N management are more complex (Wagger et al. 1998; Schomberg and Cabrera 2001; Schomberg and Endale 2004).

Winter rye and crimson clover are grown as winter cover crops in the southeastern USA (Reeves 1994). Rye establishes rapidly and produces significant biomass early, which can help reduce soil erosion and contribute to increased soil carbon. Crimson clover is slower to establish and produces less biomass than rye; but because it is a legume, it can provide additional N (30 to 90 kg ha^{-1}) to subsequent crops (Wagger et al. 1998) along with food and refuge for beneficial insects, thus enhancing system diversity (Tillman et al. 2004).

Black oat and oilseed radish are grown in southern Brazil and Paraguay and could be good cover crops for use in the southeastern USA. Black oat is used widely in southern Brazil for grazing, grain production, and as a cover crop (Derpsch 2002). Dry matter production is similar to rye; and like rye, the residues have a large carbon to nitrogen ratio

(C/N) which can influence soil N mineralization–immobilization (Derpsch 1990). Bauer and Reeves (1999) found that cotton (*Gossypium hirsutum* L.) yields were 120 kg ha^{-1} greater following black oat than following rye on a coastal plain soil in South Carolina, USA. Greater cotton yield following black oat may have been due to greater N availability because C/N of black oat has been shown to be lower than that of rye (Ceretta et al. 2002).

Oilseed radish has been used in southern Brazil as a fodder crop and cover crop. It grows rapidly in the fall and spring and can scavenge significant quantities of N, but the residues decompose very rapidly due to their low C/N ratio. In addition to its influence on N cycling, oilseed radish contains glucosinolates (thioglucoside-*N*-hydroxysulfates), the precursors of isothiocyanates, chemicals known for their fungicidal, bacteriocidal, nematocidal, and allelopathic properties and are the focus of medical research because of their potential cancer chemoprotective attributes (Fahey et al. 2001).

Understanding cover crop influences on N mineralization is important for developing N management strategies in conservation systems. One approach for determining N mineralization rates in different management systems is through the use of soil cores in conjunction with ion exchange resins (DiStefano and Gholz 1986; Cabrera et al. 1994; Kolberg et al. 1997; Brye et al. 2002). Undisturbed soil cores, because they are not subject to physical disturbance, provide realistic estimates of mineralization rates under field conditions by incorporating the many factors that control N mineralization rates including resource quality and climate. Field incubations are, however, subject to greater variability because cores are not homogeneous composite samples and because of the inherently large spatial variability of N mineralization (Kolberg et al. 1997; Mahmoudjafari et al. 1997; Carpenter-Boggs et al. 2000; Brye et al. 2002). Even with these limitations, in situ soil cores can be useful for evaluating management influences on N mineralization in agroecosystems (Brye et al. 2002; Kolberg et al. 1999; Schomberg and Endale 2004).

Limited information is available on the suitability of black oat and oilseed radish as winter cover crops in the southeastern USA. More information is needed on the growth potential as well as their effects on short- and long-term N availability in conservation tillage systems. Of particular interest are their effects on soil organic C and N and potential N availability, which is critical for developing appropriate N management strategies. This study compares growth and effects on N mineralization of black oat and oilseed radish to rye and crimson clover to determine the potential for black oat and oilseed radish to be useful cover crops in the southeastern USA.

Materials and methods

Experimental design and agronomic operations

Winter cover crop growth and effects on N mineralization in conservation tillage systems were evaluated from fall 1998 to 2002 at the J. Phil Campbell, Sr., Natural Resource Conservation Center (USDA Agricultural Research Service, Watkinsville, GA; 33°59′N, 83°27′W). Four cover crops, crimson clover, oilseed radish, black oat, and rye, were compared in a randomized complete block with six replications. Plots were 6 m wide by 30 m long and were on a Cecil soil (sandy clay loam, fine, kaolinitic, thermic Typic Kanhapludult, with 2–3% slope), typical of the Southern Piedmont landscape, that was used for bermudagrass (*Cynodon dactylon* L. Pers.) hay production during the previous 4 years. Preparation for the study began 15 September 1998, when the area was sprayed with glyphosate [*N*-(phosphonomethyl)glycine] and disked about 2 weeks later. Cover crops were planted using a no-till drill 16 October 1998, 5 November 1999, 15 December 2000, and 17 October 2001. They were killed with glyphosate each spring approximately 3 weeks prior to planting the summer crop. Soybean (*Glycine max* L. Merr.) was grown in 1999, but due to excessive deer (*Odocoileus virginanus* Zimm.) damage, cotton was grown in 2000, 2001, and 2002. Summer crops were planted in 76 cm rows with a four-row no-till planter 20 May 1999, 24 May 2000, 26 May 2001, and 15 May 2002 and were harvested 29 October 1999, 15 November 2000, and 8 November 2002. Because of poor cover crop establishment and growth in winter of 2001, cover crop biomass and N mineralization measurements were not collected during the summer of 2001. The cotton crop planted in spring of 2001 was not harvested but was mowed near the end of September.

Cover crop mass and N content

Cover crop biomass was determined each year in the spring prior to application of herbicides. Plant material in a 0.75-m quadrate was cut near the soil surface from two locations per plot and then dried in a force draft oven at 55°C for 72 h before weighing to determine dry mass. Samples were ground and analyzed for C and N content using near infrared reflectance spectroscopy (NIRS). A subgroup of samples identified from the NIRS data was analyzed with a combustion type C and N analyzer to develop calibration regressions. The R^2 values for these regressions were greater than 95%.

Soil N mineralization

Nitrogen mineralization during the summer growing season was determined using in situ undisturbed soil cores (10 cm depth, 5 cm diameter) incubated for successive 2–5 week periods (DiStefano and Gholz 1986; Kolberg et al. 1997). The Cecil soil is typical of the Piedmont region where soils were degraded by the combined effects of a long history of conventional row cropping and loss of top soil due to erosion. Organic matter levels are often less than 0.5% for the plow layer. The soil C content of the study site is near 1.5% at the surface (0 to 2 cm), but declines to 0.5% below 5 cm. The majority of the N mineralized therefore comes from the upper soil depth with little contribution to N mineralization from below 8 to 10 cm. The soil cores used in this study therefore focus on the top 10 cm of soil. In 1999 and 2000, two cores per plot were incubated each period and analyzed separately. In 2002, three cores per plot were incubated each period but were composited for analysis. Cores were located between summer crop rows by driving an 11-cm long aluminum cylinder into the ground and removing it with the soil intact. A 25-mm-wide chisel with a square steel rod attached 1 cm from the tip was used to remove the lower 1 cm soil from the core. A mesh bag (made from nylon stockings) containing approximately 15 g (25 ml) of a 50:50 mixture of anion and cation exchange resins (Sybron Ionac ASB-1, C-249)[1] was placed in the cavity to capture NO_3^- and NH_4^+ leaching from the soil core (DiStefano and Gholz 1986; Kolberg et al. 1997). The complete assembly was returned to the same hole. An additional soil core was collected at each location to determine starting soil inorganic N content for each period. At the end of an incubation period, cylinders were removed from the ground, placed in clean plastic bags, and kept in a cooler until transported to the laboratory (usually within 2–3 h). New cores were established the same day that incubated cores were removed from the field. Cores were stored at 3°C and extracted within 3–5 days.

Soil was removed from the cores, passed through a 6.35-mm screen, and thoroughly mixed. A field moist sample equivalent to 10-g dry weight was extracted with 50 ml of 1 M KCl by shaking on a flatbed shaker for 1 h and then filtering through prewashed filter paper. Resin bags were extracted using three successive 20 min shakings with 20 ml of 1 M KCl (60 ml total). Three extractions recovered more than 85% of the N in the resin bags. An automated analysis system was used for determining NO_3^- and NH_4^+ (Technicon Industrial Systems 1977a,b).

Net N mineralized in each period was calculated as in Raison et al. (1987) as follows:

$$N_{\mathrm{min}}(t_1) = N_{\mathrm{soilcore}}(t_1) + N_{\mathrm{resin}}(t_1) - N_{\mathrm{soil}}(t_0) \tag{1}$$

where the initial inorganic soil N at time t_0 [$N_{\mathrm{soil}}(t_0)$] is subtracted from the inorganic N content at time t_1 contained in the incubated cores [$N_{\mathrm{soilcore}}(t_1)$] and in the resin bags [$N_{\mathrm{resin}}(t_1)$]. Cumulative N mineralization ($C_{\mathrm{um}}N_{\mathrm{min}}$) was calculated by summing the mineralized N for the summer growing season. A nonlinear regression approach was used to solve the following equation for N_0 (potentially mineralizable soil N) and the first-order rate constant (k):

$$C_{\mathrm{um}}N_{\mathrm{min}}(t_i) = N_0\left(1 - \exp^{-\mathrm{kt}}\right) \tag{2}$$

where $C_{\mathrm{um}}N_{\mathrm{min}}(t_{\mathrm{i}})$ is the cumulative N mineralized at time i (Cabrera et al. 1994). Water content of the soil cores was determined gravimetrically by drying a 10-g subsample for 48 h at 60°C. Soil bulk density, determined from core` volume and soil mass, was adjusted for water content and used in converting data to an area basis.

Model fitting and data analysis

Data were analyzed using Statistical Analysis System version 9.1 (SAS Institute 2004). The MIXED procedure in SAS STAT was used for evaluating differences among cover crops for biomass, total N content, and C/N ratio. Cover crop was considered a fixed effect, whereas year, replication, and the two-way interactions among year, replication, and cover crop were treated as random effects. Means were estimated as least square means. Values for k and N_0 in Eq. 2 were determined for each replication and cover crop within each year using the MODEL procedure in SAS ETS. Cover crop and year effects on N mineralized after 90 days (N_{min90}), N_0, and k were evaluated by mixed model analysis of variance using the MIXED procedure in SAS STAT (Littell 1989). Fixed and random effects were the same as for the above analyses. Due to nonconvergence in the fitting process, the number of replications for a cover crop is different among years. The KENWARDROGER option was used to adjust degrees of freedom for differences in number of replications. Because rye is the standard cover crop in the southeastern USA, analysis of variance contrasts were used to evaluate differences for response variables between rye and the other three cover crops. Differences were considered significant at α=0.10 unless otherwise stated. Relationships among measured variables were investigated through correlation analysis using the CORR procedure of SAS BASE. Pearson correlations were determined and used with graphic output.

Results and discussion

Cover crop biomass, total N content, and C/N ratio

Climatic conditions for the cover crop growing seasons are presented in Fig. 1a,b. The 1998–1999, 1999–2000, and 2001–2002 growing seasons had temperatures typical for the region. Each year experienced short periods of sustained freezing temperatures in December through March. Fall of 2000 was wet and cool which delayed field operations. Cover crop establishment was slow after late planting, and a long period of freezing temperatures caused significant winter kill. These factors eliminated the possibility of data collection in 2001. Rainfall during 1999–2000 was close to normal, whereas rainfall for 1998–1999 and 2001–2002 was below normal.

Aboveground biomass was significantly influenced by year (P=0.011), type of cover crop (P=0.005), and the interaction between cover crop and year (P<0.001) (Table 1). Biomass production was greatest in spring 1999 compared to the other 2 years, whereas biomass production in spring 2000 was not different from that in spring 2002. Lower biomass production in 2000 and 2002 was related to two factors: first cover crops planted in the fall of 1998 were

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[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA–Agricultural Research Service.

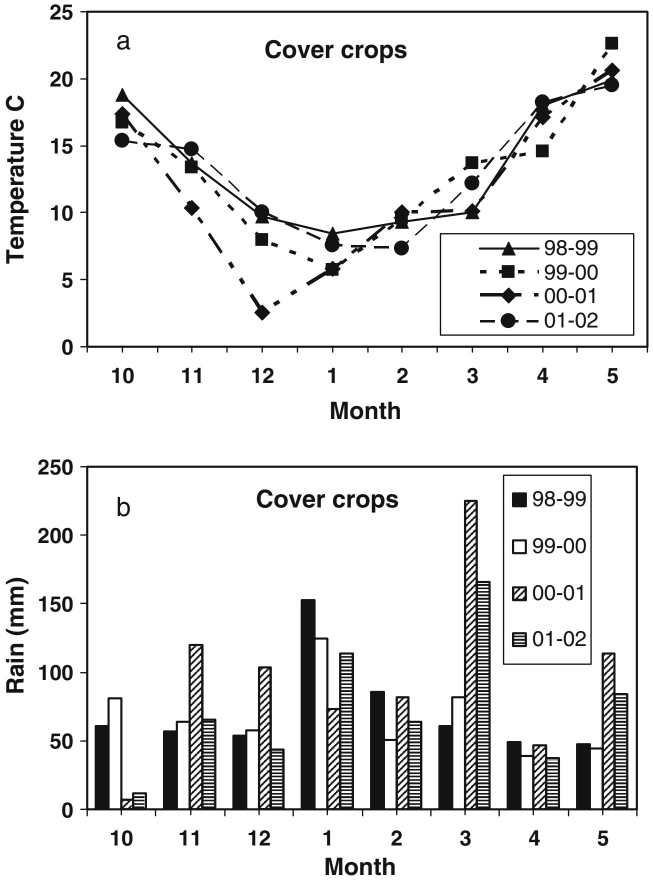

Fig. 1 Monthly average air temperature (**a**) and monthly rainfall (**b**) for the cover crop growing seasons

planted into a disked soil which would have been warmer, thus promoting faster establishment. We also added N to the cover crops, except crimson clover because the soil fertility for the area had not been maintained over the past 4 years. Cover crops in subsequent years were planted directly into standing summer crop residues and did not receive additional N because we were applying N to the cotton crop. Late planting dates for the cover crops also contributed to the lower biomass production. Cover crops were planted later in the fall of 1999 and 2000 compared to fall of 1998 and 2001. No data were collected on the plots during the summer of 2001 because of weather-related difficulties described in the Materials and methods. Compared with rye, the other cover crops produced about 40 to 60% less biomass depending on the year. The largest difference between rye and the other cover crops occurred in 2000, and the smallest difference in 1999.

Total N content of the aboveground biomass was influenced by a significant interaction between year and type of cover crop ($P<0.001$). In 1999 and 2002, total N content of rye was less than crimson clover, but was not different from black oat or oilseed radish. In 2000, rye had more total N than the other three cover crops. The greater aboveground biomass accumulation of rye resulted in more N compared to the other cover crops in 2000. Nitrogen in rye, black oat, and oilseed radish came from mineralized soil organic N or residual mineral N following the summer crop, whereas a portion of the N in crimson clover was derived from N_2-fixation. Crimson clover N content was thus increased over that of rye in 1999 and 2002, even with less biomass which would often be expected for legumes capable of fixing large quantities of N (Hargrove 1986). The other cover crops were apparently good at scavenging residual N remaining in the soil following the soybean and cotton crops. Averaged across the 3 years, total N content in the biomass of the four cover crops was similar.

The C/N ratio of cover crops was significantly influenced by year (P=0.001), type of cover crop ($P<0.001$), and the interaction between year and cover crop ($P<0.001$) (Table 1). The C/N ratios were greater in 1999 than in 2000 and 2002 (32.4 vs 22.9 and 18, respectively). Earlier cover crop planting date in 1999 resulted in greater phenological development. The C/N ratio of rye was greater than that of the other cover crops all 3 years, but was less than 50. Greater C/N ratios have been reported for mature rye, but our values are similar to others reported for rye used as a cover crop (Reeves 1994). We expected crimson clover to have a greater N concentration and possibly a greater N content than the other cover crops, but this was not true in all years. Black oat had a smaller C/N ratio than rye all 3 years, and in 2000 and 2002, the C/N ratio of black oat was more similar to that of crimson clover and oilseed radish. Black oat often appeared to have more leaves than rye, which would contribute to the smaller C/N ratio.

Biomass, N, and C/N ratios for the cover crops over the 3 years were similar to those reported previously for similar conditions in the southeastern USA. Reeves (1994) reported that rye biomass varied from 1.8 to 7.4 Mg ha^{-1} with N contents of 13 to 100 kg ha^{-1} and C/N ratios of 25 to 52, whereas crimson clover produces 2.4 to 7.2 Mg ha^{-1} biomass with 56 to 170 kg ha^{-1} N and has C/N ratios of 11 to 25. Bauer and Reeves (1999) reported ranges for black oat from 1.7 to 3.5 Mg ha^{-1} biomass, 16 to 32 kg ha^{-1} N, and C/N ratios 33 to 43 for October and November planting dates. Derpsch (1990) summarized data indicating that aboveground N content of black oat was greater than rye and wheat because of greater biomass and a smaller C/N ratio of black oat (28:1) than rye (42:1) or wheat (38:1). In Santa Maria, RS, Brazil, oilseed radish used as a cover crop produced 3.4 and 5.3 Mg ha^{-1} biomass, 45 and 73 kg N ha^{-1}, and had C/N ratios of 28 and 30 for 2 years (Ceretta et al. 2002).

N mineralized in 90 days

Weather conditions for the summer cropping seasons are presented in Fig. 2a,b. For 1999, 2000, and 2002, temperatures were similar to long-term averages, but rainfall was well below normal. Rainfall during the first month after planting was similar for the 3 years. Frequent small showers helped maintain adequate soil moisture for crop growth. Long periods of drought (20 to 30 days) were apparent for each year and usually occurred in July and August. Irrigation was required during a few of the extended drought periods during 2000 and 2002 to maintain

Table 1 Cover crop biomass, total N, and C/N ratio for 3 years and means across years and cover crops

Year	Crop	Biomass[a] (kg ha^{-1})	$P>t$[b]	Total N[a] (kg ha^{-1})	$P>t$[b]	C/N[a]	$P>t$[b]
1999	Black oat	5,193	0.001	72.5	0.312	32.0	0.001
1999	Crimson clover	5,052	0.001	105.8	0.054	19.9	0.001
1999	Oilseed radish	6,240	0.001	94.6	0.314	28.9	0.001
1999	Rye	9,397		83.6		48.7	
	CL±	827		16.2		3.1	
2000	Black oat	3,018	0.001	71.1	0.065	18.2	0.001
2000	Crimson clover	2,029	0.001	50.4	0.005	16.7	0.001
2000	Oilseed radish	3,267	0.001	74.7	0.097	18.1	0.001
2000	Rye	7,643		103.5		34.3	
	CL±	1,093		27.9		3.1	
2002	Black oat	2,150	0.000	77.5	0.908	12.4	0.001
2002	Crimson clover	4,276	0.067	146.0	0.003	12.7	0.001
2002	Oilseed radish	3,036	0.002	90.3	0.578	14.1	0.001
2002	Rye	5,642		79.7		32.7	
	CL±	1,021		25.5		1.6	
Means							
1999		6,470.3		89.1		32.4	
2000		3,989.1		76.5		21.9	
2002		3,775.8		85.0		18.0	
	CL±	636		10.9		3.1	
	Black oat	3,453	0.002	73.7	0.513	20.9	0.001
	Crimson clover	3,786	0.002	100.7	0.610	16.4	0.001
	Oilseed radish	4,181	0.004	86.5	0.916	20.4	0.001
	Rye	7,561		88.9		38.6	
	CL±	2,218		29.5		11.5	

[a] Values are least square means, and confidence limits (CL) were estimated at the 90% level

[b] Test of difference between rye and the other cover crops where $P>t$ indicates the level of significance for the test

crop growth and is included in the rainfall amounts in Fig. 2b.

We compared the cumulative N mineralized at 90 days ($N_{\mathrm{min}90}$) after planting to determine the influence of cover crop on N availability for summer crops. Year (P=0.087), cover crop (P=0.053), and year by cover crop (P=0.054) effects were apparent from the analysis of variance and indicated that differences in $N_{\mathrm{min}90}$ due to cover crop were not the same each year (Table 2). Values for $N_{\mathrm{min}90}$ were 44% greater in 2000 and 2002 compared to 1999. Among cover crop treatments, $N_{\mathrm{min}90}$ was 1.3 to 2.2 times greater following black oat, crimson clover, and oilseed radish compared to rye with the greatest differences in 2000. No differences in $N_{\mathrm{min}90}$ were found between black oats, crimson clover, and oilseed radish in 1999 and 2000. The $N_{\mathrm{min}90}$ following oilseed radish in 2002 was greater than expected for this soil. The amount of mineral N at the second sampling date was larger in several of the oilseed radish plots, which was probably the result of uneven fertilizer application or rapid release of mineral N from decomposing above- and below-ground residues of oilseed radish. Vyn et al. (1999) found that soil NO_3–N concentrations were higher in May following oilseed radish than following red clover (*Trifolium pratense* L.) or no cover crop, which suggests that N was released faster from oilseed radish than from red clover. In addition, N application to the summer crop may have stimulated N mineralization. Fertilization has been shown to increase microbial ammonification and specific respiration (Lovell and Hatch 1998) and the rate of mineralization of soil N (Woods et al. 1987) and cover crop residue N (Azam et al. 1995).

The in situ soil core method appears to be especially sensitive to high spatial variability of inorganic N in N-fertilized agroecosystems (Brye et al. 2002). Kolberg et al. (1997) observed a high degree of variability in a dryland agroecosystem. We observed greater amounts of N mineralized in 2000 and 2002 compared to 1999, and the estimates had a large variability. Nitrogen fertilizer may have increased N mineralization through a priming effect. Bingeman et al. (1953) suggested that N mineralization is different in fertilized and unfertilized agricultural soils. Significantly higher rates of net N mineralization following addition of fertilizer N have been observed by Brye et al. (2002) and Kolberg et al. (1999) using in situ soil cores.

N_0 and k

The amount of potentially mineralizable N as indicated by N_0 was different among years (P=0.029), but was not different due to cover crop (P=0.465) (Table 2). In 2000 and 2002, N_0 was 1.5 times greater than in 1999. The greater N_0 in 2000 and 2002 probably resulted from N inputs for summer crops. In 1999, no N was added to soybean, whereas N was added to cotton in 2000, 2001, and 2002. It was surprising that N_0 was not greater in 2002 than in 2000 because cotton was not harvested in 2001, thus leaving

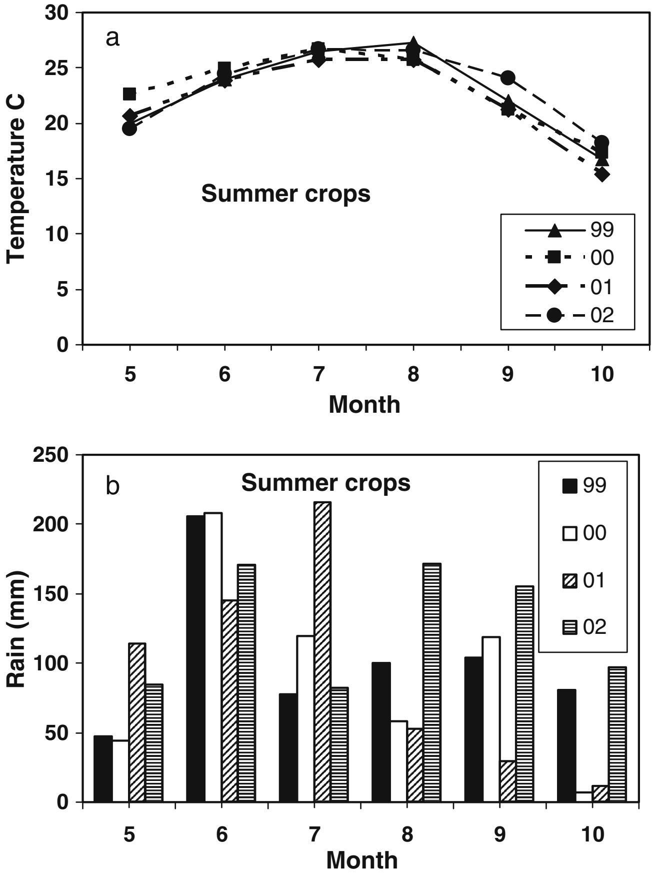

Fig. 2 Monthly average air temperature (**a**) and monthly rainfall (**b**) for the summer crop growing seasons

more N in the system following that cropping season. The analysis of variance contrast comparing rye to the other cover crops indicated a significant difference in N_0 between rye and crimson clover across years at P=0.07. This difference may be related to long-term inputs of N from N_2-fixation by crimson clover.

The rate of N mineralization was significantly influenced by the interaction between year and cover crop treatment (P=0.059) (Table 2). In 1999, k values in soil following black oat, crimson clover, and oilseed radish were similar and two times greater than in soil following rye. In 2000, k was 2.0, 1.8, and 1.4 times greater in soil following black oat, crimson clover, and oilseed radish than following rye. In 2002, k was 1.9 times greater in soil following oilseed radish compared to soil following rye, but was not different among soils following black oat, crimson clover, and rye. The 3-year averages indicate that k was 1.6, 1.8, and 2.0 times greater in soil following black oat, crimson clover, and oilseed radish than following rye. Across the 3 years, k values for the rye treatment were less variable than for the other three cover crops. Surprisingly, yearly mean values of k were 0.0100, 0.0100, and 0.0099 for 1999, 2000, and 2002, respectively.

Our results are similar to those of other researchers showing that small grain residues with large C/N ratios reduce N_0 and k, whereas crop residues with small C/N ratios increase N_0 and k (Kuo and Sainju 1998). Kuo and Sainju (1998) showed that N_0 was about 30% greater in a soil amended with vetch (*Vicia villosa* Roth subsp. *villosa*) residue compared to soils amended with rye or annual ryegrass (*Lolium multiflorum* Lam.). This was attributed to the greater N demand of microorganisms in soil following rye, causing N immobilization and a slower apparent rate of N mineralization. They hypothesized that the greater supply of soluble carbohydrates in rye and ryegrass residues contributed to an increased microbial demand for soil N. Reinertsen et al. 1984 found that greater soluble carbohydrate pools increased N immobilization in soils with decomposing wheat residues. In our system, residues with smaller C/N ratios more adequately supplied the N demand of microorganisms and therefore did not increase demand for mineral N from the soil pool.

Relationships among cover crop biomass and soil N mineralization

Correlations were used to evaluate how strongly the measured soil N mineralization parameters could be related to cover crop properties. Cover crop biomass was related negatively to N_{min90} (−0.517, P<0.0001), N_0 (−0.419, P=0.0008), and k (−0.202, P=0.1217), whereas cover crop total N was not correlated with the soil N mineralization measurements. The C/N ratio of the cover crops was also negatively correlated with N_{min90} (−0.51700, P<0.0001) and N_0 (−0.46336, P<0.0002) and had a slightly positive correlation to soil C (0.18062, P=0.1289). The negative correlations between cover crop biomass and soil N mineralization measurements were strongly influenced by the effects of the rye residues on N availability. Rye produced a large amount of residue having a large C/N ratio which would be expected to reduce N mineralization and negatively influence the correlation. Negative relationships between cover crop C/N ratio and N_{min90} and C/N ratio and N_0 were probably influenced by the rye residue amounts and also by N contents. Cover crop total N and soil N were not significantly correlated with N_{min90}, N_0, or k. This is somewhat surprising in that fast decomposing crop residues (those with smaller C/N ratios) would be expected to positively influence N availability in the short term because they would supply both C and N needed for microbial growth. The absence of a strong relationship to C/N may indicate that resource quality may be more important for defining cover crop influences on N availability.

Significant correlations were observed between N_{min90} and N_0 (0.468, P=0.0002) and between N_{min90} and k (−0.304, P=0.0179). Both N_0 and k would be expected to be strongly related to N_{min90}. In a laboratory study to assess spatial patterns of N mineralization in a Kansas agricultural field, Mahmoudjafari et al. (1997) found that both N_0 and k played critical roles in determining the spatial patterns of N mineralization. Variability in k controlled the spatial pattern of N mineralization early in the incubation period, and the variability in N_0 controlled the spatial pattern later.

Table 2 Nitrogen mineralized from 0 to 90 days (N_{min90}), potentially mineralizable N (N_0), and N mineralization rate (k)

Year	Crop	N_{min90}[a] (kg ha^{-1})	$P>t$[b]	N_0[c] (kg ha^{-1})	$P>t$[b]	k[c] (kg ha^{-1} day^{-1})	$P>t$[b]
1999	Black oat	77.6	0.14	166.8	0.09	0.011	0.06
1999	Crimson clover	92.3	0.01	199.0	0.01	0.012	0.03
1999	Oilseed radish	90.2	0.02	126.4	0.48	0.012	0.01
1999	Rye	57.5		102.7		0.005	
CL±		15.8		45.4		0.003	
2000	Black oat	133.8	0.01	222.8	0.63	0.013	0.06
2000	Crimson clover	135.8	0.01	269.3	0.10	0.012	0.14
2000	Oilseed radish	127.6	0.02	226.9	0.54	0.009	0.43
2000	Rye	62.5		203.4		0.007	
CL±		33.6		48.2		0.005	
2002	Black oat	113.2	0.05	228.7	0.67	0.0087	0.47
2002	Crimson clover	103.2	0.12	203.4	0.93	0.0100	0.20
2002	Oilseed radish	160.9	0.01	255.2	0.35	0.0137	0.02
2002	Rye	79.7		207.9		0.0070	
CL±		25.8		66.8		0.004	
Means							
1999		79.4		148.7		0.010	
2000		114.9		230.6		0.010	
2002		114.3		223.8		0.010	
CL±		19.5		27.6		0.002	
	Black oat	108.0	0.05	207.7	0.17	0.010	0.19
	Crimson clover	110.2	0.05	228.0	0.10	0.011	0.10
	Oilseed radish	119.4	0.01	202.1	0.19	0.012	0.07
	Rye	66.6		171.6		0.006	
CL±		33.6		69.9		0.004	

[a] N_{min90} is the cumulative N mineralized at 90 days in 1999, 81 days in 2000, and 86 days in 2002. Values are least square means, and confidence limits (CL) were estimated at the 90% level

[b] Test of difference between rye and the other cover crops where $P>t$ indicates the level of significance for the test

[c] N_0 and k were determined using Eq. 2. Values are least square means, and confidence limits (CL) were estimated at the 90% level

The differential response in the amount of N mineralized following the four cover crops reiterates the fact that cover crop residue characteristics such as C/N ratio and maturity at termination greatly influence N availability to the succeeding crop. Several researchers have shown that large amounts of N can be rapidly mineralized following termination of legume cover crops. Wilson and Hargrove (1986) reported that 36% of the N in surface-placed crimson clover residue was no longer in the residues after 4 weeks. Work in North Carolina showed that 44% of the N from crimson clover residues was in the mineral N pool 18 days following incorporation, and that later in the summer crop season, organic N pools were larger with crimson clover compared to mineral N fertilized plots (Crozier et al. 1994, 1998). Carpenter-Boggs et al. (2000) found that N mineralization was 7 and 42% greater following soybean and alfalfa, respectively, than following corn. Reduced N availability following nonleguminous cover crops has frequently been attributed to net N immobilization associated with cover crop biomass decomposition (Decker et al. 1994; Torbert et al. 1996; Kuo and Sainju 1998). However, the potential for greater accumulation of soil organic N over longer periods has been shown where small grain cover crops were used (Hargrove 1986; Kuo et al. 1997). Hargrove (1986) noted that a rye cover crop resulted in as much soil organic N as did crimson clover despite the fact that rye contained only one fourth as much N. Kuo et al. (1997) showed an increase in soil organic N of 8, 5, and 3% following rye, ryegrass, and hairy vetch compared to winter weeds. Carbon inputs for the three cover crops were 2.7, 3.5, and 1.5 times that of winter weeds, whereas, in contrast, N inputs were 1.9, 1.7, and 4.5 times those of winter weeds. These results indicate that longer term retention of N as soil organic N is dependent on biomass C inputs.

Conclusions

Black oat and oilseed radish cover biomass production was less than rye but similar to crimson clover, and the amount of N contained in the residues was greater than in rye. Effects of black oat and oilseed radish residues on N mineralization were more similar to that of crimson clover than to rye. Because N mineralization measurements associated with these two cover crops did not indicate net N immobilization during the summer growing season, there should be no reason to alter N fertilization recommendations. Cover crop biomass produced by these cover crops was sufficient to help control soil erosion in conservation tillage systems. Longer term impacts of the cover crops on N availability and soil C dynamics are unknown but would be expected to be intermediate between that of crimson clover and rye. Bauer and Reeves (1999) found no detrimental effects of black oat on cotton yields or fiber properties. As was observed in South Carolina, cold-hardiness may need to be addressed through breeding or selection to improve the geographic range for black oat. Because oilseed radish produced a significant amount of biomass in the fall and early spring, it could be useful in rotations where earlier planting dates are desired and for preventing leaching of residual N. Producers in the southeastern USA should consider black oat and oilseed radish as alternative cover crops to gain benefits associated with cover crop rotation, like disease and pest reduction, while maintaining soil N availability to summer cash crops.

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