Winter Legume Cover Crop Benefits to Corn: Rotation vs. Fixed-Nitrogen Effects

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ABSTRACT

The use of winter legume cover crops for erosion control and to provide additional N to the soil is well established. Other potential benefits to legume cover crops besides N additions have been recognized, but have not been quantified. The objective of this study was to separate the fixed-N effects from the rotation effects in a winter legume cover cropping system. A field study was initiated in 1989 on a Norfolk loamy sand (fine, loamy, siliceous, thermic Typic Kandiudult) in east-central Alabama. Corn (*Zea mays* L.) was grown following (i) 'Tibbee' crimson clover (*Trifolium incarnatum* L.), (ii) a partially ineffective-nodulating crimson clover, CH-1, (iii) rye (*Secale cereale* L.), and (iv) winter fallow. The plots were split into four rates of fertilizer N (0, 56, 112, and 168 kg N ha^{-1}) in a split-plot experimental plan. An evaluation of different methods of distinguishing fixed-N vs. rotation effects of the winter annual legume cover crop to a subsequent corn crop was made. Regression analysis of the effect of N application rates on N_2 fixation by crimson clover (fertilized with 45 kg N ha^{-1}) indicated that CH-1 clover biomass contained approximately 40 and 101 kg N ha^{-1} and Tibbee clover contained approximately 51 and 119 kg N ha^{-1} in 1990 and 1991, respectively. In both years of the study, crimson clover substantially increased corn yield compared with winter fallow, with a yield increase at the highest fertilizer N application level of 7 and 22% for 1990 and 1991, respectively. Estimates of yield increases due to rotation ranged from negative to 40%. The data indicated that winter cover crops improve corn yield and that besides soil N availability, there was very little difference between the beneficial effects of clover and the rye cover crops to corn.

THE USE OF WINTER COVER CROPS in corn production to provide erosion control during winter months has also been reported to have a beneficial effect on corn yields. Most of the benefits of using legume winter cover crops for corn have been attributed to increased levels of soil N following the legume, due to N_2 fixation (Baldock and Musgrave, 1980; Fleming et al., 1981; Ebelhar et al., 1984; Hesterman et al., 1986; Blevins et al., 1990). However, other benefits due to the rotation from continuous corn also contribute to the increased yields normally seen following a winter legume. Benefits such as improved soil physical (McVay et al., 1989; Folorunso et al., 1992; Jackson et al., 1993; Reeves and Wood, 1994), chemical (Ebelhar et al., 1984; Martin and Touchton, 1983; Jackson et al., 1993; Reeves, 1994), and biological (Curl, 1963; Barber, 1972; Ries et al., 1977) properties have been identified as possible rotation benefits.

The N benefit to corn is commonly reported as the N-fertilizer replacement value or the N-fertilizer equivalence, defined as the quantity of fertilizer N required to achieve the same yield with a continuous nonlegume crop as the yield obtained following a legume crop (Fox and Piekielek, 1988; Paré et al., 1992; Reeves, 1994). Nitrogen-fertilizer equivalence typically ranges between 60 and 100 kg ha^{-1}; however, the N contribution from legume cover crops is not distinguished from other rotation effects by this method (Reeves, 1994).

Baldock et al. (1981) partitioned rotation effects of legume cover crops using the difference in yield response to additions of N fertilizer when corn was grown with or without a previous legume cover crop. In their work, the total-rotation effect was defined as the sum of the fixed-N effect and rotation effect. They calculated the total-rotation effect as the yield of corn following a legume minus the yield following a nonlegume, both without added N. The rotation effect was calculated as the difference between rotations at the highest N fertilizer rate, and the fixed-N effect as the total-rotation effect minus the rotation effect. Russelle et al. (1987) calculated rotation effects as the difference in actual corn grain yield measured following a legume to that predicted from its N uptake level with a regression of N uptake vs. grain yield (calculated from data of corn not following a legume). However, rotation effects could confound the results by increasing both N utilization and fertilizer N efficiency. For example, better soil physical conditions following winter cover crops (Reeves and Wood, 1994) could promote root growth and thereby increase utilization of soil N and fertilizer N.

Techniques using ^{15}N can simultaneously determine biological N_2 fixation by legumes and follow N fate and behavior in soil (Hauck and Bremner, 1976). In some cases, ^{15}N has been used to determine the N contribution of legume crop residue to a subsequent crop. Reports of N recovery from labeled legume residues have ranged from 5 to 32% of the N in the subsequent crop (Varco et al., 1989; Reeves, 1994). Little research has been reported involving the use of ^{15}N techniques to quantify fertilizer N utilization in crops following legumes.

We conducted this study to determine the beneficial contributions of winter annual legume cover crops and to separate the fixed-N vs. rotation effects of these contributions to subsequent corn production. Our objectives were to (i) determine the N contribution to soil from N_2 fixation by a crimson clover cover crop, (ii) determine the effect of using winter cover crops on corn production, and (iii) evaluate different methods of distinguishing fixed-N vs. rotation effects of the crimson clover cover crop to a subsequent corn crop.

MATERIALS AND METHODS

Paired field studies (main study and companion experiment) were initiated in 1989 on a Norfolk loamy sand at the E.V. Smith Research Center of the Alabama Experiment Station in east-central Alabama. Surface soil pH averaged 6.0, P was in the very high range (101 kg ha^{-1}), and K was in the medium range (60 kg ha^{-1}) (Auburn University Soil Testing Laboratory, Hue and Evans, 1979). At the beginning of the second year,

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the studies were relocated a short distance away within the experiment station, on the same soil phase. Surface soil pH averaged 6.1, P averaged 57 kg ha^{-1} (high), and K averaged 128 kg ha^{-1} (high) on these plots.

Main Study

In the main study, DeKalb 689 corn was planted in a split-plot experimental design with four replications. Main plots were four winter covers: (i) 'Tibbee' crimson clover; (ii) a partially ineffective-nodulating crimson clover, 'CH-1' (Smith and Knight, 1986); (iii) rye; and (iv) winter fallow. Split plots (3.4 by 10.7 m) were four rates of fertilizer N: 0, 56, 112, and 168 kg N ha^{-1}.

Each fall, the entire plot area was chisel plowed and disked. The cover crops were planted on 12 Oct. 1989 and 8 Oct. 1990 with a plot grain drill (Brillion Sure-Stand grass seeder, Brillion Iron Works, Brillion, WI). Seeding rate for rye was 129 kg seed ha^{-1} and both clover cultivars was 17 kg seed ha^{-1}. Winter weeds were not controlled in the fallow treatment. A split application of 45 kg fertilizer N ha^{-1} was broadcast-applied as NH_4NO_3 to all winter cover crop treatments (including fallow) to ensure adequate growth of both CH-1 clover and rye. An application of 17 kg N ha^{-1} was made at planting, and the remainder (28 kg N ha^{-1}) was applied after winter dormancy in mid-February. Labeled NH_4NO_3, containing 2.0 atom % ^{15}N, was split-applied at the same rate (45 kg N ha^{-1}) to a 0.3-m^2 microplot, made by pressing a 59.5-cm-diam. metal cylinder 30 cm into the ground, inside each cover crop plot. Application of labeled fertilizer was made by dissolving a preweighed amount of labeled NH_4NO_3 in water and evenly distributing on the surface of the microplot. Plant samples for biomass and total N analyses were collected on 5 Apr. 1990 and 29 Mar. 1991 from the entire microplot area (metal cylinder) of each cover crop treatment. The predominate weed in the winter fallow biomass samples was cutleaf evening primrose (*Oenothera laciniata* Hill). Cover crops were killed with paraquat (1,1′-dimethyl-4,4′-bipyridinium ion) on 6 Apr. 1990 and 30 Mar. 1991.

Before planting corn, desiccated plant material was shredded and plots were lightly disked. After in-row subsoiling to a depth of 33 cm, corn was planted in 75-cm rows at a rate of 59 000 seeds ha^{-1}. Seeding dates were on 10 Apr. 1990 and 17 Apr. 1991. Three weeks after planting, stands were thinned to 49 400 plants ha^{-1}. Broadcast applications of 56, 112, and 168 kg N ha^{-1} were made to the corn as NH_4NO_3, with 28 kg N ha^{-1} applied at planting and the remainder applied 3 wk later. A control plot with no fertilizer N application was also included. A 1.8 by 3-m microplot (isolated from the microplot region used in the cover crops) was established inside each plot, for application of ^{15}N-depleted NH_4NO_3 containing 0.01 atom % ^{15}N at the appropriate N rate.

Grain yields were determined by machine-combining 20 m of row. Grain yields were adjusted to a moisture content of 155 g kg^{-1}. Stover dry matter was hand-harvested from a section totaling 3 m of row from the middle two rows within the microplots. Grain samples for isotope analysis were collected from within the microplots.

Companion Experiment

On an area adjacent to the main study, 1.5- by 3-m plots were established in a companion study to measure the effect of N application on total biomass and N content of the winter cover crops. The experimental design was a completely randomized block with four replications. Treatments were five N rates and three winter cover crops. The winter cover crops were Tibbee crimson clover, CH-1 crimson clover, and rye. Nitrogen application rates were 0, 34, 67, 101, and 134 kg N ha^{-1}, applied as ^{15}N-depleted NH_4NO_3 containing 0.01 atom % ^{15}N. Fertilizer application was made with one half of the total N application rate applied at planting and the remainder applied after winter dormancy in mid-February. In 1990, cover crops were seeded, followed by shallow incorporation with a rake. In 1991, planting was accomplished with a plot grain drill (same drill used in the main plots). Aboveground plant samples were collected from a 0.5-m^2 section in the center of the plots. Planting dates and plant sampling were as described for both years of the main study.

Laboratory Analysis

All plant samples were dried at 65°C (until constant weight) and ground in a Wiley mill to pass a 0.44-mm screen. Total N content of all plant samples was determined using a permanganate–reduced iron modification of a semimicro-Kjeldahl method (Bremner and Mulvaney, 1982). Distillates were concentrated for isotope-ratio analyses, which were performed as described by Mulvaney et al. (1990), using an automated mass spectrometer (Nuclide Model 3-60-RMS, Premier American Technologies Corp.,[1] Bellefonte, PA).

Fertilizer N recovery in corn and biological N_2 fixation of cover crops were determined through isotope dilution methods as described by Hauck and Bremner (1976), with rye used as the non N_2-fixing reference plant. In this paper, the term *fertilizer N* is used to denote N added to the plant–soil system through fertilizer N application to corn or cover crops. The term *fixed N* is used to denote plant N derived from biological N_2 fixation. The term *native soil N* is used to denote N from sources other than fertilizer N applied to corn (including fixed N from legumes).

Statistical analyses were performed using ANOVA procedure of SAS (SAS Institute, 1982), and means were separated using least significant difference (LSD) at an a priori 0.10 probability level. In addition, regression analyses were performed using GLM procedures (SAS Institute, 1982).

RESULTS AND DISCUSSION

In the main study, fertilizer N was added to ensure adequate growth of the winter cover crops without N_2-fixing ability. In addition, this fertilizer application allowed for measurement of N_2 fixation in the Tibbee crimson clover. The objective of the companion study was to delineate the effect of fertilizer N application on resultant soil N uptake. In addition, since applied N increases plant size and root exploration resulting in N uptake from sources other than fertilizer, the companion study permitted better partitioning of soil N vs. fertilizer N uptake as affected by N applied.

The ineffective-nodulating crimson clover CH-1 was included for separation of fixed-N and rotation effects through comparison with the Tibbee crimson clover. The ineffective-nodulation feature of this clover is a single recessive genetic characteristic (Smith and Knight, 1986). During the process of seed expansion for the production scale planting needed for the study, contamination of the CH-1 seed through cross pollination with wild crimson clover occurred, resulting in a partially

[1] Trade names and products are mentioned solely for information. No endorsement by the USDA is implied.

ineffective-nodulating CH-1 seed stock. Following the experiment, the CH-1 seed were verified to have substantial genetic contamination, resulting in plants with considerable ability for N_2 fixation. Calculation of total fixed N by the clover confirmed that significant amounts of N_2 were fixed by the CH-1 plants in both years. This contamination prevented us from using the CH-1 to discriminate between fixed-N effects and other rotation effects. However, in both 1990 and 1991, the CH-1 was less effective in N_2-fixing ability than was the Tibbee clover, resulting in significantly lower N_2 fixation (Fig. 1, estimated by ^{15}N isotope methods), therefore, these data are presented for the reader's information as partially ineffective-nodulating clover.

Fertilizer Nitrogen Effect on Cover Crops

Companion Study

As expected, N fertilization increased biomass production for rye, whereas very little increase was observed for the crimson clovers (Fig. 2), owing to N_2 fixation. Likewise, N fertilization led to a larger increase in total N uptake for rye than for either clover genotype (Fig. 3). Without fertilizer N, biomass production was lower for the rye than for clover (especially in 1991). However, with applications of at least 67 kg N ha^{-1} in 1990 and at least 134 kg N ha^{-1} in 1991, rye biomass exceeded clover biomass (Fig. 2). This indicated that rye had a greater potential for biomass production than clover at the time of cover crop burn down provided N is not limiting. However, N limitations may exist for rye when used as a winter cover crop, since fertilizer N application (other than residue fertilizer from the corn production) would not be a common practice.

While the total N content of clover plants was not affected by fertilizer N application (Fig. 3), the proportion of N in the plant from N_2 fixation was reduced by application of fertilizer N (Fig. 1). This is consistent with reports that application of fertilizer N reduces the level of N_2 fixed (Hardy and Havelka, 1975; Hardy and Gibson, 1977). With the N applications that were made to clover (45 kg ha^{-1}), calculations based on the regression equations in Fig. 1 indicate fixation by the CH-1 clover of 40 and 101 kg N ha^{-1} in 1990 and 1991, respectively. Tibbee clover fixed 51 kg N ha^{-1} in 1990 and 119 kg N ha^{-1} in 1991. Plant response differences between years was most likely related to problems with plant establishment in 1990 and to temperatures in late March and early April (before cover crop termination), which were much cooler in 1990 than in 1991.

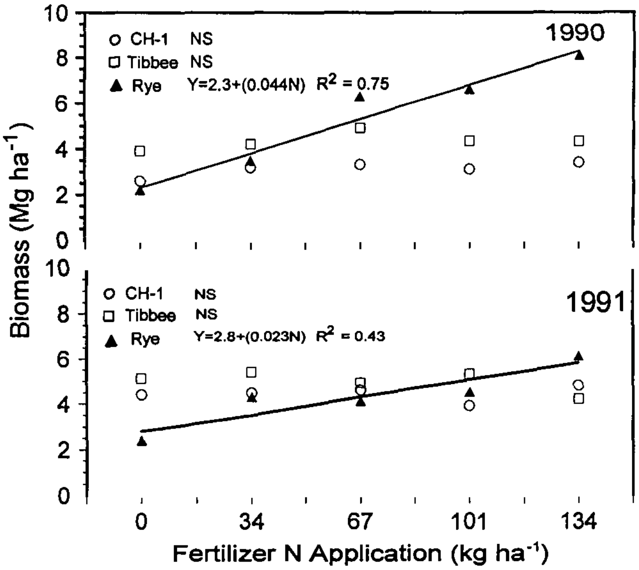

Fig. 2. Effect of fertilizer N application on biomass production in nodulating crimson clover (Tibbee), partially ineffective-nodulating crimson clover (CH-1), and rye in 1990 and 1991, companion study. NS: no significant regression line could be fitted ($P \leq 0.10$).

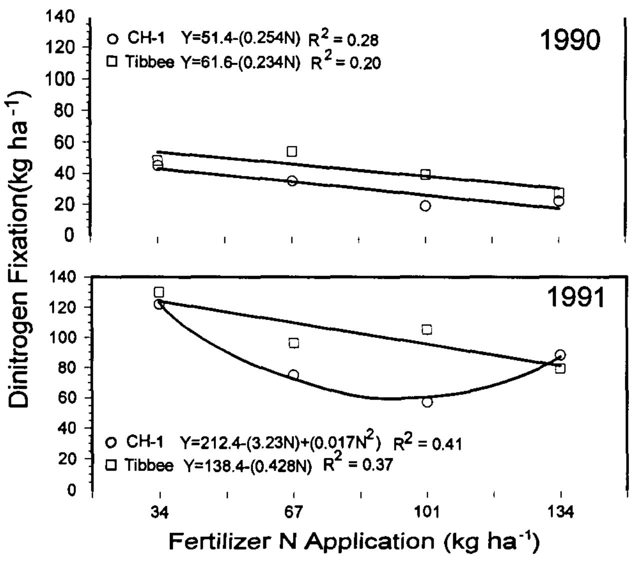

Fig. 1. Effect of fertilizer N application on N_2 fixation by nodulating (Tibbee) and partially ineffective-nodulating (CH-1) crimson clover in 1990 and 1991, companion study. Contamination of seed stock resulted in substantial N_2 fixation by CH-1 clover.

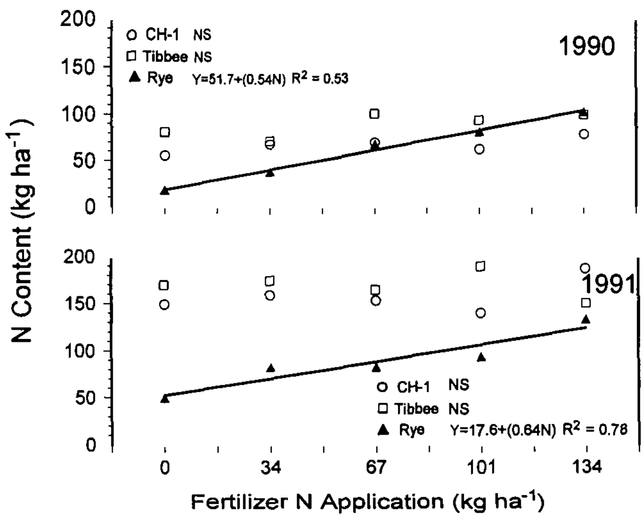

Fig. 3. Effect of fertilizer N application on total N content of nodulating crimson clover (Tibbee), partially ineffective-nodulating crimson clover (CH-1), and rye in 1990 and 1991, companion study. NS: no significant regression line could be fitted ($P \leq 0.10$).

Main Study

In both years of the main study, both crimson clover varieties and rye provided adequate ground cover for erosion control during the winter months. In both years, the two crimson clovers produced significantly higher biomass and total N compared with rye (Table 1). As in our companion study, rye had lower biomass production at the lower fertilizer N application rates (Fig. 2). This lower biomass production would likely correspond to production practices where no fertilizer N would be applied. Substantial winter weed growth occurred in the winter fallow treatment, resulting in measurable biomass production and total N content (Table 1). However, soil coverage by weeds was incomplete in the winter fallow treatment, providing less soil protection.

In 1990, biomass production for the two clovers between the main study and the companion study were very different, with the estimates being lower for the companion study (Fig. 2) than for the main study (Table 1). In the companion study, plant stands were erratic, due to hand seeding. Additionally, an intense rainfall shortly following planting disrupted seed distribution. Thus, total N and N_2 fixation by the clover were lower for the companion study than for the main study in 1990 (Table 1; Fig. 1 and 2). This too was a function of biomass production, since plant N tissue concentration and the proportion of plant N resulting from N_2 fixation were relatively consistent between the two areas (data not shown).

Biomass production in the two study areas was more comparable in 1991 than in 1990 (Table 1; Fig. 2). Unlike 1990, the same grain drill was used to plant both studies, and no large rainfall event interfered with seed distribution. However, 1991 values for total N and N_2 fixed were inconsistent within replications in the main study, resulting in no significant difference between the two clovers (Table 1). This was probably due to greater contamination of CH-1 seed.

Corn Yield and Nitrogen Uptake

A significant year × treatment interaction occurred for corn production; therefore, data are presented by

Table 1. Biomass and N content of winter cover crops at spring kill of main study in 1990 and 1991.

Trait	Cover crop†‡			
	CH-1	Tibbee	Rye	Fallow
Biomass, Mg ha^{-1}				
1990	4.9b§	7.1a	3.9b	1.3c
1991	5.0a	5.1a	3.0b	0.6c
N content, kg ha^{-1}				
1990				
Total N	95a	141b	33c	17c
N_2-fixed	66a	107b	0c	0c
1991				
Total N	154a	150a	51b	16c
N_2-fixed	119a	118a	0b	0b

† All winter cover crops were supplied with 45 kg N ha^{-1}.
‡ Cover crops: CH-1 is a partially ineffective-nodulating crimson clover; Tibbee is a normally nodulating crimson clover.
§ Within rows, means followed by the same letter do not differ significantly as determined by LSD (0.10). Values represent means of four replicates.

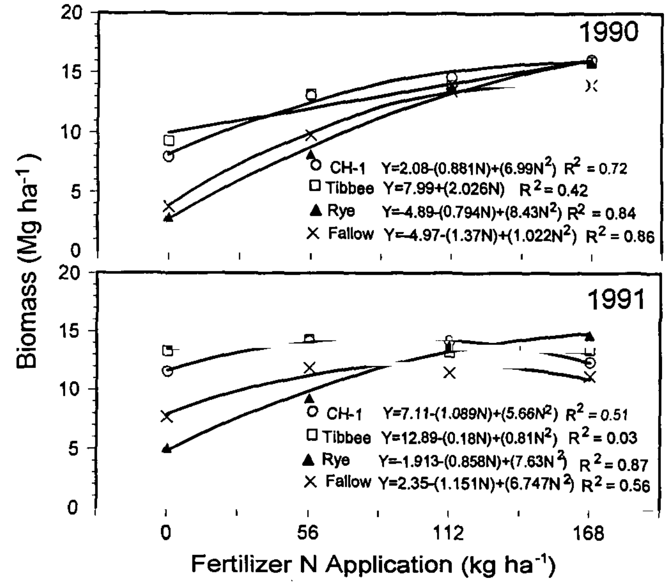

Fig. 4. Effect of fertilizer N application on corn biomass production as affected by winter cover crop in 1990 and 1991, Tibbee is nodulating crimson clover and CH-1 is partially ineffective-nodulating crimson clover.

year. In both years, with the three winter cover crops and with fallow, corn biomass production, grain yield, and total N uptake increased with increasing N application (Fig. 4–6). When averaged over fertilizer N application rates, the two crimson clovers increased corn biomass, grain yield, and total N uptake, compared with rye or fallow. On average, the 1990 corn grain yield following Tibbee was increased by 65% compared with rye and by 30% compared with fallow, while the 1991 corn yield following Tibbee increased grain yield by 36% compared with rye and by 33% compared with fallow. However, the differences between the corn yield following clovers compared with those following fallow

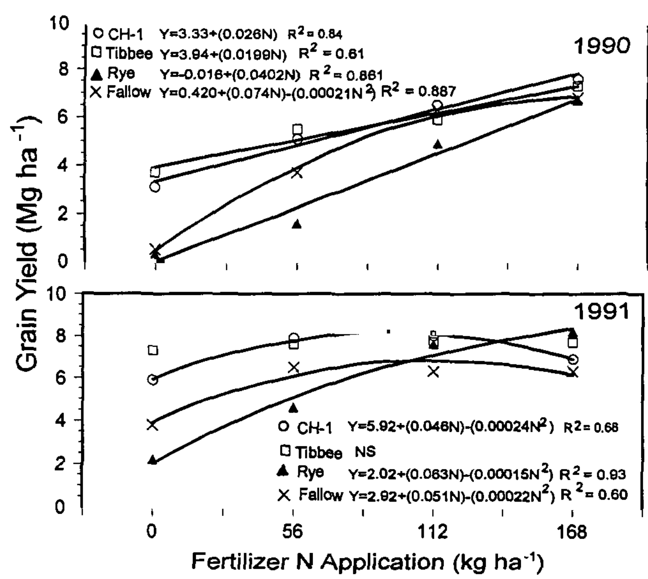

Fig. 5. Effect of fertilizer N application on corn grain yield as affected by winter cover crop in 1990 and 1991, Tibbee is nodulating crimson clover and CH-1 is partially ineffective-nodulating crimson clover. NS: no significant regression line could be fitted ($P \leq 0.10$).

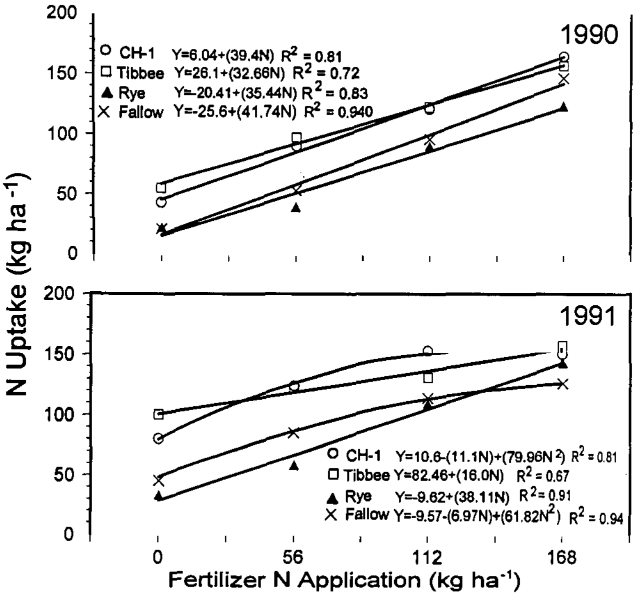

Fig. 6. Effect of fertilizer N application on total N uptake by corn as affected by winter cover crop in 1990 and 1991, Tibbee is nodulating crimson clover and CH-1 is partially ineffective-nodulating crimson clover.

or rye were greater at the lower fertilizer N application rates than at the higher rates, with corn yield following rye exceeding yields observed with clovers at the 168 kg N ha^{-1} rate in 1991 (Fig. 5). This is consistent with published reports of increased corn production following winter legume cover crops (e.g., Martin and Touchton, 1983; Ebelhar et al., 1984; Blevins et al., 1990; Reeves, 1994). A large part of the increase was attributable to the input of N from biological N_2 fixation by clover, as compared with rye or fallow (Table 1). In both 1990 and 1991, total N uptake without fertilizer N was substantially greater for corn following either crimson clover genotype than for corn that followed fallow or rye (Fig. 6). Likewise, isotope analysis of corn plant N when fertilizer N was applied indicated substantially higher uptake of native soil N by the corn that followed crimson clover as compared with the corn that followed rye or fallow (Table 2), presumably because of N_2 fixation by the clover. In 1990, as fertilizer N application increased, so did native soil N uptake. A similar result in plant uptake of native soil N occurred following rye and fallow winter cover in 1991, but no increase in native soil N uptake with increasing fertilizer N application occurred following clover (Table 2). Nitrogen uptake by corn following Tibbee clover increased an average of 33 kg N ha^{-1} in 1990 and 38 kg N ha^{-1} in 1991 averaged over all fertilizer N levels, as compared with corn following fallow. These increases represent 31 and 32% of the calculated N_2-fixed in crimson clover at termination in 1990 and 1991, respectively (Table 1).

In 1990, while total N uptake by corn was similar between the two clover treatments (Fig. 6), the native soil N contribution to plant N uptake was smaller and the fertilizer N contribution was greater for CH-1 than for Tibbee (Table 2). These differences can be attributed to a lower level of N_2 fixation by the CH-1 clover, as compared with Tibbee (Fig. 1). This indicates that legume cover crops may improve corn N utilization regardless of N source—i.e., fertilizer N, or native soil N (soil N and N in legume residue).

Figure 7 presents regression analysis of corn grain yield vs. total plant N uptake for all cover treatments. In 1990, fallow performed better than either crimson clover or a rye cover crop between the levels of 60 and 120 kg corn N uptake ha^{-1} (Fig. 7). In 1991, no significant regression line for total N uptake vs. grain yield was found for the Tibbee crimson clover, but corn following the CH-1 clover had higher yield compared with fallow between the levels of 60 and 140 kg corn N uptake

Table 2. Uptake of fertilizer N and native soil N by corn plants as affected by winter cover crop and N fertilizer.

	N content in corn, by cover crop†									
	CH-1		Tibbee		Rye		Fallow		Mean	
N rate	Soil N‡	Fert. N‡	Soil N	Fert. N	Soil N	Fert. N	Soil N	Fert. N	Soil N	Fert. N
kg ha^{-1}	kg ha^{-1}									
1990										
0	43	0	55	0	22	0	21	0	35a§	0a
56	61	28	74	23	24	14	28	25	47b	16b
112	65	56	81	41	39	51	46	50	58c	50c
168	84	80	86	70	56	66	68	79	74d	74d
Mean	63	41	74	34	35	33	41	39		
	LSD (0.10) for cover crop treatment vs. soil N = 16.9									
	LSD (0.10) for cover crop treatment vs. fertilizer N = 11.3									
1991										
0	80	0	100	0	33	0	46	0	65a	0a
56	102	22	99	23	40	18	60	25	75b	22b
112	101	51	85	47	57	52	60	54	76b	51c
168	79	73	86	71	62	81	52	74	70b	75d
Mean	91	37	93	35	48	38	55	38		
	LSD (0.10) for cover crop treatment vs. soil N = 8.6									
	LSD (0.10) for cover crop treatment vs. fertilizer N = 2.7									

† Cover crops: CH-1 is a partially ineffective-nodulating crimson clover; Tibbee is a normally nodulating crimson clover.
‡ Native soil N includes all N other than fertilizer N, including cover residue N; fertilizer N (Fert. N) is the N in plants that can be attributed to fertilizer N application, calculated from ^{15}N isotope analysis.
§ Within rows, means followed by the same letter do not differ significantly as determined through LSD (0.10). Values represent means of four replicates.

ha^{-1}. In this year, grain yield between the levels of 120 and 160 kg corn N uptake ha^{-1} was highest with a rye cover crop, with approximately 1.5 and 0.8 Mg ha^{-1} additional grain yield for corn following rye compared with corn following fallow and CH-1 clover, respectively.

Separation of Fixed-Nitrogen vs. Rotation Effects

Contamination of CH-1 seed by nodulating clover pollination compromised comparisons between the CH-1 and Tibbee crimson clover. No difference between clovers was observed in estimates of N_2 fixation from the main study in 1991 (Table 1); however, the companion study indicated reduced N_2 fixation by the CH-1 clover compared with Tibbee in 1990 and 1991 (Fig. 1). Regardless of whether N_2 fixation was lower for CH-1 clover than for Tibbee clover, there was no apparent difference in the beneficial effect between the two clover cover crops to subsequent corn yield (Fig. 4–6).

In 1990, N_2 fixation was lower for CH-1 than for Tibbee, with a corresponding difference in total N content in the cover crop biomass (Table 1; Fig. 1 and 3). However, little difference was observed between the two clover cover crops in corn grain yield, total biomass accumulation, or total N uptake (Fig. 4–6). Compared with the fallow or rye cover crop, in 1990 at the lower fertilizer N application rates, the two clovers increased corn production as evidenced by increased grain yield, total biomass accumulation, and total N uptake (Fig. 4–6). While no significant difference was observed for total N uptake by corn between the two clovers, isotope analysis of N source indicated that corn following Tibbee tended to have higher levels of native soil N uptake, whereas corn following CH-1 had higher levels of fertilizer N uptake (Table 2). Even though Tibbee had higher levels of native soil N available due to increased N_2 fixation compared with CH-1, N uptake in corn was the same, with the corn following CH-1 utilizing more fertilizer N to make up the difference. This indicates that soil N availability alone may not explain all of the benefits observed in the corn following clover (as evidenced by increased grain yield, total biomass accumulation, and total N uptake) but that rotation effects may provide a significant contribution to corn growth.

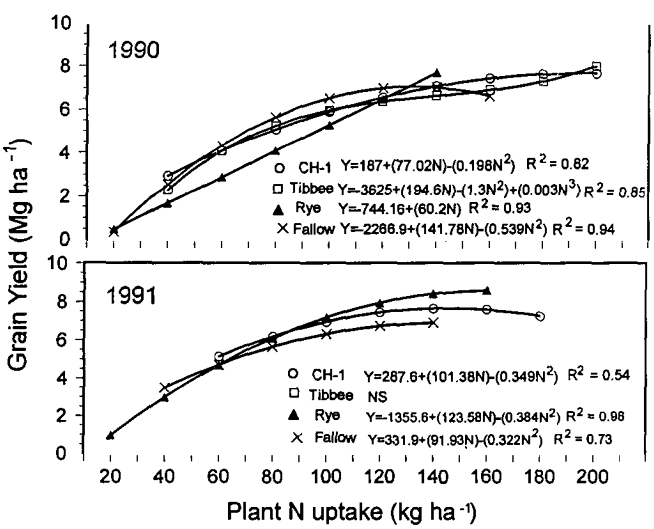

Fig. 7. Regression analysis of corn grain yield vs. corn plant N uptake as affected by winter cover crop in 1990 and 1991, Tibbee is nodulating crimson clover and CH-1 is partially ineffective-nodulating crimson clover. NS: no significant regression line could be fitted ($P \leq 0.10$).

While no difference was detected between the beneficial effect of the two clovers, a benefit to corn grain production from clover compared with fallow and rye was observed at the lower fertilizer N application rates (Fig. 5). This benefit can be calculated as the N-fertilizer replacement value or equivalence, defined as the quantity of fertilizer N required to achieve the same yield with a non legume crop as that achieved with the crop following a legume without fertilizer N additions (Fox and Piekielek, 1988). Calculated from regression of grain yield vs. fertilizer N application, the N-fertilizer replacement value of Tibbee clover was approximately 56 kg N ha^{-1} compared with fallow and 98 kg ha^{-1} compared with rye in 1990. In 1991, the N-fertilizer replacement value for Tibbee clover was approximately 112 kg N ha^{-1} compared with rye. Corn yield following fallow at all N fertilizer application rates was below the corn yield following Tibbee clover (7.3 Mg ha^{-1}) with no fertilizer N application, with the corn yield following fallow reaching a maximum yield with approximately 105 kg fertilizer N ha^{-1} application (Fig. 5).

Baldock et al. (1981) calculated the total effect as the yield of corn following a legume minus the yield following a non legume, both without added N and the rotation effect was calculated as the difference between rotations at the highest N fertilizer rate. The fixed-N effect was then calculated as the total effect minus the rotation effect.

Separation of rotation and fixed-N effects by the method of Baldock et al. (1981) indicated that, compared with corn following fallow, Tibbee clover increased grain production by a total of 3.2 and 3.5 Mg ha^{-1} in 1990 and 1991, respectively (Table 3). According to this approach, rotation effects (i.e., effects other than fixed-N effects) accounted for 16 and 40% of the total yield increase

Table 3. Calculated cover crop effects on corn grain yield compared to winter fallow in 1990 and 1991.†

Cover effects	Corn grain yield, by cover crop		
	Tibbee	CH-1	Rye
		Mg ha^{-1}	
1990			
Total	3.2	2.6	−0.2
Rotation	0.5	0.8	0.1
N benefit§	2.7	1.8	−0.3
1991			
Total	3.5	2.1	−1.6
Rotation	1.4	0.6	1.9
N benefit	2.2	1.5	−3.5

† Cover crop effects were calculated by the procedures of Baldock et al. (1981).
‡ Cover crops: CH-1 is a partially ineffective-nodulating crimson clover; Tibbee is a normally nodulating crimson clover.
§ N benefit is the rotation effect attributable to N from winter cover crops. In the case of the clovers, this would be the N_2-fixed effect.

obtained with Tibbee clover in 1990 and 1991, respectively.

Similar calculations for rye showed a negative total cover crop effect but a positive rotation effect in both 1990 and 1991 (Table 3). In this case, the negative N-benefit effect (fixed-N effect) calculated for rye reflects the negative effect of N immobilization on corn yield following rye. These effects were apparent in the regression analysis of corn yield (Fig. 5).

Russelle et al. (1987) discerned rotation effects by attributing yield increases that could not be explained by increased plant N uptake to rotation effects, using yield means and a regression of corn grain yield vs. total N uptake. With their procedures, the total effect is calculated from the difference in yield means between corn following fallow and corn following a legume at a specified N application rate. The rotation effect is separated by calculating the difference in mean yield of corn following a legume compared with the predicted yield based on its N uptake from a regression of yield vs. N uptake calculated with data of corn yields following fallow.

Separation of rotation effects by the procedure of Russelle et al. (1987) is illustrated in Fig. 8, with a comparison of corn following winter fallow with corn following Tibbee clover at both the 112 and 168 kg ha^{-1} fertilizer N application rates. These rates were chosen because they were within the normal range of fertilizer N application to corn in this region. In 1990, Tibbee had a negative rotation effect at the 112 kg N ha^{-1} rate, decreasing grain yield approximately 1.0 Mg ha^{-1}. At the 168 kg N ha^{-1} rate, a positive total effect of 0.5 Mg ha^{-1} was calculated, all of which would be attributed to rotation effects. In 1991, at the 112 kg N ha^{-1} rate, the total effect was calculated to be 1.4 Mg ha^{-1} grain yield, with 0.6 Mg ha^{-1} attributable to the fixed-N effect and 0.8 Mg ha^{-1} attributable to the rotation effect. At the 168 kg N ha^{-1} rate, even though the total N uptake changed, the calculated rotation effects were identical, because yield levels did not change with the additional N in both the Tibbee and fallow.

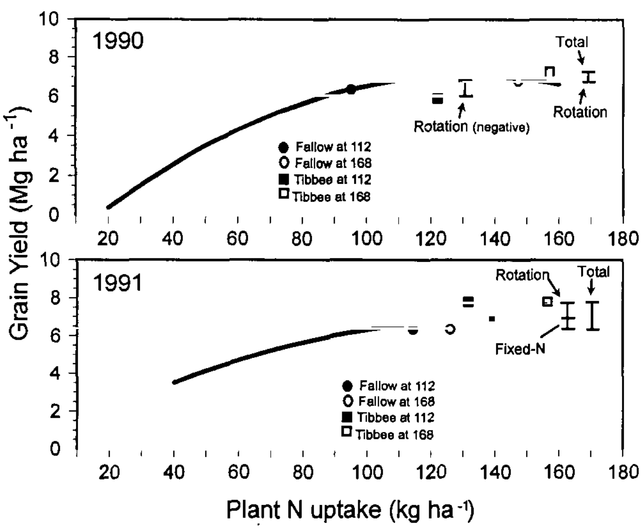

Fig. 8. Relationship among total effects, fixed-N effects, and rotation effects for corn yield following fallow compared with corn yield following Tibbee crimson clover, calculated at 112 and 168 kg ha^{-1} fertilizer N application rate. Regression line represents corn grain yield vs. total N uptake calculated from corn yields following winter fallow; symbols represent the mean of corn grain yields following either Tibbee crimson clover cover crop or winter fallow.

Comparison of Procedures

A potential limitation of both the procedures described by Baldock et al. (1981) and Russelle et al. (1987) is that neither explicitly considers that the rotation effect may be due in part to an increase in the plant's ability to access soil N and utilize N more efficiently. For example, with the procedures of Russelle et al. (1987), the calculated rotation effects change with the rate of fertilizer N application. This would not occur if the rotation effects and the N utilization were independent of each other.

The fact that N utilization in plants and the rotation effects in plants are interrelated can be demonstrated by comparison of the calculated N-fertilizer replacement value and the actual fertilizer N replacement in corn as determined from isotope analysis. Data in Table 2 indicate that corn uptake of native soil N in plants following Tibbee, increased (fertilizer N replacement) by a range of 30 to 50 and 24 to 67 kg N ha^{-1} compared with rye and by a range of 18 to 51 and 25 to 54 kg N ha^{-1} compared with fallow in 1990 and 1991, respectively. This compares with a calculated N-fertilizer replacement value (discussed earlier) for Tibbee of approximately 98 and 112 kg N ha^{-1} compared with rye in 1990 and 1991, respectively, and 56 and at least 105 kg N ha^{-1} compared with fallow. While utilization of native soil N was greater (including N from biological N_2 fixation) following clover, the actual increase in the contribution of native soil N was well below the calculated N-fertilizer replacement value.

These observations are consistent with other reported work (Hesterman et al., 1987; Harris and Hesterman, 1990). For example, Harris and Hesterman (1990) found that alfalfa (*Medicago sativa* L.) supplied an average of 24 kg N ha^{-1} to corn, whereas the N-fertilizer replacement value was calculated to be over 100 kg N ha^{-1}. Hesterman et al. (1987) indicated that N-fertilizer replacement values may be exaggerated by as much as 132%. However, there is no exaggeration of the beneficial effect of a legume cover crop on corn yield or of the lower fertilizer requirement when corn is grown following such a crop. The N-fertilizer replacement value measures the overall rotation effects of a cover crop, whereas the isotope analysis measures the actual contribution of native soil N (i.e., N other than that from fertilizer) in the corn plants (Harris and Hesterman, 1990). A discrepancy between these two methods would be expected if rotation effects were responsible for a portion of the increased yield response.

A priming effect could account for the difference between the N-fertilizer replacement value and the actual measured native soil N uptake by corn (Bruulsema and Christie, 1987). Similar to the priming effect by fertilizer N application (Jenkinson et al., 1985), legume cover crops can have a priming effect by contributing to corn growth with better utilization of available soil N, either fertilizer N or native soil N. For example, rotation effects may result in healthier corn plants that have more extensive root systems, and cover crops can improve soil structure and increase soil water infiltration and storage (McVay et al., 1989; Folorunso et al., 1992; Jackson et al., 1993; Reeves and Wood, 1994; Reeves, 1994) and thereby result in more effective rooting and consequent N uptake by corn plants. Also, healthier plants (due to rotation effects) could produce more biomass with the same amount of N. A similar effect could explain differences between the rye cover crop and the fallow, except that N limitations due to N immobilization limited its effect compared with the clover cover crops at the lower fertilizer N application rates.

Regression analysis was used to compare total corn uptake of fertilizer N to corn biomass (Fig. 9). This analysis indicated a rotation benefit to corn from winter cover crops. At the zero level of fertilizer N uptake (similar to the procedure of Baldock et al., 1981), total cover crop effects, including both fixed-N effects and rotation effects, were observed. As the rate of fertilizer N uptake increased, the importance of fixed-N effect was reduced. At the point where additional fertilizer N uptake did not affect the level of biomass production, differences were attributed to rotation effects.

This procedure combines the procedures of Russelle et al. (1987), Baldock et al. (1981), and fertilizer N replacement value. The procedure has an advantage over the regression against total N uptake, because unlike native soil N and therefore total N, the rate of fertilizer N application was consistent among cover crops. Also, unlike regression of fertilizer N application vs. yield (used in calculation of the N-fertilizer replacement value), this regression considers the plant response at the same level of fertilizer N uptake, limiting differences

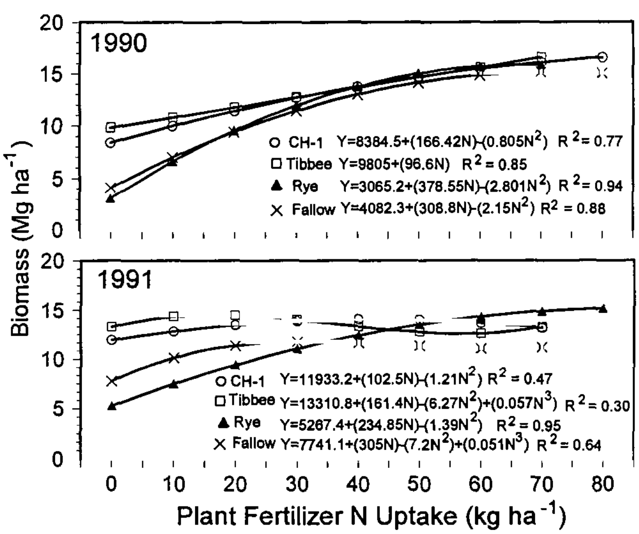

Fig. 9. Regression analysis of corn biomass production vs. plant fertilizer N uptake as affected by winter cover crop in 1990 and 1991, Tibbee is nodulating crimson clover and CH-1 is partially ineffective-nodulating crimson clover. Fertilizer N uptake was determined through ^{15}N analysis.

due to varying levels of available N. This procedure measures the yield response over a range of fertilizer N application treatments, but by comparing fertilizer N uptake, the comparisons are made under equivalent conditions for the plants (much as the method of Russelle et al., 1987).

In 1990, the two clovers produced higher yields at the lower rates of fertilizer N uptake, with the increase in yield being approximately 5.7 and 6.7 Mg ha^{-1} with the Tibbee crimson clover compared with fallow and rye, respectively (Fig. 9). With increase in the level of fertilizer N uptake, the difference in biomass between covers was reduced. At approximately 40 kg fertilizer N uptake ha^{-1}, biomass production was the same with rye and clover. This indicates that, besides soil N availability, there was very little, if any, difference between the beneficial effects of the clover and rye cover crops to corn. Likewise, the difference in biomass production between fallow and the clovers was reduced with increases in the level of fertilizer N uptake. However, unlike following rye, corn dry matter production following fallow was below that of clover even at the highest level of fertilizer N uptake. The Tibbee crimson clover resulted in approximately 0.7 Mg ha^{-1} additional corn biomass production compared with fallow winter cover. Since fertilizer N uptake above 60 kg fertilizer N ha^{-1} did not affect biomass production after fallow, this difference (an approximate 5% increase in biomass production) would be calculated as a rotation effect.

In 1991, an increase in corn biomass production was observed with the two clovers as compared with fallow and the rye at zero fertilizer N, but, unlike the fallow treatment, application of fertilizer N to corn following clover led to very little increase in biomass production because the corn N requirement was largely supplied by fixed N from clover. While higher uptake of fertilizer N occurred with higher fertilizer N application, there was little effect on biomass production. For corn following fallow, biomass production increased with fertilizer N uptake to approximately 30 kg fertilizer N ha^{-1}, but never reached the level of biomass production achieved with either clover. This difference between fallow and clover at fertilizer N uptake above 30 kg ha^{-1} is calculated as a rotation effect of approximately 2.3 Mg ha^{-1}, a 17% increase in biomass production due to clover. Without added fertilizer N, the rye cover crop produced lower biomass than either clover or fallow (i.e., rye had a negative N-benefit effect), the difference being approximately 2.5 and 8.0 Mg ha^{-1} as compared with fallow and Tibbee, respectively. The lower yield of corn following rye at the zero level of fertilizer N uptake was due to N immobilization. Increasing fertilizer N uptake provided an increase in biomass production (rotation effect), until biomass production with rye exceeded that observed with the clovers. At the 70 kg fertilizer N ha^{-1} uptake level, rye produced approximately 1.6 and 3.7 Mg ha^{-1} additional biomass compared with Tibbee crimson clover and fallow cover crops, respectively. As in 1990, rye produced a substantial rotation effect for corn in 1991 (even above that of clover in 1991), but this effect was masked by soil N limitations at fertilizer N application rates below 40 kg N ha^{-1}.

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