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# Biculture Legume–Cereal Cover Crops for Enhanced Biomass Yield and Carbon and Nitrogen

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## ABSTRACT

**Biculture legume–cereal cover cropping may enhance above- and belowground biomass yields and C and N contents. The increase in C and N supply to the soil has the potential to improve soil quality and crop productivity compared with monoculture cover crop species. We examined above- and belowground (0- to 120-cm soil depth) biomass yields and C and N contents of a legume [hairy vetch (*Vicia villosa* Roth)], nonlegume [rye (*Secale cereale* L.)], and biculture of legume and nonlegume (vetch and rye) cover crops planted without tillage in the fall of 1999 to 2001 in central Georgia. After cover crop kill in the spring, cotton (*Gossypium hitsutum* L.) and sorghum [*Sorghum bicolor* (L.) Moench)] were planted using three tillage practices (no-till, strip till, and chisel till) with three N fertilization rates (0, 60 to 65, and 120 to 130 kg N ha$^{-1}$). The field experiment was arranged in a split-split plot treatment with three replications on a Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults). Aboveground biomass yield of rye decreased from 6.1 to 2.3 Mg ha$^{-1}$ from 2000 to 2002, but yield of hairy vetch varied (2.4 to 5.2 Mg ha$^{-1}$). In contrast, biomass yield of vetch and rye biculture (5.6 to 8.2 Mg ha$^{-1}$) was greater than that of rye and vetch planted alone in all years. Compared with winter weeds in no cover crop treatment, C content in rye (1729 to 2670 kg ha$^{-1}$) was greater due to higher biomass yield, but N content in vetch (76 to 165 kg ha$^{-1}$) was greater due to higher N concentration, except in 2002. As a result, C (2260 to 3512 kg ha$^{-1}$) and N (84 to 310 kg ha$^{-1}$) contents in biculture were greater than those from monocultures in all years. Similarly, belowground biomass yield and C and N contents were greater in biculture than in monocultures. In 2001, aboveground biomass yield and C and N contents in cover crops were also greater in strip till with biculture than in other treatments, except in chisel till with vetch and biculture, but belowground biomass yield and N content were greater in chisel till with biculture than in no-till, strip till, and chisel till with weeds. Cotton lint yield was lower with biculture than with rye, but sorghum grain yield and cotton and sorghum biomass (stems + leaves) yields and N uptake were greater with biculture than with rye. Because of higher biomass yield and C and N contents, biculture of hairy vetch and rye cover crops may increase N supply, summer crop yields, and N uptake compared with rye and may increase potentials to improve soil organic matter and reduce N leaching compared with vetch.**


Winter cover cropping compared with bare fallow can maintain or increase organic C and N concentrations in the soil by providing additional crop residue that increases C and N inputs to the soil (Hargrove, 1986; Kuo et al., 1997a, 1997b; Sainju et al., 2000). Winter cover crops use soil residual N that may otherwise leach into groundwater after crop harvest in the fall, and depending on the species, can sequester atmospheric C and/or N, thereby reducing the amount of N fertilizer required for summer crops (Hargrove, 1986; Meisinger et al., 1991; Kuo et al., 1997a, 1997b). Other benefits of cover crops include increased soil aggregation and water infiltration capacity (McVay et al., 1989; Drury et al., 1991; Roberson et al., 1991), improved water-holding capacity (Smith et al., 1987), reduced soil erosion (Frye et al., 1985; Langdale et al., 1991), and increased root growth of summer crops (Sainju et al., 2001) compared with no cover crop. Cover cropping can provide opportunities to conserve soil organic C and N concentrations in regions, such as in southeast USA, where organic matter concentration is lower than in the northern areas and where mild winter allows cover crop growth (Hargrove, 1986; Doran, 1987; Doran and Smith, 1987).

Legume cover crops can supply N to succeeding crops and increase crop yields compared with nonlegume or no cover crops (Hargrove, 1986; Clark et al., 1994, Kuo et al., 1997b). In contrast, nonlegume cover crops are effective in increasing soil organic matter by supplying C through increased biomass production (Kuo et al., 1997a, 1997b; Sainju et al., 2000) compared with legume or no cover crops. Nonlegume cover crops also reduce $NO_3$–N leaching from the soil profile better than legume or no cover crops do (Meisinger et al., 1991; McCracken et al., 1994). A mixture of legume and nonlegume cover crops would be ideal to supply both C and N inputs in adequate amounts that help to improve soil quality and reduce N leaching compared with legumes and increase crop productivity compared with nonlegumes.

The N content or C/N ratio of cover crops is a principal determinant factor for soil N availability, regardless of placement of their residues in the soil (Hargrove, 1986; Smith et al., 1987; Ranells and Wagger, 1996). As N content of plant residue is increased or C/N ratio decreased, initial soil N mineralization potential and N mineralization rate increased (Frankenberger and Abdelmagid, 1985; Kuo and Sainju, 1998), and the crossover time for net N mineralization decreased (Kuo and Sainju, 1998). Therefore, one of the management options to increase N content or reduce C/N ratio of nonlegume cover crops is to mix legumes and nonlegumes as bicultural treatments because nonlegume cover crops, such as rye, typically have low N content or high C/N ratio and thus have little effect on soil N availability and crop yields (Clark et al., 1994; Ranells and Wagger, 1996; Kuo and Jellum, 2002). Research has shown that including hairy vetch or crimson clover (*Trifolium incarnatum* L.) with rye in biculture increased N content or decreased C/N ratio of rye, thereby reducing the potential for N immobilization from rye residue (Sullivan et al., 1991; Ranells and Wagger, 1996; Vaughan and

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Evanylo, 1998). As legumes and nonlegumes are grown together, N is transferred from legumes to nonlegumes, thereby resulting in better N nutrition of nonlegumes and increasing the herbage and protein yields of the biculture crops (Ta and Faris, 1987; Russelle and Hargrove, 1989).

A legume–grass biculture may produce similar or greater biomass yield and N content than either monoculture alone. Studies have shown that biomass yield and N content in hairy vetch and rye biculture, using seeding rates as half of rye and two-thirds of hairy vetch for that used in monocultures, were as much as or greater than those in monocultures (Clark et al., 1994; Ranells and Wagger, 1996; Kuo and Jellum, 2002). Besides, biomass yield and N content from belowground portion of cover crops, such as roots, have been estimated to be as much as 10% of aboveground portion for hairy vetch and 25% for rye (Shipley et al., 1992). Root biomass yield and C and N contents in hairy vetch and rye at 0- to 20-cm depth can account for 8 to 32% of aboveground biomass yield and C and N contents (Kuo et al., 1997a, 1997b). As adequate information is available for aboveground biomass yield and C and N contents in monoculture cover crops, little is known about belowground biomass yield and C and N contents in monocultures and above- and belowground biomass yields and C and N contents in legume–cereal biculture cover crops.

Our objectives were to: (i) examine biomass yield, C and N concentrations, and C and N contents in above- and belowground portions of fall-planted hairy vetch, rye, biculture of hairy vetch and rye, and winter weeds (no cover crops); (ii) evaluate the effectiveness of biculture in biomass yield, C and N contents, and C/N ratio and yields and N uptake of cotton and sorghum compared with monocultures; and (iii) determine the effects of tillage and N fertilization applied to previous summer crops (cotton and sorghum) on cover crop biomass yield and C and N contents.

## MATERIALS AND METHODS

### Site Description and Experimental Design

The experiment was conducted from 1999 to 2002 at the Agricultural Research Station farm, Fort Valley State University, Fort Valley, GA. The soil was a Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults) with pH of 6.5 and sand content of 650 g kg$^{-1}$ soil, silt 250 g kg$^{-1}$ soil, and clay 100 g kg$^{-1}$ soil at 0- to 30-cm depth. The clay content increased to 350 g kg$^{-1}$ below 30 cm. The soil sampled in October 1999 before cover crop planting had organic C of 8.8 g kg$^{-1}$ and organic N of 620 mg kg$^{-1}$ at 0 to 30 cm. Previous summer crops (10 yr) were double cropping of wheat (*Triticum aestivum* L.) and soybean [*Glycine max* (L.) Merr.], followed by tomato (*Lycopersicum esculentum* Mill) and silage corn (*Zea mays* L.). Temperature and rainfall data were collected from a weather station, 20 m from the experimental site.

The experiment consisted of three tillage practices (no-till, strip till, and chisel till), four cover crops (hairy vetch, rye, hairy vetch and rye biculture, and winter weeds or no cover crop), and three N fertilization rates (0, 60–65, and 120–130 kg N ha$^{-1}$) applied to summer crops. The strip till was considered as reduced till where in-row subsoiling in a narrow strip of 30-cm width was done over the row to 35-cm depth for planting cotton and sorghum, thereby leaving the area between rows undisturbed. The surface-tilled zone is leveled by coulters behind the subsoiler. The chisel till was considered as conventional till where plots were tilled to a depth of 15 cm with a disc harrow and chisel plow. No-till plots were left undisturbed except for planting cover crop, cotton, and sorghum. The recommended rate of N fertilization is 120 kg N ha$^{-1}$ for cotton and 130 kg N ha$^{-1}$ for sorghum in central Georgia (Univ. of Georgia, 1999, 2001). Tillage and N fertilization were applied to cotton and sorghum plants in the summer from 2000 to 2002, but cover crops were grown without any tillage and fertilization in the fall after summer crop harvest from 1999 to 2001. As a result, cover crops in 1999 received residual effects of conventional tillage (chisel till) and N fertilization (180 kg N ha$^{-1}$) applied to silage corn in the previous spring. In 2000 and 2001, cover crops received residual effects of tillage (no-till, strip till, and chisel till) and N fertilization (0, 60 to 65, and 120 to 130 kg N ha$^{-1}$) applied to cotton and sorghum in the previous spring. Treatments were laid out in a split-split plot arrangement in randomized complete block, with tillage as the main plot, cover crop as the split plot, and N fertilization rate as the split-split plot treatment. Each treatment had three replications. The split-split plot size was 7.2 by 7.2 m.

### Field Methods

Cover crops were planted in October–November 1999 to 2001 in the same plot every year. This was done to examine the long-term effects of cover cropping on soil organic matter (as a part of another study). Rye seeds were drilled at 80 kg ha$^{-1}$ and hairy vetch seeds at 28 kg ha$^{-1}$ after inoculating with *Rhizobium leguminosarum* (bv. *viceae*), using a row spacing of 15 cm. In rye and hairy vetch biculture, rye was drilled at 40 kg ha$^{-1}$ (50% of monoculture), followed by drilling of hairy vetch at 19 kg ha$^{-1}$ (68% of monoculture) in between rye rows. The rates of rye and hairy vetch in biculture were used as recommended by Clark et al. (1994). Cover crops were drilled in plots with a no-till drill without any tillage because previous studies have shown that cover crop biomass yields and C and N contents were not significantly influenced by tillage practices (Sainju et al., 2001, 2002b). Similarly, no fertilizers, herbicides, or insecticides were applied to cover crops to supply additional nutrients or control weeds and pests.

In April 2000 to 2002, cover crop biomass yield was determined by harvesting plant samples from two 1-m$^2$ areas randomly within each plot and weighing in the field. A subsample (100 g) was collected for determinations of dry matter yield and C and N concentrations, and the rest was returned to the harvested area where it was spread uniformly by hand. In the plots without cover crop, winter weeds, dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenolthera laciniate* Hill), were collected using the same procedure. Subsamples were oven-dried at 60°C for 3 d, weighed, and ground in a Wiley mill to pass a 1-mm screen. After sampling, cover crops and weeds were mowed with a rotary mower to avoid dragging of the residue during tillage operation. Thereafter, cover crops were killed by spraying 3.36 kg a.i. ha$^{-1}$ of glyphosate [*N*-(phosphonomethyl) glycine] in no-till and strip till plots and by disc harrowing and chisel plowing in chisel till plots. Residues were allowed to decompose in the soil for 2 wk before cotton and sorghum planting.

Within 1 wk after cover crop kill, soil samples were collected from 0- to 120-cm depth in the two middle rows from each plot using a hydraulic probe (5 cm i.d.) attached to a tractor to collect belowground (root) biomass. Samples were collected from three holes within each plot, two from the row and one within the row. These were separated into 0- to 15-, 15- to

30-, 30- to 60-, 60- to 90-, and 90- to 120-cm depths, composited within a depth, and stored at 4°C until roots were separated from the soil.

In May 2000 and 2002, P {from triple superphosphate [$Ca(H_2PO_4)_2$], 44% P} fertilizer at 36 kg ha$^{-1}$, K [from muriate of potash (KCl), 60% K] fertilizer at 75 kg ha$^{-1}$, and B [from boric acid ($H_3BO_3$), 18% B] fertilizer at 0.23 kg ha$^{-1}$ were broadcast-applied to cotton based on the soil test and crop requirement. Similarly, in May 2001, P (from triple superphosphate) fertilizer at 40 kg ha$^{-1}$ and K (from muriate of potash) fertilizer at 80 kg ha$^{-1}$ were broadcast-applied to sorghum based on the soil test. The fertilizers were left at the soil surface in no-till, partly incorporated in strip till, and completely incorporated into the soil in chisel till by plowing. Nitrogen fertilizer as $NH_4NO_3$ was applied at three rates (0, 60, and 120 kg N ha$^{-1}$) for cotton in 2000 and 2002, half of which was broadcast at planting and the other half at 6 wk later. Similarly, $NH_4NO_3$ was applied at three rates (0, 65, and 130 kg N ha$^{-1}$) for sorghum in 2001, two-thirds of which was broadcast at planting and the other one-third at 6 wk later. While no-till plots were left undisturbed except for drilling cover crop seeds and planting cotton and sorghum, strip till plots were subsoiled in rows, 0.9 m apart, where cotton and sorghum were planted. In chisel till, plots were harrowed using a disc harrow two to three times, followed by chiseling and leveling with a S-tine harrow.

Immediately after fertilization and tillage, glyphosate-resistant cotton [cv. DP458BR (Delta Pine Land Co., Hartsville, SC)] at 8 kg ha$^{-1}$ in 2000 and 2002 and grain sorghum [cv. 9212Y (Pioneer Hi-Bred Int. Inc., Huntsville, AL)] at 12 kg ha$^{-1}$ in 2001 were planted in eight-row (each 7.2 m long) plots (0.9-m spacing) with a no-till-equipped unit planter. Cotton and sorghum were applied with appropriate herbicides, pesticides, and growth regulators to control weeds, pests, and vegetative growth. Irrigation (equivalent to 25 mm of rain at a time using reel rain gun) was applied immediately after fertilization and during dry periods to prevent moisture stress. In October–November 2000 and 2002, cotton lint yield was determined by hand-harvesting two central rows (6.2 by 1.8 m$^2$), and biomass (stems and leaves) yield was determined by hand-harvesting stalks from an area of 1.8 by 1.8 m$^2$. Similarly, in November 2001, sorghum grain yield was determined by hand-harvesting heads from two central rows (6.2 by 1.8 m$^2$), and biomass (stems and leaves) yield was determined by hand-harvesting stalks from an area of 1.8 by 1.8 m$^2$. Cotton and sorghum stalks were oven-dried at 60°C to obtain dry matter yield and ground to 1 mm for N determination. After harvesting the rest of cotton lint and sorghum grain from the plots, cotton and sorghum stalk were mowed with a rotary mower, and residues were left at the soil surface.

To measure soil residual N at the time of cover crop planting in October–November 1999 to 2001, soil samples were collected with a probe (5 cm i.d.) from 0- to 20-cm depth from five holes randomly within the middle rows of the plot, composited, air-dried, and sieved to 2 mm. To determine bulk density, soil samples were collected with a separate core (5 cm i.d.) from 0 to 20 cm from each plot and oven-dried at 105°C for 24 h.

### Laboratory Analysis

Nitrogen concentration (g N kg$^{-1}$ plant) in aboveground cover crop and weed samples, cotton lint and biomass, and sorghum grain and biomass was determined by the $H_2SO_4$–$H_2O_2$ method as described by Kuo et al. (1997b). Carbon concentration (g C kg$^{-1}$ plant) in cover crops was determined by the Walkley–Black method (Nelson and Sommers, 1996) without using correction factor, which assumes that all plant C was oxidized during digestion (Kuo et al., 1996, 1997a; Sainju et al., 2000, 2002a). For this, 0.02-g plant sample was used, as observations have shown that the Walkley–Black method can oxidize all plant samples of up to 0.02 g for C determination (data not shown). Carbon and N contents (kg ha$^{-1}$) in cover crops and weeds and N uptake in cotton lint, sorghum grain, and their biomass were determined by multiplying dry matter weight by C and N concentrations after using proper unit conversions. Total N uptake in cotton and sorghum was determined by adding N uptake in lint or grain and stalks.

The $NH_4$–N and $NO_3$–N concentrations (g N kg$^{-1}$ soil) in the soil samples for analyzing residual soil N were determined by steam-distillation method after extracting with 2 *M* KCl (Mulvaney, 1996). Inorganic N content (kg ha$^{-1}$) at 0 to 20 cm was determined by multiplying the sum of $NH_4$–N and $NO_3$–N concentrations as influenced by cover crops by appropriate factors that account for bulk density and soil depth.

Soil samples collected for determining belowground biomass were thoroughly washed with water in a nest of 1.0- and 0.5-mm sieves. About 500 g of soil was washed at a time with a fine spray of water at the top and bottom sieves, and roots retained at both sieves were picked by a tweezers and collected in a plastic bag. As a result, all of the coarse and most of fine roots were collected. The process was repeated several times until all soil from a sample was washed and roots separated. Roots were oven-dried at 60°C for 3 d and weighed. Concentrations and contents of C and N in roots were determined as for aboveground biomass samples.

### Data Analysis

Data for above- and belowground (0- to 120-cm) biomass yields, C and N concentrations, and C and N contents in cover crops, residual soil inorganic N after summer crop harvest in the fall, and cotton and sorghum yields and N uptake in each year were analyzed using the MIXED procedure of SAS after testing for homogeneity of variance (Littell et al., 1996). Sources of variation that were considered fixed effects included tillage, cover crop, N fertilization rate, and their interactions. Random effects were replication and tillage × replication interaction. For analyzing belowground biomass yield, C and N concentrations, and C and N contents at individual soil depths, depth was considered as the split-split-split plot treatment, and data in each year were analyzed using the MIXED procedure as above. For above- and belowground biomass yields and C and N contents in cover crops in 2000, cover crop was considered as fixed effect and replication as random effect because tillage and N fertilization treatments were initiated only for the following cotton after the cover crop kill. Means were separated using the least square means test when treatments and their interactions were significant. Statistical significance was evaluated at $P \leq 0.05$.

## RESULTS AND DISCUSSION

### Climate

Temperature and rainfall during the growing season (October to April) can influence germination, growth, and biomass yield of cover crops. Average monthly temperature from November to January was higher in 2001–2002 than in the 1999–2000 and 2000–2001 growing seasons and the 41-yr long-term average (Fig. 1A). Total monthly rainfall in March was greater in 2000–2001 than in other years (Fig. 1B). Total rainfall from October to April was higher in 2000–2001 (449 mm) than in 1999–2000 (397 mm) and 2001–2002 (305 mm) but lower than the 41-yr average (707 mm).

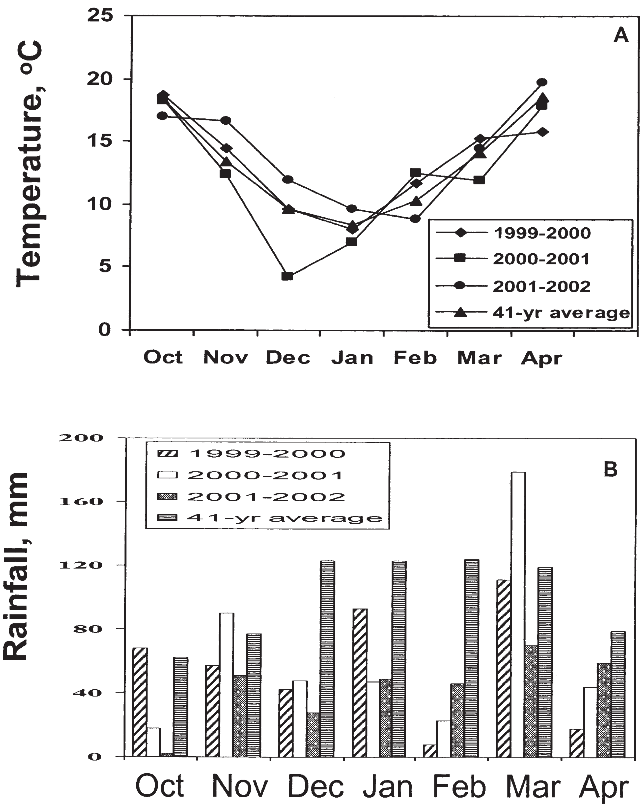


**Fig. 1. (A) Average monthly temperature and (B) total monthly rainfall from October to April 1999 to 2002 and the 41-yr average in Fort Valley, GA.**

## Aboveground Biomass Yield and Carbon and Nitrogen Contents

The aboveground biomass yield, C and N concentrations, and C and N contents varied for different cover crop species (Table 1). Aboveground biomass yields of cover crops were greater than those of winter weeds in the no cover crop treatment, and rye had greater yield than hairy vetch in 2000 and 2001 but a lower yield in 2002 when averaged across tillage and N fertilization treatments (Table 2). The biculture of vetch and rye had greater biomass yield than the monoculture of either species.

Carbon concentration was higher in rye than in weeds and biculture in 2000, greater in rye and biculture than in weeds and vetch in 2001, and greater in rye than in vetch, biculture, and weeds in 2002 (Table 2). Nitrogen concentration had slightly different results, being higher in vetch than in rye and weeds and similar in the biculture of vetch and rye as vetch in 2000 and 2002. As a result, the C/N ratio was higher in rye and lower in vetch and biculture than in weeds, except for biculture in 2001.

As with biomass yield, C content, averaged across tillage and N fertilization, was greater in rye than in vetch in 2000 and 2001 but was greater in vetch than in rye in 2002 (Table 2). Except for vetch in 2002, C content was greater in biculture than in rye, vetch, and weeds. In contrast, N content was greater in vetch and biculture than in rye and weeds.

The decrease in biomass yield and C and N contents in rye from 2000 to 2002 (Table 2) is probably due to decreasing availability of N in the soil, followed by lower rainfall during the cover crop growing season from October to April in 2001–2002. A difference of 4.6 kg $ha^{-1}$ of soil residual inorganic N ($NH_4$–N + $NO_3$–N) content at 0 to 20 cm before cover crop planting in October–November 1999 to 2001 occurred under rye compared with −0.4 kg $ha^{-1}$ under vetch and 1.7 kg $ha^{-1}$ under vetch and rye biculture (Table 3). Since $NO_3$–N content was measured only at 0 to 20 cm, this difference between cover crops may not provide a true picture because roots grow and take up N from a depth greater than 20 cm (Fig. 2 and 3). Rye responds favorably to residual soil N by increasing biomass growth and N uptake (Meisinger et al., 1991; McCracken et al., 1994; Sainju et al.,

**Table 1. Analysis of variance for aboveground biomass yield and C and N contents in cover crops from 2000 to 2002.**

| Source | Biomass yield | Concentration C | Concentration N | Content C | Content N | C/N ratio |
|---|---|---|---|---|---|---|
| | | **2000** | | | | |
| Cover crop (C) | *** | * | * | *** | *** | *** |
| | | **2001** | | | | |
| Tillage (T) | NS† | NS | NS | NS | NS | NS |
| C | *** | *** | *** | *** | *** | *** |
| T × C | * | * | * | * | * | NS |
| N fertilization (F) | * | NS | NS | * | * | NS |
| T × F | NS | NS | NS | NS | NS | NS |
| C × F | NS | NS | NS | NS | NS | NS |
| T × C × F | NS | NS | NS | NS | NS | NS |
| | | **2002** | | | | |
| T | NS | NS | NS | NS | NS | NS |
| C | ** | ** | ** | ** | *** | *** |
| T × C | NS | NS | NS | NS | NS | NS |
| F | NS | NS | NS | NS | NS | NS |
| T × F | NS | NS | NS | NS | NS | NS |
| C × F | NS | NS | NS | NS | NS | NS |
| T × C × F | NS | NS | NS | NS | NS | NS |

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† Not significant.

**Table 2. Effects of cover crop species on aboveground biomass yield and C and N contents in cover crops averaged across tillage and N fertilization rates from 2000 to 2002.**

| Cover crop† | Biomass yield | Concentration C | Concentration N | Content C | Content N | C/N ratio |
|---|---|---|---|---|---|---|
| | Mg $ha^{-1}$ | g $kg^{-1}$ | | kg $ha^{-1}$ | | |
| | | **2000** | | | | |
| Weeds | 1.65d‡ | 370b | 15b | 587d | 25d | 24b |
| Rye | 6.07b | 430a | 15b | 2670b | 68c | 29a |
| Vetch | 5.10c | 394ab | 33a | 2006c | 165b | 12c |
| Vetch/rye | 8.18a | 366b | 38a | 3512a | 310a | 10c |
| | | **2001** | | | | |
| Weeds | 0.75d | 391b | 20b | 277d | 15b | 20c |
| Rye | 3.81b | 448a | 8d | 1729b | 32b | 57a |
| Vetch | 2.44c | 398b | 32a | 964c | 76a | 12c |
| Vetch/rye | 5.98a | 434a | 14c | 2693a | 84a | 32b |
| | | **2002** | | | | |
| Weeds | 1.25c | 375b | 18b | 476c | 23b | 21b |
| Rye | 2.28b | 434a | 11b | 986b | 25b | 40a |
| Vetch | 5.16a | 361b | 36a | 2094a | 167a | 10c |
| Vetch/rye | 5.72a | 381b | 33a | 2260a | 186a | 11c |

† Cover crops are cereal rye (rye), hairy vetch (vetch), hairy vetch and rye biculture (vetch/rye), and winter weeds (weeds).
‡ Numbers followed by the different letter within a column of a year are significantly different at $P \leq 0.05$ by the least square means test.

1998). In contrast, soil N availability does not seem to be a limiting factor for vetch biomass production and C and N contents, probably because hairy vetch fixes N from the atmosphere. Clark et al. (1994) found that rye biomass growth and N uptake is influenced by soil residual N level, but hairy vetch biomass growth and N uptake become more competitive when residual soil N is low. Since average monthly temperature from November to January was higher in 2001–2002 than in 1999–2000 (Fig. 1A) and total rainfall from October to April was lower in 2001–2002 than in 1999–2000 and 2000–2001 (Fig. 1B), the lower biomass yield and C and N contents in rye in 2002 could also be attributed to reduced rainfall during the growing season. Both soil residual N and climatic conditions, especially temperature and rainfall, can influence biomass yield and N accumulation in rye (Wagger, 1989; Holderbaum et al., 1990; Utomo et al., 1990). In contrast, hairy vetch biomass yield and C and N contents increased with higher temperature in November to January in 2001–2002 than in other years. Lower biomass yield and C and N contents in vetch in 2001 may be due to lower temperature in December 2000 that may have reduced its population. The aboveground biomass yield and N content in rye (2.3 to 6.1 Mg ha$^{-1}$ and 25 to 68 kg ha$^{-1}$) and hairy vetch (2.4 to 5.2 Mg ha$^{-1}$ and 84 to 167 kg ha$^{-1}$) were

**Table 3. Soil residual inorganic N ($NH_4$–N + $NO_3$–N) content at 0- to 20-cm depth at cover crop planting in October–November 1999 to 2001 averaged across tillage and N fertilization rates.**

| | Inorganic N | | |
|---|---|---|---|
| Cover crop† | 1999 | 2000 | 2001 |
| | kg ha$^{-1}$ | | |
| Weeds | 36.0a‡ | 41.1a | 32.9b |
| Rye | 36.0a | 41.5a | 31.4b |
| Vetch | 36.0a | 44.1a | 36.4a |
| Vetch/rye | 36.0a | 42.4a | 34.3ab |

† Cover crops are cereal rye (rye), hairy vetch (vetch), hairy vetch and rye biculture (vetch/rye), and winter weeds (weeds).
‡ Numbers followed by the different letter within a column are significantly different at $P \leq 0.05$ by the least square means test.

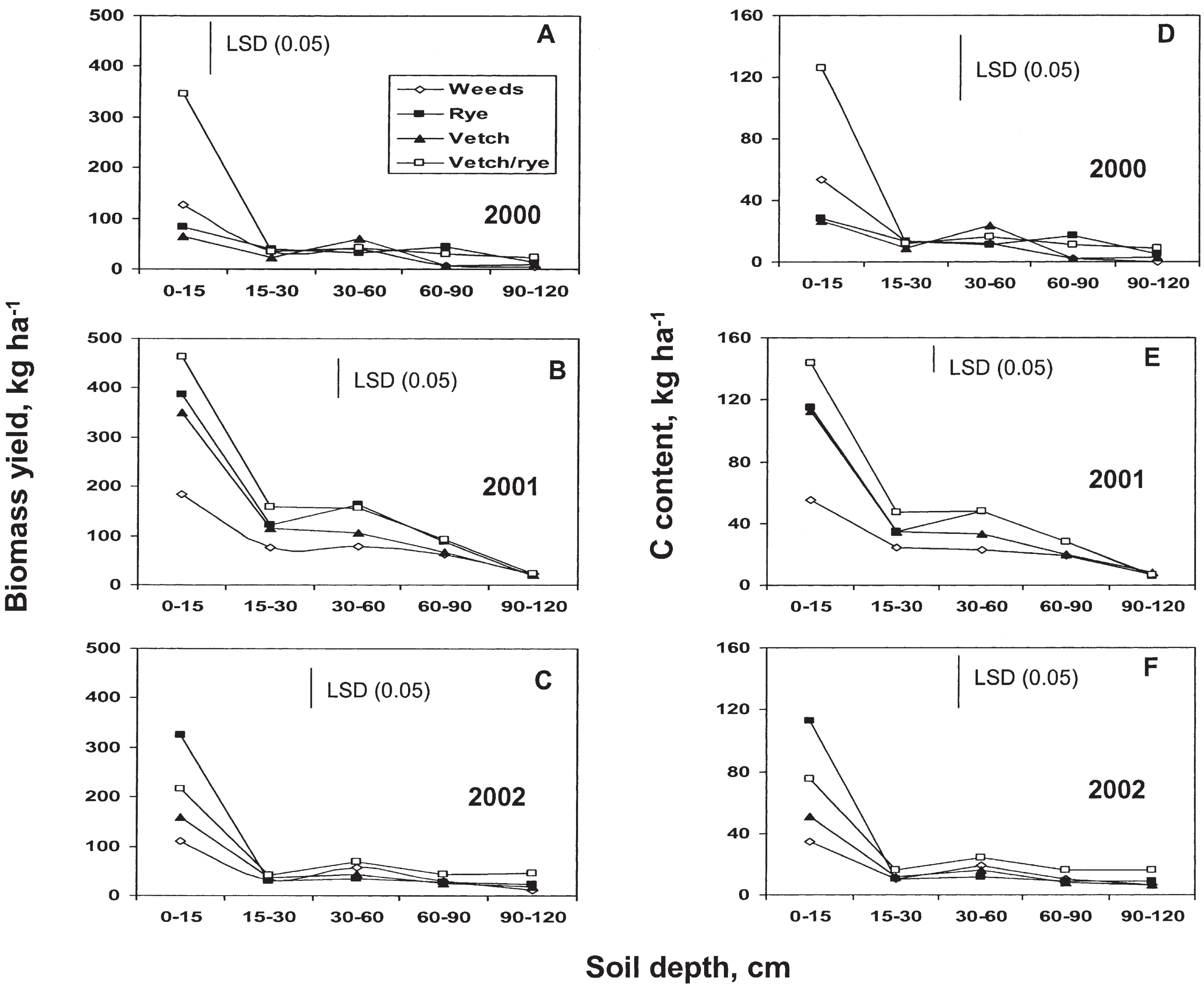


Fig. 2. Biomass yield in (A) 2000, (B) 2001, and (C) 2002 and C content in (D) 2000, (E) 2001, and (F) 2002 in belowground biomass of cover crops from 0- to 120-cm soil depth. Weeds denote winter weeds; rye, cereal rye; vetch, hairy vetch; and vetch/rye, hairy vetch–rye biculture. LSD (0.05) denotes least significant difference between cover crops at $P \leq 0.05$.

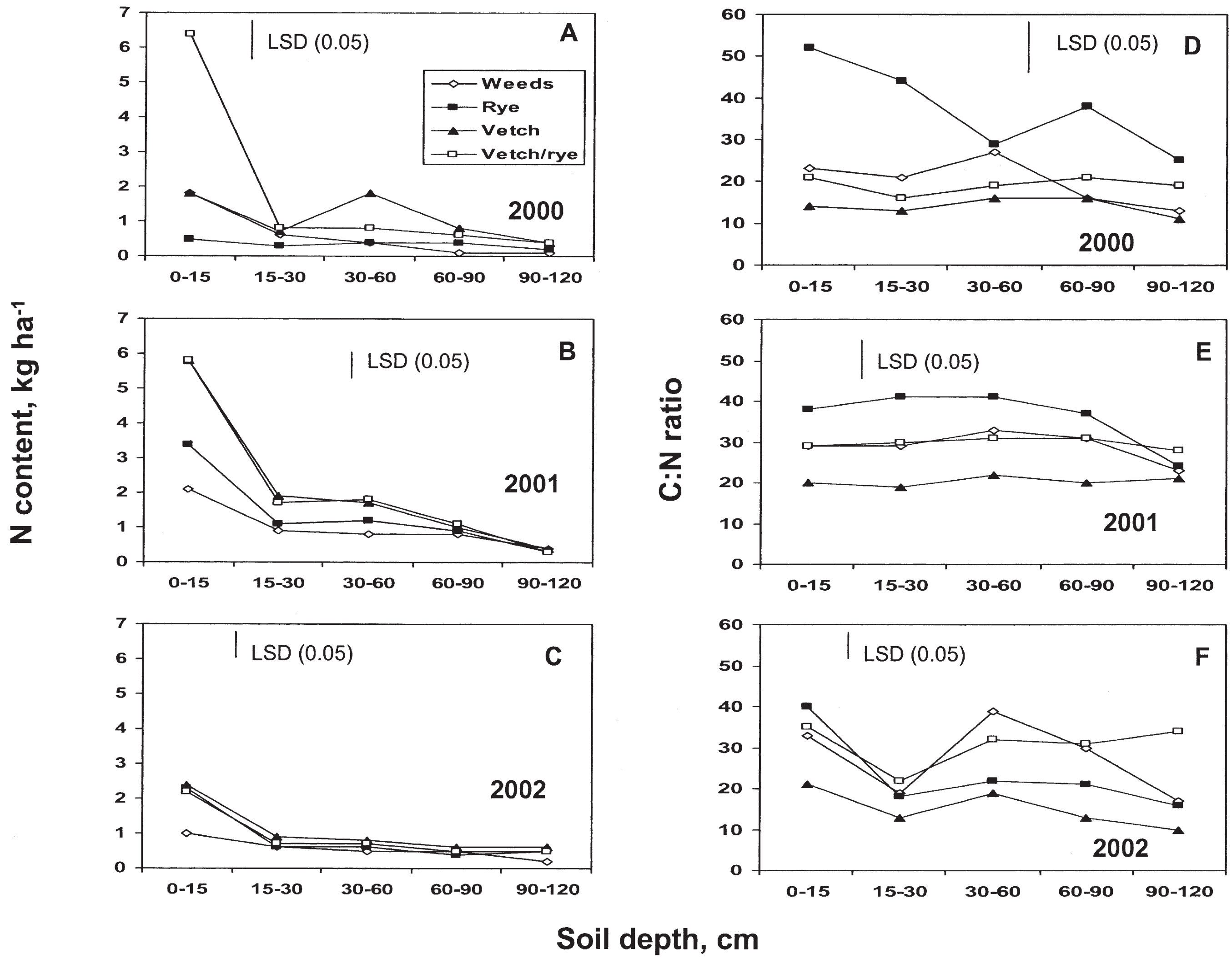


**Fig. 3. Nitrogen content in (A) 2000, (B) 2001, and (C) 2002 and C/N ratio in (D) 2000, (E) 2001, and (F) 2002 in belowground biomass of cover crops from 0- to 120-cm soil depth. Weeds denote winter weeds; rye, cereal rye; vetch, hairy vetch; and vetch/rye, hairy vetch–rye biculture. LSD (0.05) denotes least significant difference between cover crops at $P \leq 0.05$.**

within the range obtained by several researchers for rye (1.0 to 10.4 Mg ha$^{-1}$ and 12 to 124 kg ha$^{-1}$) and hairy vetch (0.7 to 5.2 Mg ha$^{-1}$ and 38 to 182 kg ha$^{-1}$) (Clark et al., 1994; Ranells and Wagger, 1996; Vaughan and Evanylo, 1998; Kuo and Jellum, 2002).

Higher C content in rye than in vetch resulted from higher biomass yield and C concentration while greater N content in vetch than in rye and weeds resulted from higher N concentration (Table 2). Biculture of vetch and rye had greater biomass yield and C and N contents than monocultures. This could have resulted from: (i) N being transferred from vetch to rye, thereby increasing the biomass yield and N concentration of rye in biculture than in monoculture (Ta and Faris, 1987; Russelle and Hargrove, 1989; Ranells and Wagger, 1996); (ii) higher seeding rates of vetch and rye used in biculture than in monocultures, thereby increasing biomass yield because of reduced interspecies competition (Clark et al., 1994); (iii) growth habits of vetch and rye in biculture, such as the upright growth habit of rye providing an excellent scaffold for the viney growth habit of hairy vetch to grow upward, thereby intercepting a greater percentage of light and reducing the growth competition between the two species (Ranells and Wagger, 1996; Kuo and Jellum, 2002); and (iv) higher biomass yield and C concentration in rye and higher N concentration in vetch in biculture, similar to those found in monocultures. Greater biomass yield and N content in hairy vetch and rye biculture than in monocultures have been reported by several other researchers (Clark et al., 1994; Ranells and Wagger, 1996; Vaughan and Evanylo, 1998; Kuo and Jellum, 2002). The values of biomass yield and N content for hairy vetch and rye biculture obtained in this study (5.7 to 8.2 Mg ha$^{-1}$ and 84 to 310 kg ha$^{-1}$) were close to ranges observed by other researchers (1.7 to 10.0 Mg ha$^{-1}$ and 40–200 kg ha$^{-1}$) (Clark et al., 1994; Ranells and Wagger, 1996; Vaughan and Evanylo, 1998; Kuo and Jellum, 2002).

Although nonlegume cover crops, such as rye, improve soil organic matter and reduce N leaching (McCracken et al., 1994; Kuo et al., 1997a, 1997b; Sainju et al., 2000), they typically have lower N concentration or higher C/N ratio compared with legume cover crops, thereby having little effects on crop production (Clark et al., 1994;

**Table 4. Effects of tillage, cover crops, and N fertilization rates applied to previous crop (cotton) on aboveground biomass yield and C and N contents in cover crops in 2001.**

| | Cover crop† | Biomass yield | Concentration | | Content | | C/N ratio |
|---|---|---|---|---|---|---|---|
| | | | C | N | C | N | |
| | | Mg ha$^{-1}$ | g kg$^{-1}$ | | kg ha$^{-1}$ | | |
| Tillage | | | | | | | |
| No-till | weeds | 0.69 | 363 | 19 | 250 | 13 | 19 |
| | rye | 4.19 | 420 | 8 | 1760 | 34 | 53 |
| | vetch | 2.49 | 354 | 25 | 881 | 62 | 14 |
| | vetch/rye | 5.19 | 403 | 15 | 2092 | 78 | 27 |
| Strip till | weeds | 0.93 | 342 | 21 | 318 | 20 | 16 |
| | rye | 3.82 | 406 | 8 | 1551 | 31 | 51 |
| | vetch | 2.03 | 352 | 37 | 715 | 75 | 10 |
| | vetch/rye | 6.55 | 401 | 14 | 2627 | 92 | 29 |
| Chisel till | weeds | 0.64 | 355 | 21 | 227 | 13 | 17 |
| | rye | 3.53 | 386 | 9 | 1363 | 32 | 43 |
| | vetch | 2.73 | 371 | 34 | 1013 | 93 | 11 |
| | vetch/rye | 6.22 | 410 | 13 | 2550 | 81 | 32 |
| LSD (0.05) | | 0.94 | 23 | 6 | 397 | 16 | – |
| N fertilization rate (kg N ha$^{-1}$) | | | | | | | |
| 0 | | 3.02b‡ | 376a | 19a | 1137b | 57b | 20a |
| 60 | | 3.18ab | 381a | 19a | 1211b | 60ab | 20a |
| 120 | | 3.57a | 384a | 18a | 1371a | 64a | 21a |

† Cover crops are cereal rye (rye), hairy vetch (vetch), hairy vetch and rye biculture (vetch/rye), and winter weeds (weeds).
‡ Numbers followed by the different letter within a column are significantly different at $P \leq 0.05$ by the least square means test.

Ranells and Wagger, 1996; Kuo and Jellum, 2002). As the C/N ratio of plant residues increases above 25:1, potential for N immobilization in the soil increases (Allison, 1966). The C/N ratio of rye ranged from 29 to 57 in 2000 and 2001 while the C/N ratio of hairy vetch ranged from 10 to 12 (Table 2). When vetch was grown with rye in biculture, the C/N ratio of the biculture ranged from 10 to 32. As a result, the potential of rye in biculture compared with monoculture to immobilize soil N was reduced, probably due to different amounts of vetch and rye in the biculture (Wagger, 1989). Ranells and Wagger (1996) observed that as N concentration in rye increased from monoculture to biculture with hairy vetch, the C/N ratio decreased from 42 to 16. As a result, more N was released from hairy vetch and rye biculture residue in the soil than from rye residue. Therefore, legume–cereal biculture can reduce the C/N ratio of cereal cover crops and increase the potential for soil N mineralization and availability for the succeeding crop.

Biomass yield and C content, averaged across N rates, were greater in strip till with vetch and rye biculture than in other treatments, except in chisel till with biculture (Table 4). Nitrogen content was greater in chisel till with vetch than in other treatments, except in no-till, strip till, and chisel till with biculture. Biomass yield and C and N contents, averaged across tillage and cover crops, were also greater in 120 than in 0 kg N ha$^{-1}$. This suggests that tillage and N fertilization applied to cotton in 2000 increased biomass yield and C and N contents in cover crops compared with weeds and in hairy vetch and rye biculture compared with monocultures in 2001.

## Belowground Biomass Yield and Carbon and Nitrogen Contents

Cover crops influenced belowground (0- to 120-cm depth) biomass yield, C and N contents, and C/N ratios (Table 5). In 2000, belowground biomass yield, averaged across tillage and N fertilization, was greater in biculture than in hairy vetch, rye, or winter weeds at 0- to 15-cm depth (Fig. 2A). In 2001, biomass yield was greater in cover crops than in weeds at 0 to 15 cm and greater in rye and biculture than in weeds at 30 to 60 cm (Fig. 2B). In 2002, biomass yield was greater in rye and biculture than in weeds at 0 to 15 cm (Fig. 2C). Total belowground biomass yield from 0 to 120 cm was greater in biculture than in vetch, rye, and weeds in 2000; greater in biculture than in vetch and weeds in 2001; and greater in rye and biculture than in vetch and weeds in 2002 (Table 6). The root/shoot ratio was greater in weeds than in cover crops in 2000 and 2001 but was greater in rye than in vetch and biculture in 2002.

Carbon content in belowground biomass, averaged across tillage and N fertilization rates, followed patterns similar to belowground biomass yield at all depths and years (Fig. 2D, 2E, and 2F). Carbon content was greater

**Table 5. Analysis of variance for belowground (0- to 120-cm depth) biomass yield and C and N contents in cover crops from 2000 to 2002.**

| Source | Biomass yield | Content C | Content N | C/N ratio |
|---|---|---|---|---|
| | 2000 | | | |
| Cover crop | ** | ** | ** | ** |
| | 2001 | | | |
| Tillage (T) | NS† | NS | NS | NS |
| Cover crop (C) | *** | *** | *** | *** |
| T × C | * | NS | ** | ** |
| N fertilization (F) | NS | NS | NS | NS |
| T × F | NS | NS | NS | NS |
| C × F | NS | NS | NS | NS |
| T × C × F | NS | NS | NS | NS |
| | 2002 | | | |
| T | NS† | NS | NS | NS |
| C | * | * | ** | *** |
| T × C | NS | NS | NS | NS |
| F | NS | NS | NS | NS |
| T × F | NS | NS | NS | NS |
| C × F | NS | NS | NS | NS |
| T × C × F | NS | NS | NS | NS |

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† Not significant.

**Table 6. Effects of cover crop species on belowground (0- to 120-cm depth) biomass yield and C and N contents in cover crops averaged across tillage and N fertilization rates from 2000 to 2002.**

| Cover crop† | Biomass yield | Content C | Content N | C/N ratio | Root/shoot ratio |
|---|---|---|---|---|---|
| | kg ha$^{-1}$ | kg ha$^{-1}$ | | | |
| | | 2000 | | | |
| Weeds | 208b‡ | 73b | 3.0b | 24b | 0.13a |
| Rye | 174b | 60b | 1.3c | 45a | 0.03b |
| Vetch | 147b | 59b | 4.0b | 14c | 0.03b |
| Vetch/rye | 421a | 154a | 8.1a | 19bc | 0.05b |
| | | 2001 | | | |
| Weeds | 423c | 130c | 5.0b | 25b | 0.56a |
| Rye | 772ab | 250ab | 6.9b | 33a | 0.20b |
| Vetch | 656b | 208b | 10.6a | 20c | 0.27b |
| Vetch/rye | 880a | 269a | 10.6a | 25b | 0.15b |
| | | 2002 | | | |
| Weeds | 175b | 57c | 1.7b | 33a | 0.14ab |
| Rye | 395a | 137a | 3.6a | 38a | 0.17a |
| Vetch | 236b | 78bc | 4.2a | 19b | 0.05c |
| Vetch/rye | 372a | 130ab | 4.0a | 32a | 0.10bc |

† Cover crops are cereal rye (rye), hairy vetch (vetch), hairy vetch and rye biculture (vetch/rye), and winter weeds (weeds).
‡ Numbers followed by the different letter within a column of a year are significantly different at $P \leq 0.05$ by the least square means test.

in rye and biculture than in weeds at 0 to 15 cm. Nitrogen content was greater in biculture than in vetch, rye, and weeds at 0 to 15 cm and greater in vetch than in rye and weeds at 30 to 60 cm in 2000 (Fig. 3A). In 2001, N content was greater in vetch and biculture than in rye and weeds at 0 to 15 cm (Fig. 3B). In 2002, N content was greater in cover crops than in weeds at 0 to 15 cm (Fig. 3C). Total C content from 0 to 120 cm was greater in biculture than in vetch, rye, and weeds in 2000; greater in biculture than in vetch and weeds in 2001; and greater in rye than in vetch and weeds in 2002 (Table 6). Total N content was greater in biculture than in vetch, rye, and weeds in 2000; greater in vetch and biculture than in rye and weeds in 2001; and greater in cover crops than in weeds in 2002. The C/N ratio was greater in rye than in vetch and biculture (Fig. 3D, 3E, and 3F; Table 6).

Averaged across N rates in 2001, total belowground biomass yield from 0 to 120 cm was greater in chisel till with vetch and rye biculture than in no-till with vetch, biculture, and weeds; strip till with rye and weeds; and chisel till with vetch and weeds (Table 7). Nitrogen content was greater in strip till with vetch than in other treatments, except in strip till with biculture and chisel till with vetch and biculture. The C/N ratio was greater in strip till with rye than in no-till with vetch and weeds, strip till with vetch and biculture, and chisel till with vetch, biculture, and weeds.

The surface 0 to 15 cm of soil had 42 to 55% of the total belowground biomass yield and C and N contents from 0- to 120-cm depth (Fig. 2 and 3). The higher biomass yield and C and N contents at 0 to 15 cm suggest that surface soil is more favorable for root growth than the subsurface soil (Bedford and Henderson, 1985; Box and Ramseur, 1993; Sainju et al., 1998). Similarly, slight increase in biomass yield and C and N contents at 30 to 60 cm compared with 15 to 30 or 60 to 120 cm probably suggest root proliferation in a site containing higher clay content with increased water-holding capacity because clay content increased below 30-cm depth.

**Table 7. Effects of tillage and cover crop species on belowground (0- to 120-cm soil depth) biomass yield and C and N contents in cover crops averaged across N fertilization rates in 2001.**

| Tillage | Cover crop† | Biomass yield | C content | N content | C/N ratio |
|---|---|---|---|---|---|
| | | kg ha$^{-1}$ | | | |
| No-till | weeds | 489 | 149 | 6.0 | 26 |
| | rye | 847 | 252 | 8.2 | 30 |
| | vetch | 492 | 154 | 7.8 | 21 |
| | vetch/rye | 731 | 226 | 7.6 | 33 |
| Strip till | weeds | 392 | 108 | 3.6 | 37 |
| | rye | 587 | 182 | 4.8 | 40 |
| | vetch | 805 | 353 | 15.6 | 17 |
| | vetch/rye | 770 | 241 | 9.9 | 28 |
| Chisel till | weeds | 388 | 113 | 5.3 | 23 |
| | rye | 880 | 260 | 7.6 | 37 |
| | vetch | 672 | 232 | 8.6 | 25 |
| | vetch/rye | 1139 | 347 | 14.2 | 26 |
| LSD (0.05) | | 371 | – | 7.0 | 11 |

† Cover crops are cereal rye (rye), hairy vetch (vetch), hairy vetch and rye biculture (vetch/rye), and winter weeds (weeds).

Belowground biomass yield and C and N contents varied in similar patterns among cover crops as aboveground parameters. Belowground biomass of rye had greater C content due to higher yield, but biomass of vetch had greater N content due to higher N concentration. Greater root biomass yield and C content or greater minirhizotron root count in rye than in hairy vetch and winter weeds had been reported by several researchers (Kuo et al., 1997a; Sainju et al., 1998). As a result, higher C and N contents in biculture of rye and vetch were due to higher biomass yield, followed by N level in between those of rye and vetch. Higher seeding rate in biculture compared with monocultures promoted both shoot and root growth. The C/N ratio in belowground biomass of rye was similar to that in aboveground biomass, but C/N ratio in belowground biomass of vetch and biculture was higher than that in aboveground biomass. This suggests that belowground biomass of vetch and biculture probably decomposes and releases N slower than aboveground biomass. Puget and Drinkwater (2001) reported that roots of hairy vetch decompose slower than shoots and that roots improve soil structure while shoots provide N for the following crop. As with aboveground biomass, a biculture of rye with hairy vetch had a lower C/N ratio (27) than rye (35) grown as a monoculture.

The nonsignificant effect of tillage on total belowground biomass yield and C and N contents from 0 to 120 cm in cover crops (Table 5) suggests that cover crop roots can grow as well in conservation tillage as in conventional tillage system. Similar results have been observed for the aboveground biomass. This is consistent with earlier results, which reported that cover crop biomass yield and C and N contents were not influenced by tillage (Sainju et al., 2001, 2002a). However, chisel till increased belowground biomass of biculture when compared with other tillage and cover crops in 2001 (Table 7). Higher N content in strip till and chisel till with vetch and biculture than in other treatments in 2001 may have resulted from higher N concentration in vetch and biculture roots, followed by increased root growth due to soil disturbance in strip till and chisel till.

**Table 8. Effects of cover crops on cotton lint and sorghum grain yields, biomass (stems + leaves) yield, and N uptake averaged across tillage and N fertilization rates from 2000 to 2002.**

| Cover crop† | Lint or grain yield | Biomass yield | N concentration | N uptake |
|---|---|---|---|---|
| | kg ha$^{-1}$ | Mg ha$^{-1}$ | g kg$^{-1}$ | kg ha$^{-1}$ |
| | | 2000 Cotton | | |
| Weeds | 1075b‡ | 7.4b | 16.8b | 124b |
| Rye | 1352a | 9.2ab | 4.1c | 130b |
| Vetch | 1015b | 11.3a | 19.5a | 220a |
| Vetch/rye | 1086b | 10.5a | 18.1a | 190a |
| | | 2001 Sorghum | | |
| Weeds | 2800bc | 12.0ab | 10.5ab | 132ab |
| Rye | 2300c | 9.4b | 8.6b | 81b |
| Vetch | 3500ab | 14.1a | 12.4a | 175a |
| Vetch/rye | 4000a | 14.2a | 9.8b | 138a |
| | | 2002 Cotton | | |
| Weeds | 1511a | 10.6a | 13.5b | 143b |
| Rye | 1513a | 10.3a | 14.8b | 152b |
| Vetch | 1077c | 12.0a | 17.5a | 210a |
| Vetch/rye | 1272b | 12.3a | 17.5a | 215a |

† Cover crops are cereal rye (rye), hairy vetch (vetch), hairy vetch and rye biculture (vetch/rye), and winter weeds (weeds).
‡ Numbers followed by the different letter within a column of a set are significantly different at $P \leq 0.05$ by the least square means test.

The hard pan layer that occurs below 20-cm depth in Dothan soil in this experiment was probably broken by subsoiling during strip till, which may have promoted root growth.

The average root/shoot ratio ranged from 0.09 in biculture to 0.13 in rye (Table 6). These findings suggest that belowground biomass contributed 9 to 13% of aboveground biomass in cover crops, except winter weeds. As a result, belowground biomass constitutes an important source of C and N inputs for enriching soil organic matter. Shipley et al. (1992) estimated that root biomass constituted 10% of aboveground biomass for hairy vetch and 25% for rye. Similarly, Kuo et al. (1997a, 1997b) found that belowground biomass to a depth of 0 to 20 cm was 8% of aboveground biomass for hairy vetch and 32% for rye. Our average value of 12% for hairy vetch was similar, but 13% for rye was lower than that reported in the literature. Because belowground biomass can vary more than aboveground biomass due to variation in root growth in the soil profile as a result of heterogeneity, the proportion of root to shoot biomass can vary. Also, the difference in methods used to determine root biomass can influence the root/shoot ratio. While Kuo et al. (1997a, 1997b) excavated a 900-cm$^2$ area from 0- to 20-cm depth for determining root biomass, we used three soil cores of 5 cm (i.d.) to a depth from 0 to 120 cm collected randomly in and between the crop rows in a plot. The random soil sampling of three 5-cm-diam. holes in a plot size of 7.2 by 7.2 m$^2$ to collect root samples may not accurately measure belowground biomass yield. Nevertheless, similar root/shoot ratios in cover crops suggest that both roots and shoots grow in similar proportion.

## Cotton and Sorghum Yields and Nitrogen Uptake

In 2000, cotton lint yield was greater with rye than with vetch, vetch and rye biculture, and weeds, but biomass yield, N concentration, and N uptake were greater with vetch and biculture than with weeds (Table 8). In 2001, sorghum grain yield, biomass, and N uptake were greater with vetch and biculture than with rye. In 2002, cotton lint yield was greater with rye and weeds than with vetch and biculture, but N concentration and uptake were greater with vetch and biculture than with rye and weeds.

The reduced cotton lint yield but increased biomass yield and N uptake with vetch and vetch and rye biculture compared with rye or winter weeds could be due to excess N supplied by vetch in both monoculture and biculture since N content in above- and belowground biomass was greater in vetch and biculture (Tables 2 and 6). Since the data were averaged across tillage and N fertilization rates, it may be possible that N supplied by vetch together with that added from N fertilizer could have reduced cotton lint yield at the expense of increased vegetative growth. In contrast, increased N added from N fertilizer in rye and weed treatment could have increased lint yield. Boquet et al. (2004) observed that cotton lint yield increased with increased N fertilization rates from 0 to 118 kg N ha$^{-1}$ with wheat cover crop or native cover but decreased with hairy vetch. The tolerance of cotton lint yield following rye to high N rates was probably related to N immobilization caused by high C/N ratio of rye residue (Dabney et al., 2001). It may also be possible that unidentified factors retard cotton's vegetative growth in rye residue (Hicks et al., 1989). The interacting effects of tillage, cover crops, and N fertilization rates on cotton lint and biomass yields and N uptake will be described in a separate paper. However, reduced cotton lint yield but increased sorghum grain yield, cotton and sorghum biomass yields, and N uptake with vetch and biculture compared with rye suggests that N supplied by cover crops and some unidentified factors can variably influence the growth and production of cotton and sorghum. Similar cotton and sorghum yields, biomass, and N uptake with vetch and biculture suggest that hairy vetch and rye biculture are equally effective in increasing crop yield and N uptake as vetch.

## SUMMARY AND CONCLUSIONS

Above- and belowground biomass yields and C and N contents in cover crops varied by species and years. While rye had greater biomass yield and C content in 2000 and 2001, hairy vetch had greater N content than winter weeds from 2000 to 2002. As a result, biculture of rye and vetch had greater biomass yield and C and N contents than monoculture of each species in all years. The C/N ratio of biculture was significantly lower than that of rye, thereby increasing the potential for N mineralization. Although cotton lint yield is reduced, sorghum grain yield, cotton and sorghum biomass yields, and N uptake were greater with biculture than with rye. Because of higher biomass yield and C and N contents, rye and hairy vetch cover crops may be grown together to supply N need and increase succeeding crop yields compared with rye and potentially improve soil organic matter and reduce N leaching compared with vetch, for which either of the species alone was not effective enough. The feasibility of biculture cover crops compared with monocultures, however, needs to be widely accessed by growing them in different soil and climatic conditions, and their cost needs to be evaluated so that the management practice is acceptable to the producers.

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