Cover Crop and Nitrogen Fertilization Influence Soil Carbon and Nitrogen Under Bioenergy Sweet Sorghum

Upendra M. Sainju,* Hari P. Singh, Bharat P. Singh, Wayne F. Whitehead, Anuj Chiluwal, and Rajesh Paudel

ABSTRACT

Sustainable production of sweet sorghum (Sorghum bicolor [L.] Moench) grown for bioenergy production depends on practices that maintain soil C and N levels. The objective of this study was to evaluate the effect of winter cover crops (hairy vetch [Vicia villosa Roth], rye [Secale cereale L.], hairy vetch/rye mixture, and the control [no cover crop]) and N fertilization rates (0 and 90 kg N ha⁻¹) on soil organic C (SOC), total N (STN), NH₄–N, and NO₃–N contents at the 0- to 30-cm depth from 2010 to 2014 in the southeastern USA. Cover crop biomass yield and C content were greater with vetch/rye than vetch and the control and N content greater with vetch and vetch/rye than the control in 2013 and 2014. The SOC and STN at 0 to 5 cm were greater with vetch/rye than the control and at 15 to 30 cm were greater with vetch than vetch/rye. At 0 to 5 cm, SOC increased at 0.55 Mg C ha⁻¹ yr⁻¹ and STN at 0.06 Mg N ha⁻¹ yr⁻¹, regardless of treatments. At most depths, NH₄–N content was greater with rye than the control and greater with 0 than 90 kg N ha⁻¹, but NO₃–N content was greater with vetch/rye than vetch. Because of greater cover crop C and N inputs, soil C and N stocks can be enhanced and N availability can be optimized by growing vetch and vetch/rye mixture cover crops to replace the stocks reduced by the removal of aboveground sweet sorghum biomass.

Core Ideas

• Removal of aboveground biomass may affect soil C and N under sweet sorghum.
• The effect of cover crop and N fertilization on soil C and N under sweet sorghum was examined.
• SOC and STN were greater with vetch and vetch/rye mixture than other cover crops
• NH₄–N was greater with rye and NO₃–N greater with vetch/rye than other cover crops.
• Vetch and vetch/rye can enhance soil C and N storage and optimize N availability.

Sweet sorghum has been considered a promising crop for bioenergy production because of its high sugar content which can be easily converted to ethanol (Rooney et al., 2007; Tamang et al., 2011). Furthermore, lignocellulose and starch from grain, stalk, and bagasse (stalls after sugar extraction) can also be used for ethanol production (Tamang et al., 2011). Compared with other bioenergy crops, such as corn (Zea mays L.), sweet sorghum is widely adapted in warm regions, is drought tolerant, requires less water, and produces greater biomass (Howell et al., 1997; Rooney et al., 2007; Evers et al., 2013). Sweet sorghum can also remain in vegetative stage late in the growing season even in dryland or rainfed conditions and can regrow after harvest, resulting in greater biomass yield through multiple cuttings, especially in regions with a longer growing season (Ketterings et al., 2007; Rooney et al., 2007). Such bioenergy crops could replace about 30% of the US total current petroleum consumption by 2030 (Perlack et al., 2005; USDOE, 2011).

Aboveground biomass (grain, leaves, and stems) of sweet sorghum is usually harvested for bioenergy production. As a result, belowground biomass (root) becomes the main supplier of C and N to maintain or increase soil C and N in bioenergy crop production. Continuous removal of aboveground biomass can reduce soil and environmental quality (Wilhelm et al., 2004; Blanco-Canqui and Lal, 2007); therefore, improved management practices are needed to enhance C and N inputs to the soil, sustain soil C and N stocks, reduce N leaching, and mitigate greenhouse gas emissions by sequestering atmospheric C and N in bioenergy cropping systems. Enhancement of soil C and N stocks also has an indirect effect of improving soil fertility, such as increased soil water-nutrient-crop productivity relationships (Bauer and Black, 1994; Blanco-Canqui and Lal, 2007). There is a paucity of information regarding the effect of crop residue removal on soil C and N storage and N leaching under bioenergy crops (Blanco-Canqui and Lal, 2007; Blanco-Canqui, 2010).

One of the management practices to maintain or enhance soil C and N stocks and reduce N leaching is to grow winter cover crops after harvest of bioenergy crops in the fall (Kuo et al., 1997a, 1997b; Sainju et al., 2006, 2007). By providing additional residues and enhancing C and N inputs to the soil,

*Corresponding author (upendra.sainju@ars.usda.gov).

Abbreviations: SOC, soil organic C; STN, soil total N; vetch, hairy vetch; vetch/rye, hairy vetch and rye mixture.

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winter cover crops can increase soil C and N stocks compared with no cover crop (Kuo et al., 1997a, 1997b; Sainju et al., 2006).

Legume cover crops can fix N from the atmosphere, supply N to succeeding crops, reduce N fertilization rates, and increase subsequent crop yields (Clark et al., 1994; Kuo et al., 1997b; Kuo and Jellum, 2002; Hill et al., 2016). In contrast, nonlegume cover crops can increase soil C and N stocks and reduce N leaching due to their extensive root system and greater biomass yield than legumes or no cover crop (Kuo et al., 1997a, 1997b; Sainju et al., 2006; Moore et al., 2014; Thomas et al., 2017). As much as 29 to 94% of N leaching can be reduced by nonlegume cover crops compared with 6 to 48% by legume cover crops (Sainju and Singh, 1997). None of the cover crops, however, are effective enough to simultaneously supply N, sustain crop yields, increase soil C and N stocks, and reduce N leaching. As a result, Sainju and Singh (1997) suggested that a mixture of legume and non-legume cover crops might provide most of these benefits. Several researchers (Sainju et al., 2006; Sainju and Singh, 2008) have reported greater soil C and N stocks with hairy vetch/rye mixture than hairy vetch or rye alone and no cover crop.

Nitrogen fertilization can also increase soil C and N stocks by increasing crop biomass yield and the amount of residue returned to the soil compared with no N fertilization (Gregorich et al., 1996; Omay et al., 1997). As N is required in large amount to enhance sweet sorghum biomass yield and biofuel production (Tamang et al., 2011; Maughan et al., 2012), N rates to sweet sorghum can vary from one place to another, depending on soil and climatic conditions and management practices (Ketterings et al., 2007; Tamang et al., 2011; Maughan et al., 2012). In contrast, several researchers (Russell et al., 2005; Sainju et al., 2006) have found negative or no effect of N fertilization on SOC and STN. As crops can use only 50–70% of applied N, N rates beyond crops’ requirement can increase soil residual N (NH₄⁻N + NO₃⁻-N) accumulation after harvest (Hallberg, 1989; Bergström and Kirchmann, 2004). The residual N can be lost to the environment through leaching, denitrification, volatilization, surface runoff, soil erosion, and N₂O emissions which reduces air and water quality (Eickhout et al., 2006; Ross et al., 2008).

We used mono- and biculture of hairy vetch and rye cover crops and N rates to sweet sorghum to evaluate their effects on soil C and N under bioenergy sweet sorghum from 2010 to 2014 in the southeastern United States. Our objectives were to (i) quantify cover crop biomass yield and C and N contents; (ii) examine the effect of cover crops (hairy vetch, rye, hairy vetch/rye mixture, and the control [no cover crop]) and N fertilization rates (0 and 90 kg N ha⁻¹) to sweet sorghum on SOC, STN, NH₄⁻N, and NO₃⁻-N contents at the 0–to-30-cm depth from 2010 to 2014; and (iii) determine N fertilization rates that enhance sweet sorghum biomass yield. Our hypothesis was that hairy vetch/rye mixture with 90 kg N ha⁻¹ applied to sweet sorghum would increase soil C and N stocks, optimize N availability, and reduce the potential for N leaching compared with other treatments.

MATERIALS AND METHODS

Experimental Site, Treatment, and Management

The experiment was conducted at the Agricultural Research Station, Fort Valley State University, Fort Valley, GA (32°33´ N, 83°53´ W) from 2010 to 2014. The soil was a Dothan sandy loam (fine-loamy, kaolinitic, thermic, Plinthic Kandiudults), with 6.5 to 6.7 soil pH, 650 g kg⁻¹ sand, 250 g kg⁻¹ silt, and 100 g kg⁻¹ clay concentrations at the 0- to 30-cm depth. The initial SOC at 0 to 5, 5 to 15, and 15 to 30 cm was 6.67, 10.59, and 8.14 Mg C ha⁻¹ and STN was 0.57, 0.94, and 0.91 Mg N ha⁻¹, respectively, at the beginning of the experiment in November 2010. Monthly average (56-yr, 1957–2013) air temperature ranges from 8°C in January to 27°C in July and total annual precipitation is 1140 mm. The vegetation at the site at the beginning of the experiment was dominated by henbit (Lamium amplexicaule L.), cut-leaf evening primrose (Oenothera laciniata L.), and wild mustard (Brassica juncea L.) which were killed by applying glyphosate (N-[phosphonomethyl] glycine) at 3.5 kg (a.i.) ha⁻¹.

Treatments were four winter cover crops (control, rye, hairy vetch, and hairy vetch/rye mixture) as the main plot and two N fertilization rates (0 and 90 kg N ha⁻¹) applied to sweet sorghum as the split-plot variable arranged in a randomized block design with three replications. The size of the main plot was 36.6 × 5.0 m which was divided into two split plots of sizes 18.3 × 5.0 m each. In November 2010, land was prepared by harrowing to a depth of 15 to 20 cm using discs and leveling with a S-tine harrow to a depth of 10 cm. Hairy vetch seeds inoculated with Rhizobium leguminosarum (bv. viciae) were planted at 28 kg ha⁻¹ and rye seeds at 80 kg ha⁻¹ at a row spacing of 20 cm using a no-till drill. The seed rate for hairy vetch in the hairy vetch/rye mixture was 19 kg ha⁻¹ (68% of monoculture) planted at a spacing of 20 cm and for rye was 40 kg ha⁻¹ (50% of monoculture) planted between vetch rows (Clark et al., 1994). In November 2011 to 2013, cover crops were planted similarly as above but without tillage. No irrigation, fertilizers, herbicides, or pesticides were applied to cover crops. In late April following cover crop planting, cover crop biomass yield was determined by harvesting biomass from 0.5 m² areas randomly within the plot 2 d before cover crop termination. A portion of the biomass was oven dried at 70°C for 3 d to determine dry matter weight which was used to convert biomass yield to dry matter basis. In the control treatment, weed biomass was measured similarly as above. Carbon and N concentrations (g C or N kg⁻¹) in cover crop biomass samples were determined using a high induction furnace C and N analyzer (Elementar, Mt Laurel, NJ) after grinding the oven-dried samples to 1 mm. Carbon (Mg C ha⁻¹) and N (kg N ha⁻¹) contents in the biomass were calculated by multiplying biomass yield by C and N concentrations. After biomass measurement, cover crop residues were returned to the soil by mowing with a rotary mower and killed by applying glyphosate at 1.5 kg (a.i.) ha⁻¹.

In May 2011 to 2014, 2 to 3 wk after cover crop termination, sweet sorghum was planted at a population of 72, 277 plants ha⁻¹ (row spacing of 0.9 m) using a no-till drill without tillage. Phosphorus fertilizer as triple superphosphate (45% P) at 10 kg P ha⁻¹ and K fertilizer as muriate of potash (52% K) at 10 kg K ha⁻¹ were banded at 5 cm to the side and 5 cm below seeds in all plots at planting. For N-fertilized plots, N fertilizer as urea (46% N) at 90 kg N ha⁻¹ was broadcast a week after planting. Sweet sorghum did not receive irrigation, herbicides, or pesticides. In October 2011 to 2014, aboveground biomass of sweet sorghum was harvested by hand from an area of 8.2 m² in each split plot. A portion of the biomass was oven dried at 70°C for
d to determine dry matter yield, from which aboveground biomass yield of sweet sorghum on dry matter basis was calculated.

**Soil Sampling and Analysis**

In late October to early November 2011 to 2014 after sorghum harvest, soil samples were collected from random five places in the center row of each split plot using a tractor-mounted hydraulic probe (3.5 cm i.d.). Soil samples were collected from the 0- to 30-cm depth, separated into 0- to 5-, 5- to 15-, and 15- to 30-cm depth intervals, composited within a depth, air-dried, ground, and sieved to 2 mm. From each depth interval, a portion (>10 g) of the soil was oven dried at 110°C for 24 h and bulk density was calculated by dividing the weight of oven-dried soil by the volume of the core. Soil total C and STN concentrations (g C or N kg⁻¹) were determined using a high-induction furnace C and N analyzer (Elementar, Mt Laurel, NJ) after grinding a subsample to 0.5 mm. As soil samples had pH < 7.0, soil total C was considered as SOC (Nelson and Sommers, 1996). For measurement of NH₄⁻N and NO₃⁻N concentrations (mg N kg⁻¹), 5 g of soil was extracted with 50 mL of 2 mole L⁻¹ KCl for 1 h and the extract was analyzed with an autoanalyzer (Lachat Instruments, Loveland, CO), where NH₄⁻N was determined using the indophenol blue reaction and NO₃⁻N was reduced to NO₂⁻N using Cd reduction and quantified using a modified Griess-Ilosvay method (Mulvaney, 1996). The SOC, STN (Mg C or N ha⁻¹), NH₄⁻N, and NO₃⁻N contents (kg N ha⁻¹) were determined by multiplying their concentrations by the bulk density and the thickness of the soil layer. As bulk density did not differ among treatments and years, values of 1.32 (±0.03), 1.43 (±0.05), and 1.55 (±0.06) Mg m⁻³ at 0 to 5, 5 to 15, and 15 to 30 cm, respectively, averaged across treatments and years, were used for determining SOC, STN, NH₄⁻N, and NO₃⁻N contents. Total contents at 0 to 30 cm were calculated by adding contents from individual depth layers.

**Data Analysis**

The SAS-MIXED model was used to analyze cover crop biomass yield and C and N contents as well as soil C and N contents at a depth (Littell et al., 2006). Cover crop was used as the main plot treatment and the fixed effect, N rate as the split-plot treatment and other fixed effect, year as the repeated measure variable, and replication and replication × cover crop as random effects for analysis. Mean separation was performed using the least square means test when treatments and interactions were significant (Littell et al., 2006). When significant, linear regression analysis was conducted to determine the relationships between SOC and STN contents and year after considering that year 0, 1, 2, 3, and 4 represented 2010, 2011, 2012, 2013, and 2014, respectively. Statistical significance was evaluated at \( P \leq 0.05 \), unless otherwise stated. As cover crops did not grow well in 2011, cover crop biomass yield and C and N contents were not determined for that year. Soil NH₄⁻N and NO₃⁻N contents were also not determined in 2014 due to physical constraints on resources.

**RESULTS AND DISCUSSION**

**Cover Crop Biomass Yield and Carbon and Nitrogen Contents**

Cover crop biomass yield, C and N contents, and C/N ratio varied with cover crop species, biomass N and C/N ratio with N fertilization rates, and biomass yield and C and N contents with years (Table 1). Significant interactions occurred for cover crop × N rate with C/N ratio and for cover crop × year with biomass yield and C and N contents.

Averaged across N fertilization rates, biomass yield and C content were 53 to 72% greater with vetch/rye than vetch and the control in 2013 and 42 to 87% greater with vetch/rye than other cover crops in 2014 (Table 2). Biomass yield and C content were also greater in 2013 and 2014 than 2012 with

<table>
<thead>
<tr>
<th>Cover crop†</th>
<th>N rate (kg N ha⁻¹)</th>
<th>Biomass yield (Mg ha⁻¹)</th>
<th>Biomass C content (Mg C ha⁻¹)</th>
<th>Biomass N content (kg N ha⁻¹)</th>
<th>Biomass C/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0</td>
<td>0.99c§</td>
<td>0.38c</td>
<td>10.9b</td>
<td>35.9a</td>
</tr>
<tr>
<td>R</td>
<td>1.99b</td>
<td>0.79b</td>
<td>24.5b</td>
<td>37.2a</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>2.49b</td>
<td>0.96b</td>
<td>48.7a</td>
<td>23.3c</td>
<td></td>
</tr>
<tr>
<td>VR</td>
<td>4.18a</td>
<td>1.63a</td>
<td>59.4a</td>
<td>30.6b</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>2.48</td>
<td>0.94</td>
<td>41.3a</td>
<td>29.6b</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>2.33</td>
<td>0.91</td>
<td>30.5b</td>
<td>33.6a</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>0.83c</td>
<td>0.33c</td>
<td>11.4c</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>2.07b</td>
<td>0.81b</td>
<td>29.4b</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>4.12a</td>
<td>1.68a</td>
<td>66.9a</td>
<td>32</td>
<td></td>
</tr>
</tbody>
</table>

§Numbers followed by different letters within a column in a set are significantly different at \( P = 0.05 \) by the least square means test.

† Cover crops are: C, unplanted control or weeds; R, cereal rye; V, hairy vetch; and VR, hairy vetch and rye mixture.

‡ Cover crop biomass yield and C and N contents were not measured in 2011 due to poor growth.

§Significant at \( P = 0.001 \); NS, not significant.

Significance

<table>
<thead>
<tr>
<th>Cover crop (CC)</th>
<th>N rate (N)</th>
<th>CC × N</th>
<th>Year (Y)</th>
<th>CC × Y</th>
<th>N × Y</th>
<th>CC × N × Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>***</td>
<td>NS</td>
<td>NS</td>
<td>***</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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<td>***</td>
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<td>NS</td>
<td>NS</td>
</tr>
</tbody>
</table>
Averaged across N rates and years, biomass yield and C and N contents among treatments and years are significantly different at P = 0.05 by the least square means test.

### Soil Organic Carbon and Total Nitrogen

The SOC and STN varied with cover crop species at 0 to 5 and 15 to 30 cm and with years at all depths (Table 3). Averaged across N fertilization rates and years, SOC at 0 to 5 cm was 9 to 11% greater with vetch and vetch/rye than the control. At 15 to 30 cm, SOC was 11 to 15% greater with vetch/rye than the control and at 15 to 30 cm was 8% greater with vetch than vetch/rye. The STN at 0 to 5 cm was 8 to 14% greater with vetch/rye than vetch and the control and at 15 to 30 cm was 8% greater with vetch than vetch/rye. At 5 to 15 and 0 to 30 cm, SOC across treatments averaged 13.4 and 34.1 Mg C ha⁻¹ and STN averaged 1.21 and 3.16 Mg N ha⁻¹, respectively. Significant linear responses of SOC and STN with year occurred at 0 to 5 cm (Fig. 1). Averaged across treatments, SOC at 0 to 5 cm increased at 0.55 Mg C ha⁻¹ yr⁻¹ and STN at 0.06 Mg N ha⁻¹ yr⁻¹ from 2010 to 2014. The SOC and STN at other depths also increased linearly with year, but the responses were not significant. At these depths, both SOC and STN were greater in 2012 than other years. Nitrogen fertilization had no effect on SOC and STN.

Increased cover crop biomass and C and N contents appeared to increase SOC and STN at 0 to 5 and 15 to 30 cm with vetch and vetch/rye compared with rye and the control.
Cover crop biomass and C content were greater with vetch/rye and N content was greater with vetch and vetch/rye than rye and the control (Tables 1 and 2). Previous study near the same site also showed that SOC at 0 to 30 cm was 6 to 10% greater with hairy vetch/rye than hairy vetch, rye, or no cover crop under no-till cotton ([*Gossypium hirsutum* L.]) and grain sorghum due to increased cover crop biomass residue and C returned to the soil (Sainju et al., 2006). Increased SOC with vetch/rye could also be a result of greater belowground biomass C input, as belowground (root) biomass of cover crop is proportional to aboveground biomass (Kuo et al., 1997a; Sainju et al., 1998). The SOC increases linearly to increased C input rate (Rasmussen et al., 1980; Kuo et al., 1997a). Similarly, Sainju and Singh (2008) reported 5 to 12% greater STN with hairy vetch and hairy vetch/rye than rye and no cover crop in no-tilled soils under cotton and grain sorghum due to increased N inputs. Several researchers (Hargrove, 1986, McVay et al., 1989) found greater STN with legume (crimson clover [*Trifolium incarnatum* L.]) than nonlegume or no cover crop, while others (Kuo et al., 1997b) observed greater STN with nonlegume (rye) than legume (hairy vetch) or no cover crop.

Carbon and N additions from above- and belowground biomass of cover crops and belowground biomass of sweet sorghum likely increased SOC and STN at all depths from 2010 to 2014, with significant response especially at the surface layer (Fig. 1). Reduced C and N mineralization due to lower soil water availability as a result of decreased precipitation likely increased SOC and STN at 5 to 15, 15 to 30, and 0 to 30 cm in 2012 than other years.

### Table 3. Soil organic C (SOC) and total N (STN) contents at the 0- to 30-cm depth averaged across sweet sorghum N fertilization rates and years as affected by cover crop species.

<table>
<thead>
<tr>
<th>Cover crop†</th>
<th>SOC content</th>
<th>STN content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–5 cm</td>
<td>5–15 cm</td>
</tr>
<tr>
<td>C</td>
<td>8.23b‡</td>
<td>13.47</td>
</tr>
<tr>
<td>R</td>
<td>8.70ab</td>
<td>13.38</td>
</tr>
<tr>
<td>V</td>
<td>9.04a</td>
<td>13.53</td>
</tr>
<tr>
<td>VR</td>
<td>9.21a</td>
<td>13.36</td>
</tr>
</tbody>
</table>

Significance

- **CC** *NS*
- **N** *NS*
- **CC × N** *NS*
- **Year (Y)** *NS*
- **CC × Y** *NS*
- **N × Y** *NS*
- **CC × N × Y** *NS*

**Significance**

- *Significant at *P* = 0.05.
- ***Significant at *P* = 0.001; NS, not significant.

† Cover crops are C, unplanted control or weeds; R, cereal rye; V, hairy vetch; and VR, hairy vetch and rye mixture.

‡ Numbers followed by different letters within a column in a set are significantly different at *P* = 0.05 by the least square means test.

**Fig. 1.** Relationship between soil organic C (SOC) and total N (STN) at 0- to 5-, 5- to 15-, 15- to 30-, and 0- to 30-cm depths and year. Year 0, 1, 2, 3, and 4 represents 2010, 2011, 2012, 2013, and 2014, respectively.
years. Total annual precipitation was 841 mm in 2012 compared with 981 to 1809 mm in other years and the 56-yr average. Our C sequestration rate of 0.55 Mg C ha\(^{-1}\) yr\(^{-1}\) and N sequestration rate of 0.06 Mg N ha\(^{-1}\) yr\(^{-1}\) at 0 to 5 cm were greater than 0.17 Mg C ha\(^{-1}\) yr\(^{-1}\) at 0 to 10 cm and 0.02 Mg N ha\(^{-1}\) yr\(^{-1}\) at 0 to 15 cm in no-till soils under cotton and grain sorghum in central Georgia (Sainju et al., 2006; Sainju and Singh, 2008). Differences in C and N inputs due to variations in crop types and length of the experiment may have resulted in different C and N sequestration rates. Biomass yield is greater in sweet sorghum than grain sorghum (Evers et al., 2013) and cotton has lower biomass than grain sorghum (Sainju et al., 2006). The length of our experiment was 5 yr compared with 3 yr conducted by other researchers (Sainju et al., 2006; Sainju and Singh, 2008). Increased C and N inputs from cover crop and sweet sorghum residues to the soil over a longer period may have increased C and N sequestration rates under sweet sorghum in our experiment compared with shorter period under grain sorghum and cotton in Sainju et al. (2006) and Sainju and Singh (2008).

**Soil Ammonium Nitrogen**

Soil NH\(_4\)-N content varied with N fertilization rates at 15 to 30 and 0 to 30 cm and with years at 0 to 5 and 0 to 30 cm (Table 4). Interactions were significant for cover crop × N rate at 15 to 30 and 0 to 30 cm, for cover crop × year at 0 to 5, 15 to 30, and 0 to 30 cm, and for N rate × year at 15 to 30 and 0 to 30 cm. Averaged across N rates, NH\(_4\)-N content was 30 to 32% greater with vetch than other cover crops at 0 to 5 cm, but was 40 to 50% greater with rye than vetch/rye at 15 to 30 and 0 to 30 cm in 2013 (Fig. 2). Averaged across cover crops, NH\(_4\)-N content at 15 to 30 and 0 to 30 cm was 17 to 33% greater for 0 than 90 kg N ha\(^{-1}\) in 2013 (Fig. 3). At all depths, NH\(_4\)-N content increased from 2010 to 2011, decreased in 2012, and increased again in 2013. Mineralization of rye residue late in the sweet sorghum growing season in the absence of N fertilization appeared to increase NH\(_4\)-N content with rye for 0 kg N ha\(^{-1}\). The C/N ratio was greater with rye than other cover crops (Tables 1 and 2). Crop residues with higher C/N ratios mineralize N more slowly than residue with lower ratios (Kuo et al., 1997b; Sainju et al., 2007). It may be possible that N is immobilized by rye residue early in the sorghum growing season due to higher C/N ratio, but mowing of the residue mineralized N slowly late in the growing season, thereby increasing NH\(_4\)-N content with rye in the absence of N fertilization after crop harvest. When N fertilizer was applied, enhanced microbial activity due to increased N substrate availability increased nitrification, thereby reducing NH\(_4\)-N content for 90 than 0 kg N ha\(^{-1}\) with vetch and rye/rye (Table 5). This also appeared to be true for greater NH\(_4\)-N content at 15 to 30 and 0 to 30 cm with rye than other cover crops or greater for 0 than 90 kg N ha\(^{-1}\) in 2013 (Fig. 2 and 3) when annual precipitation was greater than in other years (1809 mm in 2013 compared with 841 to 1285 mm in other years). Increased soil water availability due to higher precipitation may have mineralized rye residue late in the growing season in 2013, thereby producing more NH\(_4\)-N content with rye, but increased nitrification reduced NH\(_4\)-N content with vetch and vetch/rye. An exception, however, occurred for greater NH\(_4\)-N content at 0 to 5 cm with vetch during the year with higher precipitation in 2013 (Fig. 2).

### Table 4. Soil NH\(_4\)-N and NO\(_3\)-N contents at the 0- to 30-cm depth as affected by cover crop species, N fertilization rate, and year.

<table>
<thead>
<tr>
<th>N rate × Year</th>
<th>Cover crop</th>
<th>NH(_4)-N content</th>
<th>NO(_3)-N content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>R</td>
<td>V</td>
</tr>
<tr>
<td>0–5 cm</td>
<td>2.28</td>
<td>2.55</td>
<td>2.58</td>
</tr>
<tr>
<td>N × Y</td>
<td>4.02</td>
<td>3.86</td>
<td>3.72</td>
</tr>
<tr>
<td>15–30 cm</td>
<td>5.48</td>
<td>6.40</td>
<td>5.28</td>
</tr>
<tr>
<td>15–30 cm</td>
<td>11.78</td>
<td>12.71</td>
<td>11.58</td>
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<tr>
<td>0–5 cm</td>
<td>3.34c§</td>
<td>4.20b</td>
<td>5.22a</td>
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<tr>
<td>15–30 cm</td>
<td>6.69</td>
<td>6.64</td>
<td>6.95</td>
</tr>
<tr>
<td>0–30 cm</td>
<td>5.69</td>
<td>5.67</td>
<td>7.24</td>
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<tr>
<td>15–30 cm</td>
<td>15.72c</td>
<td>16.61b</td>
<td>19.41a</td>
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<thead>
<tr>
<th>Significance</th>
<th>Cover crop (CC)</th>
<th>N rate (N)</th>
<th>CC × N</th>
<th>Year (Y)</th>
<th>CC × Y</th>
<th>N × Y</th>
<th>CC × N × Y</th>
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<td>NS</td>
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§ Numbers followed by different letters within a column in a set are significantly different at \(P = 0.05\) by the least square means test.

**Significant at \(P = 0.05\).**

***Significant at \(P = 0.01\).**

4-5 Significance at \(P = 0.001\); NS, not significant.

† Cover crops are C, unplanted control or weeds; R, cereal rye; V, hairy vetch; and VR, hairy vetch and rye mixture.

‡ Soil NH\(_4\)-N and NO\(_3\)-N contents were not measured in 2014.
Nitrogen supplied by cover crop residue and N fertilization appeared to increase NH₄⁺-N content from 2010 to 2011. Reduced mineralization of crop residue due to lower precipitation may have reduced NH₄⁺-N content in 2012. The converse was true when precipitation increased in 2013. Annual precipitation in 2011, 2012, and 2013 was 981, 841, and 1809 mm, respectively.

Soil Nitrate-Nitrogen

Soil NO₃⁻-N content varied with cover crop species at 0 to 5 and 0 to 30 cm and with years at all depths (Table 4). Significant interactions occurred for cover crop x N rate at 5 to 15 cm and for cover crop x year at 0 to 5, 5 to 15, and 0 to 30 cm.

Table 5. Interaction between cover crop and sweet sorghum N fertilization rate on soil NH₄⁺-N content at 15- to 30- and 0- to 30-cm depths and NO₃⁻-N content at the 5- to 15-cm depth.

<table>
<thead>
<tr>
<th>N rate</th>
<th>NH₄⁺-N content at the</th>
<th>NO₃⁻-N content at the</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>15–30 cm depth in various cover crops†</td>
<td>5–15 cm depth in various cover crops</td>
</tr>
<tr>
<td>kg N ha⁻¹</td>
<td>C</td>
<td>R</td>
</tr>
<tr>
<td>0</td>
<td>5.41B‡</td>
<td>7.40a§A</td>
</tr>
<tr>
<td>90</td>
<td>5.55</td>
<td>5.39b</td>
</tr>
</tbody>
</table>

† Cover crops are C, unplanted control or weeds; R, cereal rye; V, hairy vetch; and VR, hairy vetch and rye mixture.
‡ Numbers followed by different uppercase letters within a row (N fertilization rate) between cover crops in a set are significantly different at P = 0.05 by the least square means test.
§ Numbers followed by different lowercase letters within a column (cover crop) between N fertilization rates in a set are significantly different at P = 0.05 by the least square means test.

Fig. 2. Soil NH₄⁺-N content at 0- to 5-, 15- to 30-, and 0- to 30-cm depths from 2010 to 2013 as affected by cover crop species. Cover crops are C, control or weeds; R, cereal rye; V, hairy vetch; and VR, hairy vetch and rye mixture. Vertical bars show the least significant difference between cover crops within a year at P = 0.05.

Fig. 3. Soil NH₄⁺-N content at 15- to 30- and 0- to 30-cm depths from 2010 to 2013 as affected by sweet sorghum N fertilization rates. Vertical bars show the least significant difference between cover crops within a year at P = 0.05.

Fig. 4. Soil NO₃⁻-N content at 0- to 5-, 5- to 15-, and 0- to 30-cm depths from 2010 to 2013 as affected by cover crop species. Cover crops are C, control or weeds; R, cereal rye; V, hairy vetch; and VR, hairy vetch and rye mixture. Vertical bars show the least significant difference between cover crops within a year at P = 0.05.

Averaged across years, NO₃⁻-N content at 5 to 15 cm was 49% greater with vetch/rye than rye for 0 kg N ha⁻¹ and 21 to 51% greater for 90 than 0 kg N ha⁻¹ with rye and vetch (Table 5). Averaged across N rates, NO₃⁻-N content at 0 to 5 cm was 36% greater with vetch/rye than the control in 2011 and 20% greater with vetch than vetch/rye in 2013 (Fig. 4). At 5 to 15 and 0 to 30 cm, NO₃⁻-N content was 15 to 50% greater with vetch/rye than rye and the control in 2011 and greater with vetch than vetch/rye in 2012. Averaged across N rates and years, NO₃⁻-N content at 0 to 5 and 0 to 30 cm was 14 to 36% greater with vetch than rye and the control (Table 4). Regardless of treatments, NO₃⁻-N content at 0 to 5, 5 to 15, and 0 to 30 cm increased from 2010 to 2011 and then declined (Fig. 4).
The greater NO$_3^-$–N content at most depths with vetch and vetch/rye for 0 kg N ha$^{-1}$ or greater with these cover crops than rye and the control in 2011 and 2013 was likely due to increased N inputs. Cover crop biomass N content was greater with vetch and vetch/rye than rye and the control (Tables 1 and 2). Legume cover crops, such as hairy vetch, mineralize rapidly in the soil due to their higher N concentration or lower C/N ratio and enrich soil NO$_3^-$–N content than nonlegume cover crops, such as rye and no cover crop (Kuo et al., 1997b). In our study, C/N ratio was 23.3 for vetch and 30.0 for vetch/rye compared with 37.2 for rye (Table 1). Several researchers (McVay et al., 1989; Vyn et al., 1999) also reported greater soil NO$_3^-$–N content with legume than nonlegume or no cover crop. Our results of greater NO$_3^-$–N content with vetch and vetch/rye than rye and the control were similar to that reported by Sainju et al. (2007) in central Georgia. Application of N fertilizer increased NO$_3^-$–N content with 90 compared with 0 kg N ha$^{-1}$ with rye and vetch. Increased NO$_3^-$–N content with vetch, vetch/rye, and 90 kg N ha$^{-1}$ suggests that the potential for N leaching remain higher with these treatments. In contrast, NO$_3^-$–N content was lower with control and rye, indicating reduced potential for N leaching with these treatments.

Nitrogen supplied by cover crop residues and N fertilization to sweet sorghum appeared to increase NO$_3^-$–N content from 2010 to 2011, regardless of treatments (Fig. 4). In contrast, increased N uptake by sweet sorghum due to greater biomass yield and/or enhanced N leaching due to increased precipitation likely reduced NO$_3^-$–N content from 2011 to 2013. Average sweet sorghum biomass yield across treatments increased from 9.4 Mg ha$^{-1}$ in 2011 to 22.1 Mg ha$^{-1}$ in 2013. Although total annual precipitation was lower in 2012 (841 mm), higher precipitation in 2013 (1809 mm) may have reduced NO$_3^-$–N content in that year due to increased N leaching.

**CONCLUSIONS**

Soil C and N contents varied among cover crops and N fertilization rates due to differences in C and N inputs from cover crop biomass and N fertilization to sweet sorghum from 2010 to 2014. Cover crop biomass yield and C content were greater with vetch/rye and N content was greater with vetch and vetch/rye than rye and the control (no cover crop). Nitrogen content was also greater for 0 than 90 kg N ha$^{-1}$. As a result, SOC and STN at 0 to 5 and 15 to 30 cm were greater with vetch and vetch/rye than rye and the control. Both SOC and STN at 0 to 5 cm increased linearly with year, regardless of treatments. Soil NH$_4^+$–N content at most depths was greater with rye than the control, but NO$_3^-$–N content was greater with vetch and vetch/rye for 0 kg N ha$^{-1}$ or in 2013 when annual precipitation was above the average. Both NH$_4^+$–N and NO$_3^-$–N contents varied with years. Sweet sorghum N fertilization rate had little effect on soil C and N. Because of increased C and N inputs, soil C and N stocks and N availability can be increased with hairy vetch and hairy vetch/rye compared with rye and the control. As hairy vetch can increase the potential for N leaching, a mixture of hairy vetch and rye cover crop can be used to enhance soil C and N stocks and optimize N availability under sweet sorghum where aboveground biomass is harvested for bioenergy production.

**ACKNOWLEDGMENTS**

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**REFERENCES**


