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Legume Cover Crop Effects on Temperate Sugarcane Yields and Their Decomposition in Soil

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Received: 2 April 2020; Accepted: 11 May 2020; Published: 14 May 2020

Abstract: Sugarcane is commercially produced on 340,000 ha in the US and is valued at over $1 billion US annually. Cultural practices that improve sugarcane sustainability are needed to maintain yields in fields with degraded soils. Historically, leguminous rotation crops provided organic matter and biologically fixed nitrogen (N) for subsequent sugarcane crops. Currently, sugarcane is usually grown as a monoculture with only a short, 6-month fallow period. The objective of these field studies was to determine how growing cowpea (Vigna unguiculata (L.) Walp.) and sunn hemp (Crotalaria juncea L.) as cover crops during fallow affected the yield of subsequent sugarcane crops. A companion laboratory study investigated the decomposition rate of cover crops in soil at different temperatures. Cowpea and sunn hemp production produced 12.8 t/ha dry matter and 250 kg N/ha. Cowpea generally improved plant cane yields, but the effects of sunn hemp varied. However, neither cowpea nor sunn hemp reduced cane or sucrose yields consistently, and mineral N additions may have a role in mitigating yield gains or losses. Based on laboratory data, the average half-life for cowpea and sunn hemp would be 3 months. Overall, using legume cover crops should be viewed as an important component of sustainable sugarcane practices.

Keywords: sugarcane; legume cover crops; green manure; residue decomposition; sustainability

1. Introduction

Cultural practices that improve the sustainable production of regionally specific crops are needed to ensure the economic viability of rural areas and to protect natural resources. For example, sugarcane (Saccharum spp. hybrids) is commercially produced on 340,000 ha exclusively in Louisiana, Florida, and Texas (USA), at a value of $1.07 billion US annually [1]. In Louisiana, the perennial crop is usually grown on a five-year cycle that includes an 8-month fallow period followed by at least 6-months of crop establishment with limited ground cover. However, soil left bare is highly erodible due to intensive tillage required to terminate the old ratoons and plant the new seed cane, as well as annual rainfall amounts exceeding 1650 mm [2]. Historically, it was customary to rotate a leguminous crop alone, or intercropped with corn (Zea mays L.), to serve as a green manure between sugarcane plantings [3]. Today, many farmers in the US grow sugarcane as a monoculture, a practice that may limit profitable and sustainable productivity. Soil is degraded by the monoculture practice; it is more compacted [4], contains less organic matter [5], and abundant root pathogens that are harmful to crop health, including Pachymetra chaunorhiza Croft and Dick [6] and Pythium arrhenomanes Drechs. [7].
proliferate. Degraded soils contribute to sugarcane yield decline observed in Australia [8], Mauritius [9], and Ethiopia [10]. Stirling [11] presented a four-tiered approach used in Australia to improve sugarcane sustainability; it included crop residue retention, minimum tillage, a leguminous rotation crop, and controlled, GPS-guided equipment traffic.

Cover cropping may be a solution to not only soil erosion and degradation, but to control weeds, improve field trafficability, and increase soil organic carbon (C) and nitrogen (N) status [12]. Soil loss was reduced by 70% using cover crops in olive (Olea europaea L.) groves, when compared to intensive tillage [13]; Oat (Avena sativa L.) and brassica and legume + oat mixtures suppressed weed biomass by 73–85%, when compared to the fallow treatment [14]. Sunn hemp residue reportedly reduced smooth amaranth (Amaranthus lividus L.) germination (40%), plant height (48%), and dry weight (80%) [15]. A cereal rye (Secale cereale L.) winter cover crop grown following corn and soybean (Glycine max (L.) Merr.) increased soil organic matter, particulate organic matter, and potentially mineralizable N, when compared to a fallow treatment, by up to 15, 44, and 39%, respectively [16]. Similarly, sunn hemp (Crotalaria juncea L.) and crimson clover (Trifolium incarnatum L.) increased soil total C and N content within a corn-fallow cropping system by 43 and 75%, respectively, over a three-year period [17].

Cover crop adoption likely depends on the effects of the cover crop on succeeding sugarcane crops. Thawaro et al. [18] investigated the effects of growing sweet sorghum (Sorghum bicolor (L.) Moench), sunn hemp, rice (Oryza sativa L.), or soybean on the growth and yield of sugarcane planted 2 weeks after cover crops were terminated and residues plowed into the soil. They reported that although stalks counts were similar between treatments, cane yield was higher where rice (43%) and sorghum (23%) were previously grown. Neither sunn hemp (−0.4%) nor soybean (5.5%) affected yields in that study. Others observed that growing legumes between sugarcane rotations over 6–12 months improved succeeding sugarcane yields by up to 21% [19]. In Mauritius, growing hyacinth bean (Lablab purpureus (L.) Sweet cv. Rongai) as a break crop, along with reduced N fertilizer and tillage, increased succeeding sugarcane plant cane yields [9]. In Zimbabwe, soybean, grown as a break crop, improved sugarcane yields over fallowing [20]. Previous research in Louisiana demonstrated that soybean, when grown as a green manure crop, did not affect succeeding sugarcane yields of cultivars ‘CP 70-321’ or ‘L 99-226’ [21]. Similar results were obtained for soybean grown for grain, where neither cane or sugar yields for sugarcane cultivars ‘L97-128’ or ‘HoCP 96-540’ were affected [22]. Some evidence suggests that cover crop residue may exhibit an allelopathic effect on a subsequent sugarcane crop. For example, a kenaf (Hibiscus cannabinus L.) cover crop reduced stand counts (12%), cane yield (10%), and sugar yield (10%) of a sugarcane cultivar ‘HoCP 96-540’, planted 10 d after cover crop termination; on the other hand, cowpea (Vigna unguiculata (L.) Walp.) did not [23]. However, further field studies are needed to determine if leguminous cover crops act antagonistically toward subsequent sugarcane crops.

Therefore, the objective of the research was to determine the effects of growing leguminous cover crops, instead of fallowing soil, on subsequent sugarcane yields. Both cowpea and sunn hemp were chosen as cover crops because of high biomass production potential, N fixation capacity, and seed availability. Historical evidence, passed down from growers and agronomists, suggests that terminating cover crops too close to planting sugarcane can lower yields due to a composting effect of cover crop residue on the recently planted sugarcane seed cane. Therefore, a second objective was to determine the half-life of different cover crop residues in soil at a range of temperatures characteristic of temperate sugarcane production regions.

2. Materials and Methods

2.1. Alma Plantation Field Study

The study was conducted at the Alma Plantation in Lakeland, LA, USA (30°35′36″ N, 91°22′11″ W) on a Commerce silt loam soil (Fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquents). Chemical characteristics are presented in Table 1. To a 10.1 ha level graded field, iron clay cowpea was broadcast on 1 April 2011, at a rate of 56.1 kg/ha to the northern two-thirds of the
field, and the remainder of the field was left bare. The cowpea crop was not irrigated. Total annual precipitation was 1252 mm (2011) and 1586 mm (2012) (Figure 1). A month after planting cowpea, the field was sprayed with clethodim [(5RS)-2-[(1EZ)-1-[(2E)-3-chlorallyloxyimino]propyl]-5-[(2RS)-2-(ethylthio)propyl]-3-hydroxycyclohex-2-en-1-one] at 45.6 g active ingredient a.i./ha for post-emergence grass control. On 19 July 2011, four 1 m² samples of cowpea were collected from random locations within the planted area of the field to estimate dry matter production, 5.6 t/ha. The percent N by dry combustion was 2.51%, corresponding to 282 kg N/ha. On 7 August 2011, the field was mowed and disked twice to incorporate the cowpea biomass. Prior to planting sugarcane, 1.83-m spaced rows were drawn across the entire field. Sugarcane cultivar ‘L 01-283’ [24] was hand planted at a three-stalk rate with a 10% overlap on 1 October 2011. Following planting, the sugarcane seed was covered with 7–10 cm of packed soil, and a tank-mix of metribuzin [4-amino-6-tert-butyl-3-methylthio-1,2,4-triazin-5(4H)-one], at 3.4 kg a.i./ha and pendimethalin [N-(1-ethylpropyl)-2,6-dinitro-3,4-xylidine], at 2.2 kg a.i./ha was broadcast onto the soil surface for residual weed control. In March 2012, the wheel furrows and row sides were cultivated using a 3-row disk cultivator. In April 2012, UAN32 (112 kg N ha⁻¹) was injected below the soil surface on each side of the planted row. Multiple three-row strips of both cowpea and fallowed field areas were not fertilized to serve as controls. On 19 December 2012, ten-stalk bundles were harvested from four random locations within each treatment: fallow, no fertilizer; fallow, 112 kg N/ha; cowpea, no fertilizer; cowpea, 112 kg N/ha. The number of harvestable stalks on a 3.0-m long section of row were also recorded. Stalks were shredded in a rotary knife mill and juice was extracted from a 1-kg sample in a hydraulic press. The juice was analyzed for Brix (% total dissolved solids, g/100 g solution) using a refractometer, clarified using Octopol (Tiarco Chem, Dalton, GA, USA), and analyzed for pol (°Z) using an Autopol 880 saccharimeter (Rudolph Research Analytical, Hackettstown, NJ, USA). Theoretically recoverable sucrose (TRS) (g sucrose/kg cane) was estimated from Brix and pol readings. Sucrose yield was estimated using TRS and cane yield.

Figure 1. Average monthly maximum (●) and minimum (▲) air temperature and monthly precipitation (bars) recorded near the Alma Plantation site (Top, Baton Rouge Regional Airport) and the Iberia Research Station (Bottom, New Iberia Acadian Airport) for the duration of the cover crop field experiments. Data obtained from the National Oceanic and Atmospheric Association’s (NOAA) National Centers for Environmental Information (NCEI). Available online at www.ncdc.noaa.gov; assessed 23 April 2020.
Table 1. Chemical properties of the soils from the field and used for the laboratory experiments.

| Soil Series                  | Cation Exchange Capacity | pH  | Soil Organic Matter | S  | K  | P  | Ca | Mg | Na | B  | Fe | Mn | Zn | NH₄-N | NO₃-N |
|------------------------------|--------------------------|-----|---------------------|----|----|----|----|----|----|----|----|----|----|-------|-------|
| Baldwin silty clay loam     | cmol/kg                  | 1:1 | %                   | 33.7 | 5.73 | 3.76 | 9.0 | 212 | 22 | 45 | 943 | 49 | 0.4 | 304   | 36    | 1.9  | ND*  | ND   |
| Cancienne silty clay loam   | cmol/kg                  | 1:1 | %                   | 18.7 | 5.08 | 1.82 | 7.0 | 51  | 19 | 37 | 264 | 36 | 0.4 | 254   | 83    | 1.7  | 13.4 | 1.1  |
| Commerce silt loam soil     | cmol/kg                  | 1:1 | %                   | 12.5 | 6.95 | 1.19 | 8.5 | 101 | 9  | 64 | 402 | 36 | 0.3 | 275   | 37    | 1.2  | ND*  | ND   |

* ND = not determined.
2.2. Iberia Research Station Field Studies

Multiple studies were conducted at the Louisiana State University (LSU) Iberia Research Station in Jeanerette, LA, USA (29°57′33″ N, 91°42′41″ W) on a Baldwin silty clay loam soil (Fine, smectitic, hyperthermic Chromic Vertic Epiaqualfs). Chemical characteristics are presented in Table 1. Sunn hemp was planted, at 11 kg/ha, in a field previously cropped to sugarcane on 19 April 2011, by double drilling seed into 1.83-m spaced rows using a two-seat tractor-driven research planter, set to a depth of 15 mm. The field had been fallowed during the winter of 2010 and spring of 2011. No irrigation was used. Total annual precipitation was 973 mm (2011), 1403 mm (2012), 1668 mm (2013), 1280 mm (2014), and 1786 mm (2015) (Figure 1). The sunn hemp crop was mowed close to the soil surface on 24 July 2011, 96 days after planting, and incorporated using a 3-row cultivator on 8 August 2011. One m² sample of shredded sunn hemp were collected from random locations within the planted area of the field to estimate dry matter production, 13.5 t/ha. The percent N was 1.58% and corresponds to 214 kg N/ha. Sugarcane cultivar ‘L 99-226’ [25] was hand planted at a three-stalk rate with a 10% overlap on 9 September 2011 to the area previously used to grow sunn hemp, and an adjacent area that was fallowed. Following planting, the sugarcane seed was covered with 7-10 cm of packed soil, and a tank-mix of metribuzin at 3.4 kg a.i./ha and pendimethalin at 2.2 kg a.i./ha was broadcast onto the soil surface for residual weed control. In March, the wheel furrows and row sides were cultivated using a 3-row disk cultivator. On 10 April 2012, UAN32 was applied to plots at rates of 0, 45, or 90 kg N/ha. Experimental plots measured 5.5 m wide (3 rows) by 12.2 m long and included four replications. Fertilizer rates were randomly assigned to plots within the cover crop or fallow areas. Sugarcane was harvested on 21 October 2012, using a combine harvester and cane yield (t/ha) was measured using a modified dump-wagon equipped with electronic load cells and a billet sampler [26]. The entire plot yield was weighed and recorded. The billet samples were ground using a rotary knife mill and extracted juice was analyzed as described above. The first ratoon crop was cultivated and fertilized uniformly and was harvested on 31 October 2013 similarly as described for plant cane.

A second sunn hemp trial was planted on 4 April 2012, to a field previously cropped to sugarcane. The field had been fallowed during the winter of 2012 and spring of 2013. No irrigation was used. Mowing and incorporated sunn hemp residue occurred on 21 June 2012 and 3 July 2012, respectively. The sunn hemp exhibited a lower N content than the previous year, 1.46%, corresponding to an incorporation rate of 197 kg N/ha. Sugarcane cultivar ‘L 99-226’ was hand planted at a three-stalk rate with a 10% overlap on 12 September 2012 to the area previously used to grow sunn hemp, and an adjacent fallow area. Experimental plots measured 5.5 m wide (3 rows) by 10.7 m long and included four replications. Nitrogen fertilizer was applied on 6 May 2013 as described above, at rates of 0, 45, and 90 kg/ha. Fertilizer rates were randomly assigned to plots within the cover crop or fallow areas. The plant cane crop was harvested on 4 December 2013 using a combine harvester and dump wagon, and the billet samples were ground using a rotary knife mill and extracted juice was analyzed as previously described. Data on ratoon crop were not collected.

A cowpea trial was initiated in a field previously cropped to sugarcane. Cowpea was planted at a rate of 56 kg/ha on 1 May 2013, by double drilling seed into 1.83-m spaced rows using a two-seat tractor-driven research planter, set to a depth of 15 mm. The field had been fallowed during the winter of 2012 and spring of 2013. The field was sprayed with fluazifop-P-butyl [(R)-2-(4-[5-(trifluoromethyl)-2-pyridyloxy]phenoxy)propionic acid] at 0.21 kg a.i./ha for grass control on 16 June 2013. Cowpea was mowed on 24 July 2013 and incorporated on 31 July 2013. Sugarcane cultivar ‘L 01-299’ [27] as hand planted at a three-stalk rate with 10% overlap on 1 October 2013 to the area previously cropped to cowpea, and an adjacent area kept fallow. Experimental plots measured 5.5 m wide (3 rows) by 15.2 m long and included four replications. Nitrogen fertilizer was applied on 23 April 2014 as described above, at rates of 0, 45, and 90 kg/ha. Fertilizer rates were randomly assigned to plots within the cover crop or fallow areas. Sugarcane was harvested on 2 December 2014 using a combine harvester and dump wagon, and the billet samples were ground using a rotary knife mill and extracted juice was analyzed as previously described. The first ratoon crop was harvested on 31 October 2015 similarly as described for plant cane.
2.3. Laboratory Incubation

A laboratory study was undertaken to determine the effect of temperature on cover crop residue decomposition. Cancienne silt loam soil (Fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquepts) was collected from the USDA-ARS Ardoyne Farm in Schriever, LA, USA (29°38′05″ N, 90°50′12″ W) from a depth of 0 to 15 cm. The soil was passed through a 2-mm sieve to remove roots and stones. Chemical characteristics are presented in Table 1. Cowpea, sunn hemp, biomass sorghum, soybean, and sugarcane plants were grown in the greenhouse, cut at the soil surface, dried at 60 °C for 1 week, ground with a Wiley Mill No. 4 (Thomas Scientific, Swedesboro, NJ, USA) to pass a 1-mm screen, and stored in a desiccator. The entire plant was dried and ground except for sugarcane, where only the growth point and leaves were removed, dried, and ground to simulate post-harvest residue. Total C and N on each residue were determined by dry combustion using a 1112 elemental analyzer (ThermoFisher Scientific, Waltham, MA, USA). Fifty g of dry weight equivalent soil was added to 125-mL Erlenmeyer flasks. Soil was amended with water, resulting in a moisture content of 0.20 g water/g soil. A subset of the flasks received 0.125 g of each dried crop residue (equivalent to 0.25% by weight), which was mixed thoroughly with the soil using a spatula. Control flasks did not receive residue. The flasks were placed in 1 L canning jars that contained 25-mL of distilled water in the base of the jar. All flasks were sealed in separate jars with screw lids containing a rubber septa. The jars were divided into 3 groups with each group being incubated at either low (11 °C), ambient (25 °C), or high (32 °C) temperature for the duration of the experiment. Four replications of each crop residue and temperature combination were included. The incubation temperatures were chosen to represent typical field temperatures observed during winter, spring and fall, and summer of 2011–2015, respectively.

Headspace carbon dioxide (CO2) was measured 11 times over 162 d from each jar. At each sample time, jars were mixed with a 50-mL syringe prior to drawing a 0.5-mL sample with a 1.0-mL syringe that was injected onto a 2 m Porapak Q 80/100 mesh packed column fitted to a Shimadzu GC-8A gas chromatograph with a thermal conductivity detector (TCD) [28]. The amount of CO2 analyzed in the injection was calculated by comparing the TCD response (uV) for each sample injection with an injection of a 0.01 mole CO2/mole air standard. The standard injection was made numerous times during each analysis time. After injections jar lids were removed to allow gas exchange with the laboratory air to replenish oxygen and remove CO2. The total amount of CO2 analyzed (0.5 mL) was converted to the total volume of the jar (840 cm3), minus the soil, flask, and water, which was empirically determined. At each sample time, the amount of CO2-C in controls was subtracted from the CO2-C measured in samples amended with plant residue, and the value was converted to a natural log of the % residue C remaining.

2.4. Statistics

The Alma field study was a randomized strip plot design where the whole plot variable was fallow or cowpea cover, and the strip plot variable was N fertilizer, either none or 112 kg N/ha, applied in the spring. The whole plot treatment was applied to half of the field, and multiple 3-row sets of each fertilizer treatment were applied to each portion of field previously cropped to cowpea. Four plots were randomly delineated within a fertilizer strip plot, moving down the length of the rows, to serve as replicates. Only plant cane data were collected. The data were analyzed by ANOVA using Proc Mixed in SAS version 9.0 (SAS Institute, Cary, NC, USA). The type of cover and fertilizer rate were treated as fixed effects, and replicate was treated as a random effect. Means of significantly different effects were separated using the PDIFF option with the SAXTON macro at the p < 0.10 level [29]. The Iberia field studies were split plot designs where the whole plot variable was fallow or cover crop, and the split plot was N fertilizer (0, 45, or 90 kg N/ha). Each treatment combination included four replicates, randomly assigned within the whole plots. Plant cane and first ratoon data, where applicable, were analyzed separately, by ANOVA as described above. The type of cover and fertilizer rate were treated as fixed effects, and replicate was treated as a random effect. Within significant two-way interactions, data was reanalyzed to discover the source of variability using the ‘data fix’
command (similar to the SLICE option) to facilitate pairwise or main effect comparisons. Crop residue decomposition in the laboratory study was modelled using first-order kinetics:

\[ C_t = C_0 \times \exp (-k \times t) \]  

where \( C_t \) = residue carbon remaining at time = \( t \), \( C_0 \) is initial amount of residue carbon, \( k \) = the rate constant, and \( t \) = time in days. The equation was rearranged to

\[ \ln (C_t/C_0) = -kt + b \]  

where \( b \) = intercept [30]. The natural log of the % remaining, \( \ln (C_t/C_0) \), was analyzed over time using the linear regression analysis in Excel (Microsoft, Redmond, CA).

### 3. Results

For the Alma Plantation cowpea cover crop study, the cover crop and N fertilizer two-way interaction affected stalk sucrose content and sucrose yield in the plant cane sugarcane crop (Table 2). The stalk sucrose concentration was greater where cowpea was grown when no N fertilizer was applied. On average the increase in stalk sucrose concentration was about 9% in the non-fertilized, cowpea treatment, when compared to the remaining treatments. In plots with no N fertilizer, sucrose yield (kg/ha) was greater where cowpea was grown, when compared to fallow, by about 5000 kg/ha. Both fertilized treatments produced similar cane yield, stalk sucrose, and sucrose yield.

**Table 2.** Sugarcane plant cane stalk count, weight, cane yield, stalk sucrose concentration, and sugar yield for cultivar ‘L 01-283’ planted following a cowpea cover crop at ALMA PLANTATION IN LAKELAND, LA, USA, in 2012.

|                     | Fallow   | Cowpea   |
|---------------------|----------|----------|
| Nitrogen rate (kg/ha) | 0        | 112      |
| Stalk count (tha)    | 128,215 a | 137,181 a|
| Stalk weight (kg)    | 0.84 a   | 0.90 a   |
| Cane yield (t/ha)    | 107.5 a  | 124.5 a  |
| Stalk sucrose (g/kg) | 120.4 b  | 124.6 b  |
| Sucrose yield (kg/ha)| 12,970 b | 15,430 ab|

* Means in a row followed by the same letter are not different at the \( p < 0.10 \) level.

In the first sunn hemp cover crop study, the cover crop and N rate two-way interaction affected plant cane yield and sucrose yield, but not stalk sucrose concentration. (Table 3). No cover crop or N rate main effects were detected. Cane yield was greater where sunn hemp was grown and cane was fertilized with 45 kg N/ha, compared to the no N addition, by 21%. For sucrose yield, the sunn hemp + 45 kg N/ha treatment was greater than either the fallow + 90 kg N/ha or sunn hemp with 0 kg N/ha, by 20 and 27%, respectively (Table 3). The remainder of the treatments produced similar sucrose on a hectare basis. In the first ratoon crop, cane yield was affected by N rate, but not cover crop or the two-way interaction (data not shown). Increasing amounts of N fertilizer corresponded to greater first ratoon cane yields, with 68.9, 79.2, and 84.3 t/ha, resulting from 0, 45, and 90 kg N/ha, respectively. Fallowing (78.1 t/ha) and growing sunn hemp (76.8 t/ha) as a cover produced similar cane yields. For the first ratoon crop in the first sunn hemp study, stalk sucrose concentration varied by cover crop (data not shown). Cane grown in fallowed plots exhibited a higher stalk sucrose concentration, when compared to the sunn hemp cover crop plots. However, sucrose yield in the first ratoon crop was only affected by N rate, where supplemental N (either 45 or 90 kg/ha) improved yield over the 0 N rate.

In the second sunn hemp study, plant cane yield was affected by the cover crop, but not N rate, nor the two-way interaction, and mean separation was performed across fertilizer rate (Table 4). Sunn hemp treatment produced lower cane yields, when compared to fallow, by about 12%. Neither stalk sucrose concentration nor sucrose yield was affected by either cover crop, N fertilizer, or the two-way interaction for this field study. The first ratoon crop yields in the second sunn hemp study were
not evaluated due to the lack of statistical differences observed for stalk sucrose and sucrose yield in the plant cane crop.

**Table 3.** Plant cane yield, stalk sucrose concentration, and sugar yield for cultivar ‘L 99-226’ planted following a sunn hemp cover crop at Iberia Research Station in Jeanerette, LA, USA, in 2011.

|                     | Fallow     | Sunn Hemp |
|---------------------|------------|-----------|
| Nitrogen rate (kg/ha) | 0 45 90 | Mean 0 45 90 |
| Cane yield (t/ha)    | 107.0 111.8 105.5 108.1 a * | 93.9 100.8 105.5 |
| Stalk sucrose (g/kg) | 105.7 108.9 105.9 106.9 a | 109.9 115.9 110.6 111.8 a |
| Sucrose yield (kg/ha) | 11,330 12,310 11,190 11,610 a | 10,350 11,120 10,480 10,650 a |

* Means followed by the same lowercase letter in a row are not statistically different at the *p* < 0.10 level.

**Table 4.** Sugarcane plant cane yield, stalk sucrose concentration, and sugar yield for cultivar ‘L 99-226’ planted following a sunn hemp cover crop at Iberia Research Station in Jeanerette, LA, USA, in 2013.

|                     | Fallow     | Sunn Hemp |
|---------------------|------------|-----------|
| Nitrogen rate (kg/ha) | 0 45 90 | Mean 0 45 90 |
| Cane yield (t/ha)    | 119.5 122.0 120.0 120.5 a | 119.4 122.9 121.4 121.2 a |
| Stalk sucrose (g/kg) | 8410 10,680 11,840 10,310 b | 10,830 11,570 11,800 11,400 a |

* Means followed by the same lowercase letter in a row are not statistically different at the *p* < 0.10 level.

In the cowpea cover crop study at the Iberia Research Station, the cover crop treatment affected plant cane yield and sucrose yield, but not stalk sucrose concentration. The two-way interaction for each variable was not significant. Sugarcane yield for plots previously cropped to cowpea produced 10% more cane and 11% more sucrose, when compared to fallow plots (Table 5). The overall stalk sucrose concentration was 120.9 g/kg. The nitrogen rate main effect also affected plant cane and sucrose yield, but not stalk sucrose concentration (Table 5). When combined across cover crop treatments, application of either 45 or 90 kg N/ha, increased cane yield by 13 and 22%, respectively, when compared to the no N control, with means of 90.8, 98.1, and 80.6 t/ha, respectively (Table 5). Similarly, nitrogen application of 45 or 90 kg/ha improved sucrose yield across cover crop treatments by 16 and 23%, respectively, when compared to the no N control, with means of 11,130, 11,820, and 9620 kg/ha.

**Table 5.** Plant cane yield, stalk sucrose concentration, and sugar yield for cultivar ‘L 01-299’ planted following a cowpea cover crop at Iberia Research Station in Jeanerette, LA, USA, in 2014.

|                     | Fallow     | Cowpea |
|---------------------|------------|--------|
| Nitrogen rate (kg/ha) | 0 45 90 | Mean 0 45 90 |
| Cane yield (t/ha)    | 70.3 87.2 98.6 85.4 b * | 90.8 94.4 97.6 94.3 a |
| Stalk sucrose (g/kg) | 119.5 122.0 120.0 120.5 a | 119.4 122.9 121.4 121.2 a |
| Sucrose yield (kg/ha) | 8410 10,680 11,840 10,310 b | 10,830 11,570 11,800 11,400 a |

* Means followed by the same lowercase letter in a row are not statistically different at the *p* < 0.10 level.

Neither cover crop nor N application rate, or the two-way interaction, affected the first ratoon crop in the Iberia cowpea test (data not shown). Mean cane yield (95.3 t/ha), sucrose concentration (103.4 g/kg), and sucrose yield (9860 kg/ha) compared to the plant cane averages of 89.8 t/ha, 120.9 g/kg, and 10,850 kg/ha, respectively.

The crop residue used for the laboratory study varied in its TC and TN content, and therefore C:N ratio. As expected, the legume residue exhibited lower C:N ratios (18–33) when compared to the monocot crops (45–148) (Table 6). The linear regression correlation coefficients were not consistent by temperature, or by crop residue. The poorer fit, compared to other correlations (e.g., *r*² > 0.80), can be attributed to fitting a single trendline to what appeared to be multiple (usually two) kinetic rates.
However, when a sequential two pool kinetic model was used, calculated half-lives ($DT_{50}$) were very similar to a single pool kinetic model. This is possibly an indication that the initial rapid phase of decomposition represented a relatively small proportion of the total residue C decomposed over the course of the experiment. Thus, longer-term accuracy was not reasonably increased by using a more complex model. Incubation temperature resulted in basil soil respiration values of 0.42 (11 °C), 0.99 (25 °C), and 1.90 mg CO$_2$-C/kg soil day$^{-1}$ (32 °C) for the 166 day experiment (data not shown). Half-lives of crop residue at 11 °C were found to be > 157 days, further indicating slow soil microbial activity and processing at that temperature. At 25 °C, $DT_{50}$ were between 82–224% lower than those observed at 11 °C, and at 32 °C, $DT_{50}$ were between 11 higher and 203% lower than those observed at 25 °C (Table 6). At 11 °C, cowpea and sorghum exhibited the lowest $DT_{50}$; at 25 °C, cowpea and soybean residue exhibited lowest $DT_{50}$; and at 32 °C, cowpea and sorghum exhibited the lowest $DT_{50}$. 
Table 6. Cover crop and sugarcane residue total carbon (TC) and nitrogen (TN), decomposition kinetic rate constants (k/day), correlation coefficients ($r^2$), and y-intercept (b) obtained from regression analyses of observations from the laboratory experiment. Half-lives (DT$_{50}$) were calculated based on k. Elemental data are the mean of 3 samples, kinetic data are derived from 4 observations.

|            | TC  | TN  | C:N Ratio | 11 °C k | 11 °C $r^2$ | 11 °C b | 11 °C DT$_{50}$ | 25 °C k | 25 °C $r^2$ | 25 °C b | 25 °C DT$_{50}$ | 32 °C k | 32 °C $r^2$ | 32 °C b | 32 °C DT$_{50}$ |
|------------|-----|-----|-----------|---------|-------------|--------|-----------------|---------|-------------|--------|-----------------|---------|-------------|--------|----------------|
| Cowpea     | 391 | 11.8| 33.2      | 0.0044  | 0.92        | 4.467  | 157             | 0.0081  | 0.88        | 4.346  | 86              | 0.0154  | 0.68        | 4.259  | 45             |
| Sorghum    | 418 | 9.23| 45.3      | 0.0039  | 0.89        | 4.457  | 178             | 0.0067  | 0.93        | 4.383  | 103             | 0.0201  | 0.89        | 4.310  | 34             |
| Soybean    | 420 | 17.9| 23.5      | 0.0037  | 0.80        | 4.413  | 187             | 0.0082  | 0.91        | 4.270  | 85              | 0.0071  | 0.77        | 4.098  | 98             |
| Sunn hemp  | 406 | 23.0| 17.7      | 0.0020  | 0.60        | 4.434  | 347             | 0.0065  | 0.83        | 4.249  | 107             | 0.0139  | 0.69        | 4.260  | 50             |
| Sugarcane  | 431 | 2.90| 148       | 0.0020  | 0.91        | 4.575  | 347             | 0.0046  | 0.98        | 4.541  | 151             | 0.0105  | 0.91        | 4.481  | 66             |
4. Discussion

The cultivation of soybean in rotation with sugarcane for use as a hay and/or green manure was a standard practice in Louisiana nearly a century ago, partially to take advantage of the N fixed by legume [3]. Data indicated sucrose yield of up to 7% higher by average, over nine sugarcane crops, by growing soybeans, which were incorporated as a green manure, compared to soybean that was removed for hay. However, soybean haying followed by adding 45 kg mineral N ha$^{-1}$ increased sucrose yield by 13%, compared to soybean hay removal, possibly indicating that the cane crop N needs were not completely met by the green manure alone. In the field studies reported here, cover crop effects varied, but on average, produced between −10% to 20% higher sucrose ha$^{-1}$, when compared to the fallow, highest N rate treatment (Tables 2–5). The results reflect those reported where sugarcane cultivar ‘HoCP 96-540’ produced similar yields in either fallow, or fields where cowpea was incorporated into soil as a green manure 100 days after planting [23]. In two plant cane and one ratoon crop, incorporated cowpea or soybean produced similar yields of sugarcane cultivar ‘CP 96-1252’ as observed in fallow soil; whereas sweet corn reduced cane and sugar yield compared to one or more of the other cropping systems, including fallow, in one plant cane and one ratoon crop [31]. In Florida, USA, the effects of mill mud, fertilizer, and green manure on sugarcane yields was investigated in a sandy soil with a low cation exchange capacity (2.6 cmol/kg) [32]. They reported that soybean grown as a green manure increased plant cane yields by >30%, and exhibited 12, 20, and 24% greater sugarcane leaf N, K, and manganese, respectively, when compared to either fallow or forage soybean systems. But, in pairwise comparisons, green manure alone did not improve sucrose yield (7%), compared to fallow and mineral fertilizer. Green manure with mill mud and/or fertilizer resulted in significant gains in sucrose by 50%. However, other reports indicated that mixed legume/grass break crops grown for 6–12 months increased yields of the subsequent cane crop by 16%, but traditional fallow did not [19].

Incorporation of legumes as green manures altered soil N status in sugarcane fields in Nigeria [33]. In two consecutive plant cane crops (1999, 2000), after four weeks, cowpea (20.3 kg N/ha, 24.2 kg N/ha), soybean (23.4 kg N/ha, 26.3 kg N/ha), sesbania (Sesbania rostrata) (24.5 kg N/ha, 28.5 kg N/ha), and mucana (Mucuna pruriens) (28.8 kg N/ha, 30.1 kg N/ha) incorporation increased soil N levels, compared to the no-fertilizer control (0.09 kg N/ha, 0.3 kg N/ha), but only to about 50% of 120 kg ha$^{-1}$ of mineral fertilizer N (41.0 kg N ha$^{-1}$, 46.0 kg N ha$^{-1}$). Respective cane yields in green-manured plots were greater than the no-fertilizer control, but similar to the mineral fertilized plots, indicating that N source was not as important as N availability. Moreover, soil N levels at eight weeks after green manure incorporation were the same as for the mineral fertilized fields (<10 kg/ha), indicating the importance of synchronizing legume N mineralization to sugarcane nutrient uptake. Brazilian researchers studied the effect of rotating legumes within the typical fallow period for sugarcane on two oxisols under long term continuous sugarcane production (>30 y) [34]. They found no impact on soil chemical properties, including soil organic matter, pH, K, or P, but they did find an increase in soil aggregation, and a decrease in soil bulk density. In Louisiana, the mineral N fertilizer is applied after the first winter period, equivalent to about 8 months after an August cover crop termination date, making it more difficult to justify the benefits of green manuring to soil N status that directly affects sugarcane yields. For example, nitrate-N and ammonium-N levels in soil that was green-manured (7.8–8.7 t/ha) with soybean were statistically similar in fallow soil after 200 d, and the plant cane crop did not respond to green manure, in terms of cane or sucrose yield, with or without 134 kg N/ha mineral fertilizer [21]. In the laboratory experiment, the DT$_{50}$ (25°C) for sunn hemp (107 d), soybean (85 d) and cowpea (86 d) residue indicate that by 200 d, 20–30% of the cover crop residue would remain in soil. Given the relatively low C:N ratio of these cover crop residues (17.7–33.2), minimal N immobilization would be expected. Thus, it is possible a significant amount of mineralized N, originating from cover crop residues, is not plant available because of either leaching below the root zone as nitrate-N, volatilization as ammonia or nitrous oxide, or uptaken by opportunistic weedy plants.
There is ample work suggesting a soil biological component contributes to degraded soils under continual sugarcane. Less research describes the benefits of cover crops and green manure to long-term sugarcane soils. However, soil biological property changes resulting from break crops, pasturing, fallowing, or continual sugarcane production was reported for multiple locations in Australia [35]. In general, pasturing increased microbial biomass C, free-living nematodes, mycorrhizal fungi, and substrate utilization diversity, with respect to the remaining cropping systems. But, a break of 12 months (observed in the Bundaberg location) reportedly was not long enough to affect any of the biological properties measured [35]. However, in Florida, USA, microbial biomass C, but not N, was higher following cowpea or soybean cover crops, or a sweet corn crop, when compared to fallowed soil between sugarcane rotations [31]. However, 90 days after a cane crop was planted, the viable microbial biomass (by phospholipid fatty acid analysis) was similar across each cropping system [31]. Soil sampled during legume growth (between sugarcane cycles) may permit some observations into the effects of break crops on soil microbial ecology and nutrient transformations. Ammonium oxidizing bacteria and archaea, responsible for the first step of nitrification, were lower in soil cropped to soybean (~44%) and peanut (~24%), compared to fallowed soil [36]. However, the levels of nitrite oxidizing bacteria were consistent between cropping system. This is important because without the ammonium oxidizers, organic N mineralized from soil organic matter, crop residues, or other sources (e.g., mill mud) is less likely to be converted into nitrite and nitrate and subsequently made unavailable by leaching.

5. Conclusions

The growth of cowpea and sunn hemp cover crops during typical fallow period did not negatively affect subsequent sugarcane sucrose yields as determined by these field studies, at least not to levels that could not be mitigated by additions of mineral N. However, despite adding on average 250 kg N ha⁻¹, the green manures did not consistently improve sugarcane yield either. This is possibly due to the 10–11-month time span between cover crop incorporation and plant cane grand growth that typically occurs between June and September. Based on laboratory incubation data, the average DT₅₀ for cowpea and sunn hemp would be approximately 3 months. Overall, using leguminous cover crops should be viewed as an important component of sustainable sugarcane practices.

Author Contributions: Contributions are as follows: Conceptualization, P.M.W.J., H.P.V.; Methodology, P.M.W.J., G.W., H.P.V.; Formal Analysis, P.M.W.J.; Investigation, P.M.W.J., G.W., H.P.V., R.P.V., C.L.W.III; Resources, P.M.W.J., H.P.V., G.W., R.P.V., C.W.; Data Curation, P.M.W.J., H.P.V.; Writing—Original Draft Preparation, P.M.W.J.; Writing—Review and Editing, P.M.W.J., H.P.V., C.L.W.III; Project Administration, P.M.W.J., H.P.V.; Funding Acquisition, P.M.W.J., H.P.V. All authors have read and agreed to the published version of the manuscript.

Funding: The research was partially funded by a grant from the American Sugar Cane League, Inc., of the USA, Thibodaux, LA. The United States Department of Agriculture (USDA) Agricultural Research Service, Sugarcane Research Unit in Houma, LA, provided funding and laboratory space for the project, Louisiana State University Agricultural Center, Iberia Research Station, Jeanerette, LA, provided funding and land for the project, and Alma Plantation provided land for the project.

Acknowledgments: The authors would like to thank Christopher Adams, Lionel Lomax, Patra Ghergich, Kelvin Lewis, and Trevis Olivier for field and laboratory assistance. The USDA is an equal opportunity provider and employer.

Conflicts of Interest: The authors declare no conflicts of interest.
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