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Impact on Soil Organic C and Total Soil N from Cool- and Warm-Season Legumes Used in a Green Manure-Forage Cropping System

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Abstract

Annual forage legumes are important components of livestock production systems in East Texas and the southeastern US. Forage legumes contribute nitrogen (N) to cropping systems through biological N fixation, and their seasonal biomass production can be managed to complement forage grasses. Our research objectives were to evaluate both warm- and cool-season annual forage legumes as green manure for biomass, N content, ability to enhance soil organic carbon (SOC) and soil N, and impact on post season forage grass crops. Nine warm-season forage legumes (WSL) were spring planted and incorporated as green manure in the fall. Forage rye (*Secale cereale* L.) was planted following the incorporation of WSL treatments. Eight cool-season forage legumes (CSL) were fall planted in previously fallow plots and incorporated as green manure in late spring. Sorghum-sudangrass (*Sorghum bicolor* x *Sorghum bicolor* var. *sudanense*) was planted over all treatments in early summer after forage rye harvest and incorporation of CSL treatments. Sorghum-sudangrass was harvested in June, August and September, and treatments were evaluated for dry matter and N concentration. Soil cores were taken from each plot, split into depths of 0 to 15, 15 to 30 and 30 to 60 cm, and soil C and N were measured using combustion analysis. Nylon mesh bags containing plant samples were buried at 15 cm and used to evaluate decomposition rate of above ground legume biomass, including change in C and N concentrations. Mungbean (*Vigna radiata* L. [Wilczek]) had the highest shoot biomass yield (6.24 t DM ha^{-1}) and contributed the most total N (167 $\text{kg}\cdot\text{ha}^{-1}$) and total C (3043 $\text{kg}\cdot\text{ha}^{-1}$) of the WSL tested. Decomposition rate of WSL biomass was rapid in the first 10 weeks and very slow afterward. Winter pea (*Pisum sativum* L. spp. *sativum*), arrow leaf clover (*Trifolium vesiculosum* Savi.), and crimson clover (*Trifolium incarnatum* L.) were the most productive CSL in this trial. Austrian winter pea produced 8.41 t DM ha^{-1} with a total N yield of 319 kg N ha^{-1} and total C production of 3835 kg C ha^{-1}. The WSL treatments had only small effects on rye forage yield and N concentration, possibly due to mineralization of N from a large SOC pool already in place. The CSL treatments also had only minimal effects on sorghum-sudangrass forage production. Winter pea, arrow leaf and crimson clover were productive cool season legumes and could be useful as green manure crops. Mungbean and cowpea (*Vigna unguiculata* [L.] Walp.) were highly productive warm season legumes but may include more production risk in green manure systems due to soil moisture competition.

Keywords

Annual Legumes, Soil N, Soil Organic C, Green Manure, Deer Browse, Forage Cropping Systems

1. Introduction

Legumes have long been used as a source of N in cropping systems for non-N fixing crops, but performance of legumes depends greatly on their environment. Moisture, temperature, available nutrients, soil type, and pH all influence biomass production and N fixation of legumes. Despite much literature on this topic, the applicability of information on legume performance is geographically localized because performance of legumes in crop rotations is environmentally specific and complex beyond performing an N budget. As the environment affects the amount of legume N fixation, crop response will thus inherently vary as well. Additionally, legumes will impact soil water, disruption of pest and disease cycles, and SOC, which also influence crop performance. Soil organic C is an important indicator of soil health and productivity, serves as a slow-release pool of nutrients as microbial activity mineralizes organic matter [1] [2] [3] [4] and aids in soil tilth, aggregation, water infiltration [5], moisture retention [6] [7] [8], and overall sustainability of the soil. In summary, legume N fixation can provide N for subsequent crops, compete with the crop for water, and improve soil tilth, thereby affecting long-term crop performance. An analysis of the sustainability of a legume green manure can depend, therefore, on many environmental factors.

Before the advent of inexpensive inorganic N fertilizer, legumes were a regular staple in cropping rotations due to their symbiotic N fixing capabilities. The role of legumes as green manure crops faded when inexpensive, inorganic N fertilizer became commercialized; however, as energy prices and demand for fertilizers rise, the production and incorporation of legume green manures becomes more economical. Interest in sustainable agriculture practices has also risen in recent years and helped to resurrect these once common crops. The Pineywoods ecoregion of East Texas [9] is conducive to green manure crops due to a warm climate and ample rainfall (115 cm annually), which allows for extended growing seasons and reduced moisture competition. Under ideal conditions, both WSL and CSL can produce biomass yields over 4.5 t DM ha^{-1} and contribute 100 kg N ha^{-1} or more to subsequent non-legume crops [10]-[16]. For instance, Hargrove [17] reported crimson clover (*Trifolium incarnatum* L.) contributed up to 120 kg N ha^{-1} to a grain sorghum (*Sorghum bicolor* L. [Moench]) crop on a sandy loam soil in Georgia, USA.

Non-legume green manure crops are better at scavenging and conserving available nutrients in the soil; however, they cannot add N to the system through symbiotic fixation. Also, grass crops have higher C:N ratios which slow mineralization and can immobilize previously available soil N. Legume biomass composition generally has a low C:N ratio, which facilitates residue decomposition in the soil and increases availability of N and other nutrients present in the legume biomass [18] [19] [20].

Since cattle are a common component of East Texas agriculture, forage production is important in the region. Thus, this two-year study evaluated N and C yield of various WSL and CSL green manures and their impact on SOC, soil N, soil moisture, and forage yield of winter rye and sorghum-sudangrass. Biomass and N yield of WSL and CSL in conjunction with residue decomposition data will provide information on amount and timing of N mineralization. The objectives of this project were to identify the annual legumes that were best adapted to the Pineywoods ecoregion of East Texas. Simultaneously, legumes should maximize forage production of winter rye and sorghum-sudangrass crops and enhance SOC and soil N. Results will provide information to help maximize N use efficiency of leguminous N sources in primary forage crops, decrease inorganic N fertilizer requirements and environmental N losses, and increase soil productivity and sustainability.

2. Materials and Methods

2.1. Site

This experiment was conducted in 2011 and 2012 at the Texas A&M AgriLife Research and Extension Center near Overton, TX (32˚17'N, 94˚58'W). Land was previously managed as a fertilized (split-applied 145-45-45 kg·ha^{-1} N-P_2O_5-K_2O annually), permanent bermudagrass (*Cynodon dactylon* [L.] Pers.) pasture for 10 years prior to cultivation in 2009 in preparation of other agronomic research. Plots for this study were located on a Lilbert loamy fine sand (Loamy, siliceous, semiactive, thermic Arenic Plinthic Paleudult) with an initial pH of 5.12 and 4.26 at 0 to 15 and 15 to 30 cm depths, respectively. Based on initial soil samples taken on August 14, 2009, soil was limed on September 2, 2009 with 9.2 t·ha^{-1} of lime (ECCE 100), which raised pH levels to 6.93 (0 to 15 cm) seven months later. In addition, 337 kg·ha^{-1} of 0-60-60 N-P_2O_5-K_2O was broadcast applied on November 5, 2009 to meet crop nutrient demands. Weather was unseasonably hot and with extreme drought conditions in 2011 followed by more moderate temperatures and moisture in 2012 (**Figure 1** and **Figure 2**).

2.2. Field Design

Two separate experiments were conducted; one to evaluate the impact of WSL and one to evaluate the impact of CSL on SOC, soil N, soil moisture and green manure potential. Each experimental design was a randomized complete block design with four replicates. Warm-season legumes and CSL were randomly planted within replications. Individual plot size was 1.5 × 6.0 m. Because WSL were planted more than five months prior to CSL, they received an additional winter rye forage/winter fallow treatment while CSL were growing through the winter months. All plots then were planted to a sorghum-sudangrass crop to capture leguminous N contributions. All crops were planted using a Hege double-disk, single-cone small plot planter on 18-cm row centers.

2.3. Annual Legumes

Legume species and cultivars were chosen for this study to represent a range of

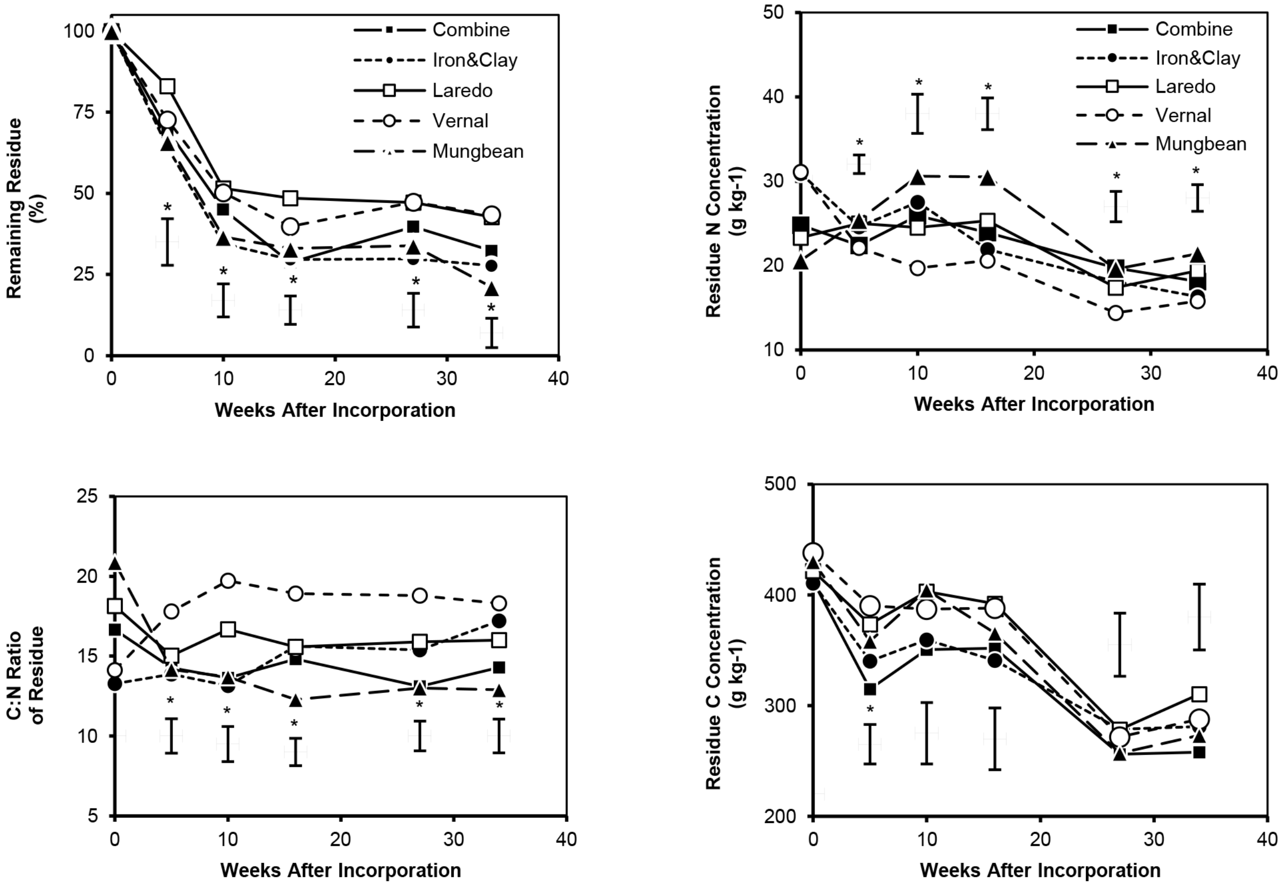

Figure 1. Change in legume residue over time after soil incorporation on August 19, 2011. Bars represent LSD values, and asterisks signify significant difference between treatments ($P = 0.05$).

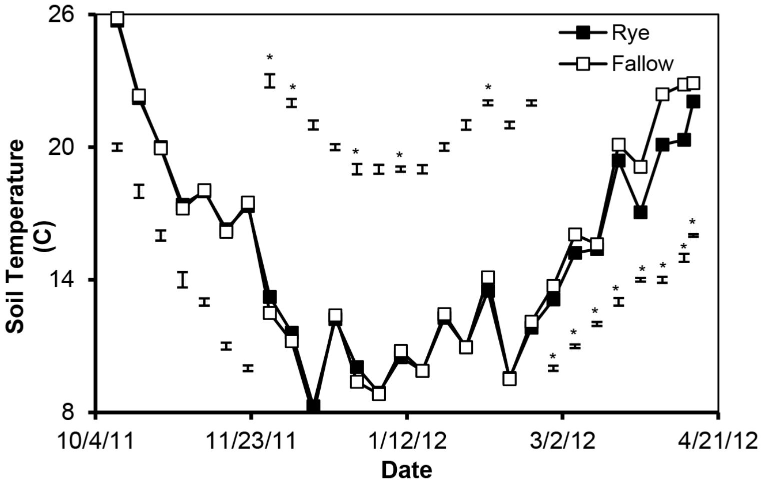

Figure 2. Effect of winter rye on soil temperature at plow depth. Bars represent LSD values, and asterisks signify significant difference between treatments ($P = 0.05$).

commercially available products that were well-adapted to local soils and climate. Nine WSL cultivars consisting of 'Iron-and-Clay' and 'Combine' cowpea (*Vigna unguiculata* [Walp]), 'Laredo' and 'Vernal' soybean (*Glycine max* L.[Merr.]), 'Rio Verde' lablab (*Lablab purpureus* L. [Sweet]), 'Kobe' lespedeza (*Kummerowia striata* [Thunb.]), mungbean (*Vigna radiata* L. [Wilczek]), alyceclover (*Alysicarpus vaginalis* L. DC), pinto bean (*Phaseolus vulgaris* L.), and a summer fallow treatment were randomly planted within each block in 1.5 × 6.0 m plots in the spring (May 24, 2011) and incorporated as green manure in the fall (August 19, 2011). Eight CSLs including 'Dixie' crimson clover (*Trifolium incarnatum* L.), 'Apache' and 'Blackhawk' arrowleaf clovers (*Trifolium vesiculosum* [Savi.]), 'R18' rose clover (*Trifolium hirtum* A.), Hairy vetch (*Vicia villosa* [Roth]), 'Whistler' and common Austrian winter pea (AWP) (*Pisum sativum* spp. Arvense L.), and caleypea (*Lathyrus hirsutus* L.) were then planted in the fallow plots in the fall (November 10, 2011). All legumes were planted at the following standard [21] seeding rates: 73 kg·ha^{-1} for pinto bean; 56 kg·ha^{-1} for cowpea, soybean, and caleypea; 39 kg·ha^{-1} for AWP; 34 kg·ha^{-1} for mungbean and lespedeza; 28 kg·ha^{-1} for lablab and vetch; 22 kg·ha^{-1} for crimson clover; 18 kg·ha^{-1} for rose clover; 17 kg·ha^{-1} for alyceclover; and 11 kg·ha^{-1} for arrowleaf clovers. Following rototilling, a roller-packer was used to create a firm seed bed for rye and sorghum-sudangrass planting.

Prior to rototilling under the WSL green manure crops in the fall, a 0.09 m^2 quadrat of shoot biomass from each plot was hand clipped and roots removed by shovel (approximately 30 cm depth) before drying at 60˚C to determine dry matter (DM) accumulation and C and N concentrations in the biomass. To compare legume impact on soil moisture, gravimetric moisture samples were taken in the fall (August 24, 2011) and spring (April 9, 2012). A single one meter (32 mm diameter) deep soil core was taken congruently with biomass samples from each plot in the fall prior to incorporation, while a composite sample was made from three (22 mm diameter) 60 cm deep subsamples in the spring.

2.4. Soil N and C

Nylon degradation bags were constructed to bury aboveground legume biomass in plots and later bags were recovered at various dates to estimate N mineralization and remaining C in the soil throughout each growing season [22]. Because of small plot sizes and limited available biomass for decomposition bags, a 1.0 kg bulk sample of each legume was harvested from outside each plot area and sorted into stems, leaves, and blossoms/pods. Blossoms were separated out for Dixie and Rose clovers, and pods were only present on mungbean and Laredo soybean at the time of incorporation. A standard ratio for each legume was calculated between leaf, stem, and blossom/pod and used to fill 10 × 18 cm nylon mesh (250 μm) bags, which were buried within plots immediately after green manure incorporation. Five bags were buried per plot at the plow depth (15 cm) and recovered 5, 10, 16, 27, and 34 weeks after burial for WSLs and 2, 4, 6,10, and 23 weeks after burial for CSLs. The HOBO Pendent® temperature sensors/data loggers (Onset Computer Corp., 2012) were installed in nine selected plots at the time of incorporation and recorded hourly soil temperature throughout the fall, winter, and spring. Recovered biomass from the bags was dried at 60˚C a nd weighed to determine remaining residue. Dried samples were then ground to 1 mm particle size and analyzed for C and N concentrations using combustion analysis. Dried plant samples (275 mg) were analyzed with an Elementar Analyzer-vario MAX CNS unit (Elementar Analysensysteme GmbH, Hanau, Germany) [22] [23].

After incorporation by rototilling, each WSL treatment was followed by winter fallow or ‘Elbon’ winter cereal rye (112 kg·ha^{-1} seeding rate) planted on November 9, 2011. Five rye forage harvests were cut on November 30, January 18, February 6, March 1, and April 10 during the 2011-2012 winter using a mechanical harvester and subsampled for moisture content to estimate total DM yield. Following the final rye forage harvest and rototilling of the winter rye stubble and CSLs, plots were rototilled and rolled to prepare a firm seedbed. Sorghum-sudangrass summer forage was planted at 39 kg·ha^{-1} over all treatments on May 9, 2012. Stand emergence was taken on May 25, 2012 by counting plants in a one-meter length section of the middle two plot rows. Sorghum-sudangrass forage color was ranked on a 1 (yellow) to 5 (dark green) scale on June 12, 2012. Three forage harvests were taken on June 25, August 15, and September 25, 2012 using a mechanical harvester and subsampled for moisture to estimate DM yield. Combustion analysis was done on rye forage samples to determine treatment effects on N concentrations of forage and estimate total N accumulation removed by the rye crop. Three soil cores were taken per plot and split into 0 to 15, 15 to 30, and 30 to 60 cm depths after each crop termination. Soil samples were dried at 60ºC and ground (<840 um), and soil C and N levels were measured using combustion analysis as described for plant samples except using 1000 mg as recommended [23]. A fizz test using 10% HCl was negative and confirmed inorganic C was below detectable levels.

2.5. Data Analysis

All crop yield and quality data were analyzed with PROC GLM model using SAS 9.2 [24]. All treatments were considered fixed effects, and replication was designated as a random effect. Fall soil data, rye forage yield and N data, and legume yield data were analyzed as one-way ANOVAs; whereas, LSD ($P > 0.05$) was used for mean separation of CSL data and WSL data separately. Spring soil data and sorghum-sudangrass forage data were separated and analyzed as a one-way ANOVA for CSL treatment effects and as a two-way ANOVA for WSL and rye treatment effects.

3. Results

3.1. Warm-Season Legumes

3.1.1. Legume Yield

At the time of legume incorporation, mungbean had the most above-ground biomass (6.24 t DM ha^{-1}) of any legume, followed by Iron-and-Clay cowpea (3.33 t DM ha^{-1}) (**Table 1**). There was no significant difference in DM among the other three legumes (average 1.24 t DM ha^{-1}). Mungbean also produced the most root biomass (0.82 t DM ha^{-1}). Total biomass production was greatly influenced by deer browsing; thus, estimates for all legumes except mungbean (low preference by deer) were lower than their potential. Iron-and-Clay cowpea had the highest N concentration in above- (31.2 $g{\cdot}kg^{-1}$) and belowground (20.6 $g{\cdot}kg^{-1}$) biomass, while mungbean was the lowest (25.2 and 12.7 $g{\cdot}kg^{-1}$ for shoot and root biomass, respectively) (**Table 1**). Because of higher biomass production, mungbean still contributed the most N (168 $kg{\cdot}ha^{-1}$) to the soil at the time of incorporation followed by Iron-and-Clay (111 $kg{\cdot}ha^{-1}$) and Combine (45 $kg{\cdot}ha^{-1}$) cowpea and Vernal (36 $kg{\cdot}ha^{-1}$) and Laredo soybean (32 $kg{\cdot}ha^{-1}$). The amount of C contributed to the soil from each legume followed a similar order, with mungbean (3043 $kg{\cdot}ha^{-1}$) producing the most and Laredo soybean (553 $kg{\cdot}ha^{-1}$) the least.

Table 1. Above- and belowground biomass yield, N concentration, C concentration, total N yield, and total C yield for warm-season legumes in 2011.

	Biomass Yield		Biomass N		Biomass C		Total N Yield		Total C Yield	
	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
	t DM ha^{-1}		$g{\cdot}kg^{-1}$		$g{\cdot}kg^{-1}$		$kg{\cdot}ha^{-1}$		$kg{\cdot}ha^{-1}$	
Combine	1.44 c[†]	0.26 b	28.6 b	16.0 b	408.8 c	417.6 ab	41 c	4 b	589 c	109 b
Iron & Clay	3.33 b	0.36 b	31.2 a	20.6 a	415.6 c	405.7 b	104 b	7 a	1384 b	146 b
Laredo	1.03 c	0.26 b	27.3 bc	16.0 b	430.1 b	422.1 a	28 c	4 b	443 c	110 b
Vernal	1.24 c	0.33 b	25.5 c	14.1 c	438.9 a	420.9 ab	32 c	5 b	544 c	139 b
Mungbean	6.24 a	0.82 a	25.2 c	12.7 d	433.8 ab	410.3 ab	157 a	10 a	2707 a	336 a

[†]Different letters within column are significant at $P = 0.05$ level.

3.1.2. Growth and Deer Browse

Legumes experienced exceptional drought conditions during the summer of 2011 resulting in differences in germination. Cowpea varieties had the highest rate of germination followed closely by both soybean cultivars and mungbean ($P < 0.01$). Alyceclover and lespedeza both had no initial germination, while lablab and pinto bean had poor establishment as well. These four crops never germinated well, even after subsequent rains and plantings, and were eventually terminated in early July.

Combine cowpea maintained the best canopy coverage throughout the summer followed closely by Iron-and-Clay ($P < 0.01$) (Table 2). Soybean cultivars

Table 2. Differences among nine warm-season annual legumes in canopy coverage, height, and deer damage.

Legume	6/21/2011	7/7/2011	7/13/2011	8/2/2011	8/11/2011
			Canopy Coverage (%)		
Combine	99 a[†]	94 a	94 a	94 a	93 a
Iron & Clay	84 b	72 b	79 b	87 a	82 ab
Laredo	72 b	54 c	59 c	57 b	38 d
Vernal	82 b	71 b	64 c	67 b	56 c
Mungbean	77 b	77 b	77 b	83 a	81 b
Lablab	14 c	23 d	0 d	0 c	0 e
Pinto	14 c	10 de	0 d	0 c	0 e
Alyceclover	0 d	3 e	0 d	0 c	0 e
Lespedeza	0 d	3 e	0 d	0 c	0 e
			Height (cm)		
Combine	14.0 ab	---	20.9 bc	31.3 c	32.8 c
Iron & Clay	15.9 a	---	23.5 b	39.0 b	38.0 b
Laredo	12.4 b	---	18.6 cd	21.0 d	20.0 d
Vernal	12.5 b	---	17.5 d	23.4 d	19.9 d
Mungbean	11.5 b	---	27.4 a	45.9 a	52.8 a
Lablab	6.6 c	---	---	---	---
Pinto	8.9 c	---	---	---	---
Alyceclover	---	---	---	---	---
Lespedeza	---	---	---	---	---
			Deer Damage (% plants browsed)		
Combine	68 ab	---	100 a	92 a	100 a
Iron & Clay	78 a	---	90 b	60 b	72 b
Laredo	52 b	---	98 ab	92 a	100 a
Vernal	58 b	---	100 a	60 b	98 a
Mungbean	28 c	---	36 c	16 c	16 c
Lablab	56 b	---	---	---	---
Pinto	32 c	---	---	---	---
Alyceclover	0 d	---	---	---	---
Lespedeza	0 d	---	---	---	---

[†]Different letters within column are significant at $P = 0.05$ level.

started near 80% coverage but declined by 38% and 56% coverage for Laredo and Vernal, respectively, by mid-August. This decline was primarily due to deer browse combined with drought stress. The number of soybean plants browsed by deer was routinely between 90 and 100% for both cultivars from mid-July until incorporation in mid-August and eventually led to some plant mortality. Deer showed a similar preference for Combine cowpea and slightly less preference for Iron-and-Clay cowpea; however, cowpea proved much more resistant to drought and defoliation by continual production of new growth and showed little plant mortality. Mungbean proved resistant to deer browse, which was evident by its height at crop termination. Deer browsed less than 20% of mungbean plants, and height (52.8 cm) was 39% taller than the next tallest legume, Iron-and-Clay cowpea ($P < 0.01$) (**Table 2**).

3.1.3. Residue Decomposition

Vernal soybean and Iron-and-Clay cowpea started out with the highest N concentrations (31.1 and 30.9 $g \cdot kg^{-1}$, respectively) of the warm season legumes, and mungbean had the lowest (20.6 $g \cdot kg^{-1}$) (**Figure 1**). However, Vernal soybean also had the highest C concentration (438.3 $g \cdot kg^{-1}$), while Iron-and-Clay cowpea had the lowest (410.7 $g \cdot kg^{-1}$) (**Figure 1**). As a result, C:N ratios of warm season legumes ranged from 13.3 to 20.9 in the order of mungbean > Laredo > Combine > Vernal > Iron-and-Clay (**Figure 1**). Interestingly, C:N ratios did not appear to be a driving force in residue decomposition. Laredo and Vernal soybeans were consistently higher in remaining residue over the 34 weeks (**Figure 1**); however, both had intermediate C:N ratios compared to the other legumes. Likewise, Iron-and-Clay cowpea and mungbean were both consistently lower in remaining residue than other legumes, despite one having the largest initial C:N ratio and the other the lowest.

As a general trend, legumes with low C:N ratios (Vernal soybean and Iron-and-Clay cowpea) at the time of incorporation had the highest C:N ratios 34 weeks after incorporation; whereas the opposite was true of legumes starting out with high C:N ratios (mungbean). Mungbean residue initially immobilized available N in the soil as suggested by the increased N concentration in the residue in the first 10 weeks; however, N concentration later declined to original levels before sorghum-sudangrass planting on May 9. Despite increasing lower soil temperatures after February 28 (**Figure 2**), winter rye failed to have a consistent impact on residue decomposition. A summer crop x winter crop interaction ($P = 0.04$) was present at week 34 for Iron-and-Clay cowpea and Vernal soybean residue C:N ratios (**Table 3**). Winter rye appeared to decrease C:N ratio for Iron-and-Clay cowpea while increasing the C:N ratio for Vernal soybean. More N was contributed to the soil by Iron-and-Clay cowpea compared to Vernal soybean and may have stimulated rye root production. More roots would secrete more root exudates and possibly stimulate microbial activity, which could in turn respire more C from the residue and lower C:N ratio. Alternatively, Vernal soybean contributed relatively little N when incorporated compared to

Table 3. Difference between legumes and effect of a subsequent winter rye crop on warm-season legume residue C:N ratio over time after soil incorporation (April 17, 2012).

Treatment		Week 0	Week 5	Week 10	Week 16	Week 27	Week 34
		C:N Ratio					
Summer	Combine	16.7	14.3 b[†]	13.6 c	14.8 b	13.1 c	14.3 cd
	Iron & Clay	13.3	13.9 b	13.2 c	15.6 b	15.4 b	17.2 ab
	Laredo	18.1	15.0 b	16.7 b	15.6 b	15.9 b	16.0 bc
	Vernal	14.1	17.8 a	19.7 a	18.9 a	18.8 a	18.3 a
	Mungbean	20.9	14.2 b	13.7 c	12.3 c	13.0 c	12.9 d
Winter	Fallow	16.6	15.1 a	14.4 b	15.5 a	14.7 b	15.6 a
	Rye	16.6	15.0 a	16.4 a	15.4 a	15.9 a	16.1 a
Fallow	Combine	16.7	15.0 bcd	13.5 de	14.6 cd	12.5 e	15.1 bcd
	Iron & Clay	13.3	13.0 d	11.8 e	16.3 bc	14.8 cde	16.9 b
	Laredo	18.1	16.1 abc	15.7 bcd	16.4 bc	15.5 bcd	16.5 bc
	Vernal	14.1	17.3 ab	18.6 ab	18.4 ab	17.4 b	15.9 bcd
	Mungbean	20.9	14.1 bcd	12.4 de	11.9 e	12.1 e	12.8 d
Rye	Combine	16.7	13.6 cd	13.8 de	15.1 cd	13.6 de	15.9 bcd
	Iron & Clay	13.3	14.7 bcd	14.5 de	14.9 cd	15.9 bcd	13.6 cd
	Laredo	18.1	14.0 cd	17.7 bc	14.8 cd	16.3 bc	17.5 b
	Vernal	14.1	18.3 a	20.9 a	19.4 a	20.2 a	20.7 a
	Mungbean	20.9	14.2 bcd	15.0 cd	12.7 de	13.5 de	13.2 d

[†] Different letters within column and crop are significant ($P = 0.05$).

Iron-and-Clay cowpea, and rye may have extracted more mineralized N from the soil, therefore reducing microbial activity and increasing C:N ratio.

After an initial drop in C concentration in the first five weeks, all residues remained constant or increased slightly through December 15 (**Figure 1**). Warm and wet weather conditions allowed microbial activity to continue through the winter months creating a noticeable decline in C concentration by week 27 (March 2). By week 34 (April 13), 21, 28, 32, 43, and 43% of residue remained for mungbean, Iron-and-Clay cowpea, Combine cowpea, and Laredo and Vernal soybean, respectively. At week 27, winter rye had increased C concentration of residues by 19% over winter fallow (**Table 4**). Roots alter chemical and physical conditions in the soil by releasing C-rich exudates, utilizing soil water, and competing for available nutrients such as NH^+ and NO^-. Extraction of mineralized N or soil water from the soil into aboveground biomass could potentially lower microbial activity and thus reduce respiration of legume residues.

3.1.4. Soil Moisture

A single soil sampling at the time of warm-season legume incorporation showed moisture depletion had occurred down to 90 cm (**Figure 3**). Laredo and Vernal

Table 4. Difference between legumes and effect of a subsequent winter rye crop on warm-season legume residue C concentrations over time after soil incorporation (April 17, 2012).

Treatment		Week 0	Week 5	Week 10	Week 16	Week 27	Week 34
		$g\ C\ kg^{-1}$					
Summer	Combine	412.7	314.9 c[†]	350.6 a	352.0 a	256.0 a	258.1 a
	Iron & Clay	410.7	340.4 bc	359.6 a	340.8 a	278.8 a	281.0 a
	Laredo	421.7	373.6 ab	403.2 a	392.1 a	278.4 a	310.4 a
	Vernal	438.3	390.4 a	387.3 a	388.3 a	271.8 a	287.9 a
	Mungbean	430.1	358.4 ab	404.5 a	365.6 a	257.0 a	273.2 a
Winter	Fallow	422.7	352.8 a	370.3 a	374.7 a	244.5 b	270.8 a
	Rye	422.7	358.3 a	391.8 a	360.9 a	291.5 a	293.2 a
Fallow	Combine	412.7	323.4 bc	310.9 c	356.2 ab	240.4 a	249.7 a
	Iron & Clay	410.7	324.4 bc	341.0 bc	341.8 ab	256.5 a	256.1 a
	Laredo	421.7	378.5 a	404.2 ab	417.5 a	255.1 a	310.7 a
	Vernal	438.3	381.3 a	362.7 abc	390.5 ab	239.6 a	259.3 a
	Mungbean	430.1	356.2 abc	432.7 a	367.3 ab	220.5 a	291.3 a
Rye	Combine	412.7	306.4 c	390.2 ab	347.7 ab	271.6 a	266.5 a
	Iron & Clay	410.7	356.3 ab	378.3 abc	339.9 b	301.0 a	305.8 a
	Laredo	421.7	368.6 ab	402.2 ab	366.8 ab	301.6 a	310.1 a
	Vernal	438.3	399.6 a	411.9 ab	386.2 ab	303.9 a	316.5 a
	Mungbean	430.1	360.5 ab	376.2 abc	363.9 ab	279.2 a	267.4 a

[†] Different letters within column and crop are significant ($P = 0.05$).

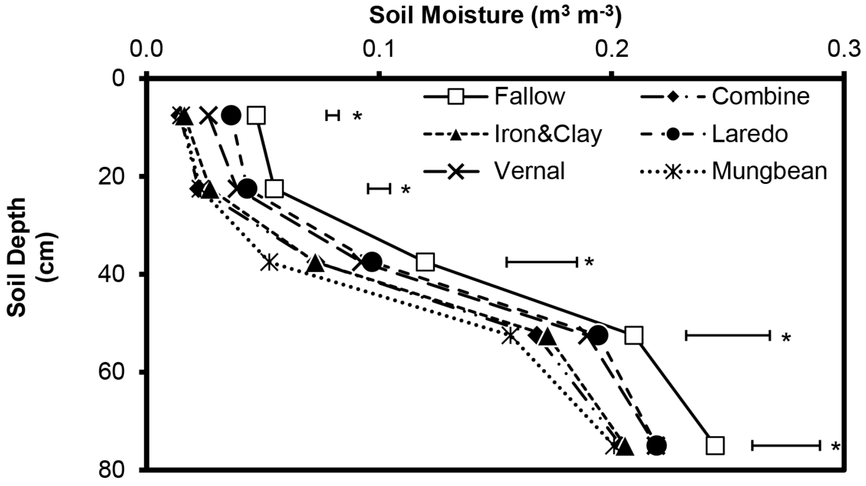

Figure 3. Final soil moisture as affected by warm-season legume green manures in the top 90 cm of soil prior to incorporation on August 21, 2011. Bars represent LSD values, and asterisks signify significant difference between treatments ($P = 0.05$).

soybean used the least amount of soil water at 0 to 15 cm (5.5 and 4.0 mm remaining, respectively) and 15 to 30 cm (6.5 and 5.8 mm remaining, respectively) depths, and soil water content deeper than 30 cm in these treatments was not significantly lower than soil water content of the fallow treatment (Table 5). Laredo and Vernal legumes used less water primarily due to defoliation from deer browse and reduction in evapotranspiration. All other legumes had significantly less water at all depths compared to summer fallow; however, mungbean had consistently the highest water use throughout the soil profile with 40.7 mm less soil water in the top 90 cm compared to summer fallow. Again, greater water use can be attributed to greater biomass production and loss of water through evapotranspiration by mungbean.

3.2. Cool-Season Legumes

3.2.1. Legume Yield

Warm and wet weather conditions in the winter of 2011 and spring of 2012 led to large biomass yields of CSLs (Table 6). Austrian winter pea produced the

Table 5. Effect of annual warm-season legumes on soil water at time of soil incorporation on August 21, 2011.

	Soil Depth (cm)					
Legume	0 - 15	15 - 30	30 - 45	45 - 60	60 - 90	Total
	soil water (mm)					
Fallow	7.1 a[†]	8.2 a	18.0 a	31.4 a	73.4 a	138.1 a
Combine	2.2 d	3.4 c	10.9 bc	25.2 bc	61.2 b	102.8 cd
Iron & Clay	2.4 d	4.1 c	10.9 bc	25.9 bc	61.7 b	105.0 d
Laredo	5.5 b	6.5 b	14.6 ab	29.1 ab	65.8 ab	121.5 b
Vernal	4.0 c	5.8 b	13.8 ab	28.4 abc	65.7 ab	117.8 bc
Mungbean	2.2 d	3.5 c	7.9 c	23.5 c	60.3 b	97.4 d

[†]Different letters within column are significant at $P = 0.05$ level.

Table 6. Above-and belowground biomass yield, N concentration, C concentration, total N yield, and total C yield for cool-season legumes during the winter of 2011-2012.

	Yield		N Concentration		C Concentration		Total N Yield		Total C Yield	
Legume	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root	Shoot	Root
	t DM ha^{-1}		g·kg^{-1}		g·kg^{-1}		kg·ha^{-1}		kg·ha^{-1}	
AWP	8.41 a[†]	0.29 a	36.6 ab	29.7 a	443.2 a	417.9 d	310 a	9 a	3716 a	119 a
Whistler	6.52 ab	0.14 c	34.5 b	22.0 b	432.2 b	427.0 cd	210 ab	3 c	2813 ab	60 c
Apache	6.86 ab	0.25 ab	28.0 c	17.3 cd	425.6 b	436.3 bc	187 b	4 bc	2924 ab	110 ab
Blackhawk	3.41 bc	0.17 bc	32.8 b	17.4 cd	429.7 b	438.3 ab	112 bc	3 c	1462 bcd	75 bc
Dixie	6.37 ab	0.18 bc	24.0 c	19.0 c	427.5 b	436.9 ab	149 bc	3 bc	2740 abc	79 abc
Rose	4.85 abc	0.16 bc	24.1 c	15.1 d	424.8 b	446.1 a	110 bc	2 c	2067 bcd	72 bc
Hairy vetch	2.68 c	0.18 bc	39.1 a	24.4 b	443.3 a	419.7 d	106 bc	4 bc	1186 cd	75 bc
Caleypea	2.15 c	0.21 abc	36.6 ab	29.3 a	447.0 a	421.8 d	79 c	6 ab	960 d	87 abc

[†]Different letters within column are significant at $P = 0.05$ level.

most ($P = 0.02$) above-ground biomass (8.41 t DM ha^{-1}), though it was not significantly different from Apache arrowleaf clover, Whistler winter pea, or Dixie crimson clover (6.86, 6.52, and 6.37 t DM ha^{-1}, respectively). The lowest producers of biomass were caleypea, hairy vetch, and Blackhawk arrowleaf clover (2.15, 2.68, and 3.41 t DM ha^{-1}, respectively). Hairy vetch, AWP, and caleypea contained the highest ($P < 0.01$) concentrations of N (37.4 g·kg^{-1}) and C (444.5 g·kg^{-1}), while Dixie crimson, Rose, and Apache arrowleaf clovers had the overall lowest N (25.4 g·kg^{-1}) and C (428.0 g·kg^{-1}) concentrations (**Table 6**). Dixie crimson and Rose clovers were lower in N and C because they matured the earliest. Dixie clover was at 100% bloom by March 30, while Rose clover was at 100% bloom by April 12 (**Table 7**). Apache arrowleaf only started to bloom (10%) by April 12; however, it produced thick stems which made up a larger fraction of its biomass compared to other CSLs and lowered N concentrations. Overall, AWP and Whistler winter pea produced the highest ($P < 0.01$) total aboveground N yield (310 and 210 kg·ha^{-1}, respectively), and caleypea produced the lowest (79 kg·ha^{-1}) (**Table 6**). Root biomass, N, and C concentrations did not necessarily correlate with aboveground biomass production; however, estimated total N contained in the roots were low and ranged between 2 and 9 kg N ha^{-1} (Rose and AWP, respectively). Average root C production was 85 kg·ha^{-1} and was not significantly different among the legume species. Between 960 and 3716 kg C ha^{-1} (caleypea and AWP, respectively) was contributed to the soil from aboveground biomass.

3.2.2. Residue Decomposition

All residues decomposed in a typical exponential fashion, with the most rapid loss of residue mass occurring in the first two weeks (**Figure 4**). The most noticeable difference among legume decomposition was with Dixie crimson clover, which decayed at a slower rate than the other legumes and had the highest ($P < 0.01$)

Table 7. Differences among eight cool-season annual legumes in stand, plant length, and bloom.

	Stand	Height	Bloom	
Legume	12/16/2011	4/12/2012	3/30/2012	4/12/2012
	plant lin m^{-1}	cm	%	
AWP	20.5 de[†]	141 a	5 c	10 b
Whistler	11.5 e	80 cd	55 b	87 a
Apache	14.3 e	99 b	10 c	10 b
Blackhawk	7.8 e	71 cd	0 c	0 b
Dixie	30.8 cd	84 bc	100 a	100 a
Rose	57.3 a	66 d	0 c	100 a
Hairy vetch	38.5 bc	126 a	0 c	10 b
Caleypea	51.5 ab	126 a	15 c	90 a

[†] Different letters within column are significant at $P = 0.05$ level.

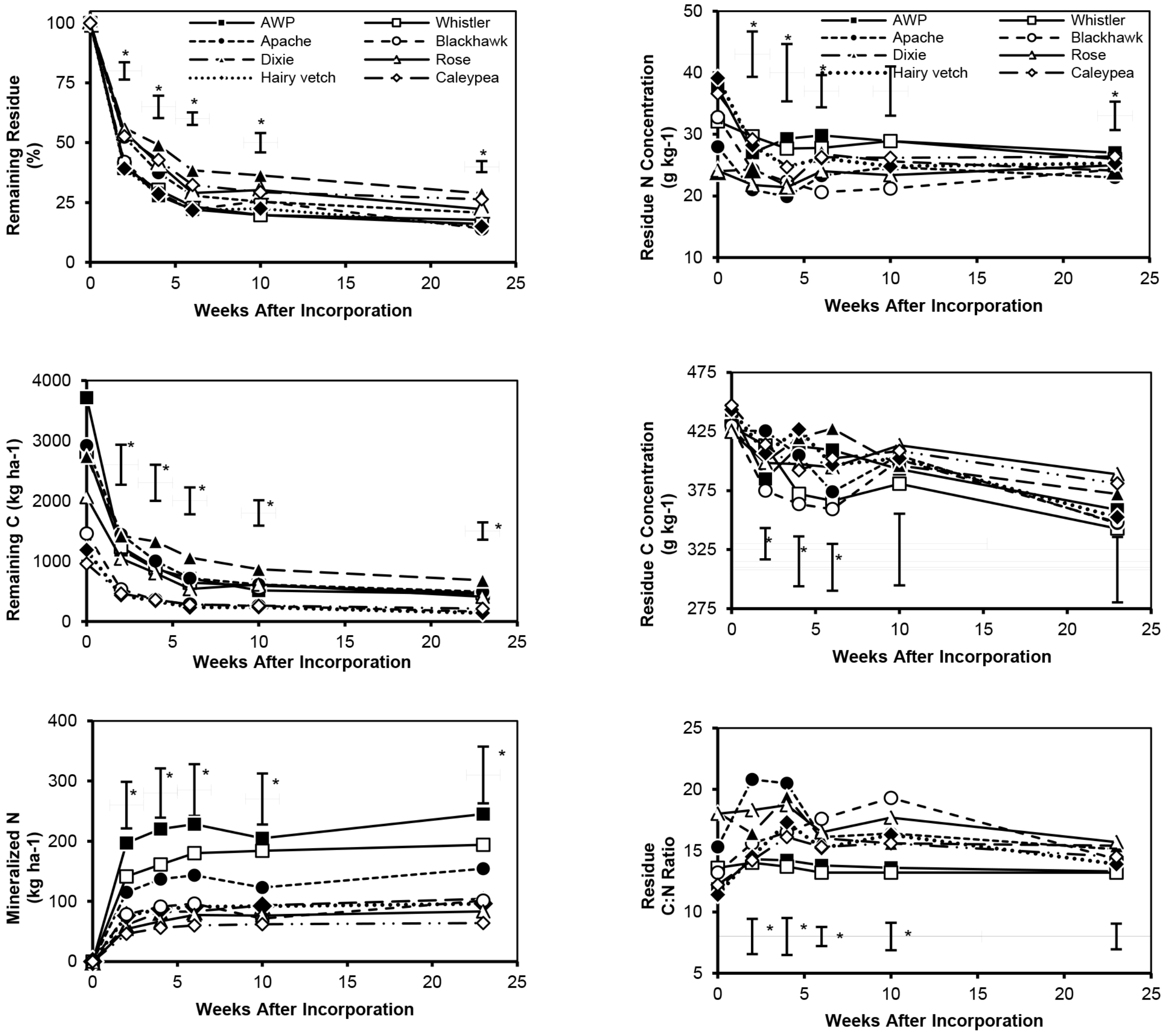

Figure 4. Change in cool-season legume residue over time after soil incorporation on April 17, 2012. Bars represent LSD values, and asterisks signify significant difference between treatments ($P = 0.05$).

remaining residue (29%) by the end of the summer. Austrian winter pea, Blackhawk arrowleaf clover, hairy vetch, and Whistler winter pea were all consistently the lowest in residue mass with only 14%, 15%, 16%, and 18% remaining, respectively, by the end of the summer. Residue from every legume initially dropped in N and C concentration after incorporation followed by a rebound in levels, though the amount and timing of that drop varied by legume (**Figure 4**). By week ten, N concentrations became constant while C concentrations continued to drop slowly. Final C:N ratios were near 15 by week 23 for all legume residues. Differences in C and N concentrations were small or insignificant by week ten for all legumes.

Initial loss of residue mass led to a large flush of mineralized N into the soil. Austrian winter pea supplied an estimated 197 kg N ha^{-1} in the first two weeks and released an additional 48 kg of N by the time the sorghum-sudangrass forage crop was terminated (**Figure 4**). Whistler winter pea did not significantly differ from AWP in N mineralization at any date, while Apache arrowleaf was not different after week six. The remaining legumes contributed between 64 and 154 kg N ha^{-1} over the course of the summer with no significant difference between treatments. Despite the largest contribution of C to the soil by AWP at the time of incorporation, Dixie crimson clover residue had the highest total C remaining in the soil by week 23 (**Figure 4**). This was likely a direct result of early maturation and greater lignification of plant biomass prior to incorporation. Complex lignin molecules are resistant to breakdown by microbial activity and remain intact longer in the soil. Blackhawk arrowleaf clover, caleypea, and hairy vetch had the least amount of C remaining in the soil by week 23, mainly because of lower biomass inputs and not because of large C:N ratios.

3.2.3. Soil Moisture

In the week prior to soil sampling, plots received 4 cm of rainfall in addition to above normal rainfall for the previous four months. Soil water content was at or above field capacity in some cases (loamy sand = 0.12 $m^3 \cdot m^{-3}$; sandy clay loam =0.27 $m^3 \cdot m^{-3}$; [25]). Despite the rainfall, differences still appeared among winter crop treatments. Whistler winter pea, AWP, and hairy vetch had consistently the highest soil water content at 0 to 60 cm depth, along with Blackhawk arrowleaf clover and winter fallow at 15 to 60 cm depth (**Table 8**).

Whistler and AWP produced a particularly dense mat of shoot biomass compared to the other legumes. This thick canopy likely reduced evaporative water losses from the soil surface and enhanced water infiltration, leading to the elevated soil water content. Also, these two legumes possess a thick cuticle layer

Table 8. Effect of annual cool-season legumes on soil water at time of soil incorporation on April 17, 2012.

	Soil Depth (cm)			
Legume	0 - 15	15 - 30	30 - 60	0 - 60
	soil water (mm)			
Fallow	24.3 bc[†]	27.3 ab	74.6 a	126.2 a
Rye	19.7 de	24.9 bc	66.6 bc	111.1 cd
AWP	29.0 a	27.8 a	67.8 abc	124.6 ab
Whistler	26.6 abc	27.7 a	70.0 abc	124.3 ab
Apache	17.8 e	22.2 d	63.0 c	103.0 d
Blackhawk	23.7 bcd	26.8 ab	70.0 abc	120.5 abc
Dixie	23.5 bcd	24.8 bcd	64.1 bc	112.4 cd
Rose	24.1 bcd	25.0 bc	64.9 bc	113.9 bcd
Hairy vetch	27.5 ab	28.3 a	70.9 ab	126.8 a
Caleypea	22.8 cd	23.9 cd	64.3 bc	111.0 cd

[†] Different letters within column are significant at $P = 0.05$ level.

over leaves compared to the other CSLs in this study, which increased water use efficiency. Whistler winter pea also had considerably more tendrils and fewer leaves, which would also increase water use efficiency compared to other legumes with similar biomass production [26].

3.3. SOC and Soil Total Nitrogen

Because legume green manures add substantial amounts of fixed C and N to the soil when incorporated, soil samples were taken at each crop termination to determine treatment effects on SOC and soil N. Prior to WSL green manure incorporation, soil analysis revealed higher SOC and soil N at both the 0 to 15 cm ($P < 0.01$) and 15 to 30 cm ($P < 0.01$) depths under Combine cowpea, Iron-and-Clay cowpea, and mungbean, which were the highest biomass producers as well. On average, these legumes increased SOC by 41% and 61% at 0 to 15 and 15 to 30 cm depths, respectively, compared to fallow plots (**Figure 5**). By

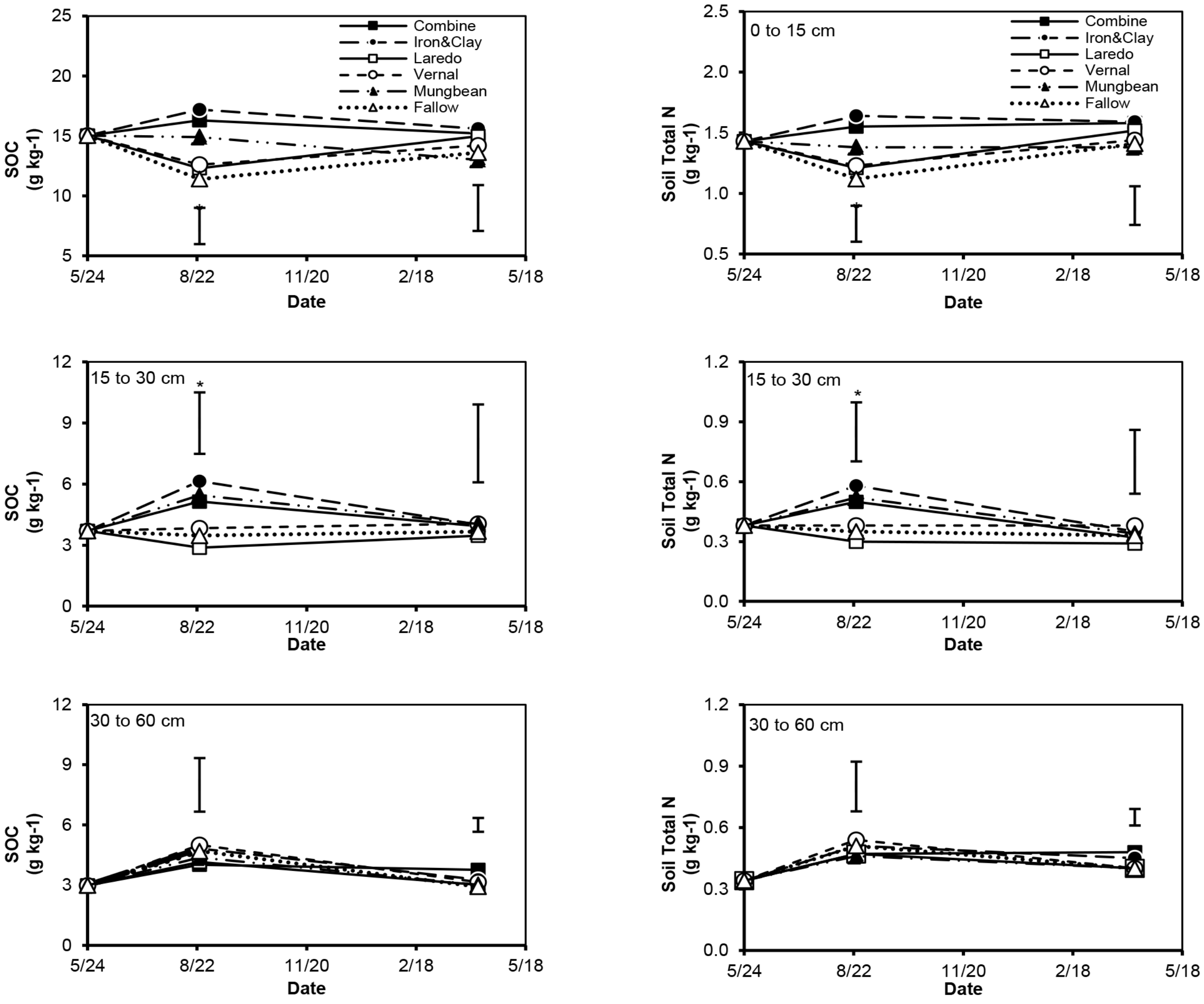

Figure 5. Effect of warm-season legume green manure on SOC and soil total N at three soil depths. Bars represent LSD values, and asterisks signify significant difference between treatments ($P = 0.05$).

April, these effects were no longer present in the upper two soil layers, but were instead significant (SOC P = 0.06; soil N P = 0.10) for Combine and Iron-and-Clay cowpea at 30 to 60 cm. Overall, SOC and soil N decreased at this depth from August through April (fallow decreased 38%); however, Combine and Iron-and-Clay cowpea cultivars appeared to minimize losses due to increased N and C inputs. These inputs may have come from downward movement of N and C in the soil due to leaching of NO_3^- and soluble SOC. If root biomass production was responsible, then effects should have been present in August.

Cool season legumes had no effect on SOC or soil N at the 0 to 15 cm or 30 to 60 cm depths; however, a winter crop treatment resulted in a significant increase in soil C and N at 15 to 30 cm. Surprisingly, winter rye had the highest significant SOC (5.0 g·kg^{-1}; P = 0.03) and soil N (0.5 g·kg^{-1}; P = 0.04) at this depth along with AWP (**Table 9**). Winter rye should have taken up soil N through the roots, incorporated it into aboveground biomass, and been removed with each forage cutting, thereby reducing overall soil N. It is unlikely that rye root production and mineralization after crop termination would have been responsible for such a response. However, visual assessment of sorghum-sudangrass indicated darker green biomass under winter rye compared to winter fallow in June.

3.4. Winter Rye Forage Production

Summer legumes had little effect on rye forage yield. In the first cut, rye yield following summer fallow (1.00 t DM ha^{-1}) was significantly higher (P = 0.08) than rye following mungbean (0.64 t DM ha^{-1}) (**Table 10**). The same was true for N concentrations in the rye biomass. Mungbean reduced (P = 0.03) N concentrations by 5% in rye forage during cut one compared to summer fallow (57.3 g·kg^{-1}). Reduction in rye yield and N concentration was likely due to soil moisture depletion, since mungbean had the least amount of soil water available by the end of the summer, and the dry fall allowed for little recharge prior to rye planting.

There were no differences in yield or N concentrations among summer treatments in subsequent rye cuttings or overall yield (12.55 t DM ha^{-1}). Average rye yields for each cut were 0.81, 2.04, 0.99, 1.37, and 7.34 t DM ha^{-1} sequentially. Increased moisture throughout the winter months should have led to an N response from the legume residue, since an average total of 376 kg N ha^{-1} was removed in rye biomass by the last forage harvest. Mineralization of N from a large SOC pool already present in the field prior to the study may have provided enough available N to mask this effect. Visual assessment supported this idea as rye plots did not exhibit yellowing on unfertilized fallow plots, which is commonly associated with N deficiency. Soil analysis confirmed adequate levels of macro- and micronutrients prior to the study and suggest nutrient deficiencies are unlikely.

Table 9. Effect of winter rye forage crop and eight cool-season legume green manures on SOC and total soil N at three soil depths at time of incorporation (April 17, 2012).

Depth	Legume	SOC	Soil Total N
		g·kg^{-1}	
0 - 15 cm	Fallow	13.0 a[†]	1.4 a
	Rye	13.3 a	1.4 a
	Apache	15.5 a	1.6 a
	AWP	13.5 a	1.4 a
	Blackhawk	13.8 a	1.4 a
	Caleypea	11.6 a	1.2 a
	Dixie	12.2 a	1.3 a
	Hairy	13.2 a	1.4 a
	Rose	13.8 a	1.4 a
	Whistler	16.1 a	1.6 a
15 - 30 cm	Fallow	3.5 bc	0.3 b
	Rye	5.0 a	0.5 a
	Apache	3.6 bc	0.3 b
	AWP	4.1 ab	0.4 ab
	Blackhawk	3.7 bc	0.3 b
	Caleypea	2.9 c	0.3 b
	Dixie	3.1 bc	0.3 b
	Hairy	3.6 bc	0.3 b
	Rose	3.6 bc	0.3 b
	Whistler	3.7 bc	0.3 b
30 - 60 cm	Fallow	3.1 a	0.4 a
	Rye	2.9 a	0.4 a
	Apache	3.7 a	0.4 a
	AWP	2.5 a	0.3 a
	Blackhawk	3.1 a	0.4 a
	Caleypea	2.4 a	0.3 a
	Dixie	2.5 a	0.3 a
	Hairy	2.7 a	0.4 a
	Rose	3.0 a	0.4 a
	Whistler	3.3 a	0.4 a

[†] Different letters within column and Depth are significant at $P = 0.05$.

Table 10. Effect of warm-season annual legumes on winter rye forage yield, N concentration, and C concentration harvested on Nov 30, Jan 18, Feb 6, Mar 1, and Apr 10 in the winter of 2011-2012.

Legume	Cut 1	Cut 2	Cut 3	Cut 4	Cut 5	Total
			t DM ha^{-1}			
Fallow	1.00 a[†]	2.18 a	0.93 a	1.25 a	7.37 a	12.72 a
Combine	0.78 a	2.10 a	1.06 a	1.52 a	7.72 a	13.19 a
Iron & Clay	0.78 a	1.89 a	1.03 a	1.35 a	7.08 a	12.12 a
Laredo	0.79 a	2.09 a	0.97 a	1.32 a	7.18 a	12.36 a
Vernal	0.86 a	2.19 a	0.93 a	1.32 a	7.46 a	12.75 a
Mungbean	0.64 a	1.80 a	1.03 a	1.46 a	7.24 a	12.17 a
			g N kg^{-1}			
Fallow	57.3 a	48.0 a	49.4 a	45.0 a	15.2 a	-----
Combine	55.9 abc	47.9 a	49.6 a	46.1 a	16.6 a	-----
Iron & Clay	55.5 bc	47.1 a	50.4 a	45.7 a	17.7 a	-----
Laredo	56.9 ab	47.6 a	48.7 a	45.0 a	15.2 a	-----
Vernal	56.9 ab	49.9 a	51.3 a	45.6 a	16.8 a	-----
Mungbean	54.6 c	48.2 a	50.5 a	45.1 a	16.6 a	-----
			g C kg^{-1}			
Fallow	435.0 c	448.9 a	447.2 a	452.6 a	425.5 a	-----
Combine	441.4 b	446.5 a	442.4 a	449.1 a	448.8 a	-----
Iron& Clay	444.0 ab	446.3 a	446.3 a	448.4 a	450.9 a	-----
Laredo	443.1 ab	447.8 a	443.1 a	451.2 a	451.6 a	-----
Vernal	440.1 bc	447.8 a	442.0 a	450.9 a	449.5 a	-----
Mungbean	446.6 a	452.7 a	449.2 a	450.5 a	451.0 a	-----

[†] Different letters within column and legume treatment are significant at $P = 0.05$ level.

3.5. Sorghum-Sudangrass Forage Production

Similar to rye, sorghum-sudangrass was largely unaffected by summer legume green manures. Initially, Iron-and-Clay cowpea treatments had increased sorghum-sudangrass stand counts (9.8 plants linear m^{-1}) over Vernal soybean (8.1 plants linear m^{-1}) or mungbean (7.1 plants linear m^{-1}) (**Table 11**); however, this stand difference did not translate into differences in forage yields. On June 12, sorghum-sudangrass was darker green in color ($P = 0.03$) following rye compared to winter fallow, suggesting a nutrient contribution (**Table 11**). Rye roots may have mined nutrients from deeper in the soil profile and released them in the upper soil layers as root material was mineralized. Root exudates from rye could have also stimulated microbial activity and thus increased mineralization of SOC and release of additional nutrients.

Cut three had a summer crop × winter crop interaction ($P = 0.02$) where a summer fallow-winter rye rotation increased sorghum-sudangrass yield (9.84 t

DM ha^{-1}) by 33% compared to a summer fallow-winter fallow rotation (7.38 t DM ha^{-1}) (**Table 12**). Following mungbean, winter rye decreased subsequent sorghum-sudangrass yield (9.71 t DM ha^{-1}) by 28% over winter fallow plots (7.01 t DM ha^{-1}). Increased sorghum-sudangrass forage yield following summer fallow-winter rye compared to summer fallow-winter fallow was surprising since rye utilized soil moisture and nutrients that were removed in forage biomass. Rye did contribute organic matter and likely some N through root production and mineralization, but amounts were much lower than N removed in aboveground forage. Yield decrease from mungbean-winter fallow to mungbean-winter rye was expected since crops generally experience a yield loss following another crop if additional fertilizer is not applied.

Cool-season legumes had minimal impact on sorghum-sudangrass. All CSLs, except for Blackhawk arrowleaf clover, increased ($P < 0.01$) the dark green color

Table 11. Effect of five warm-season legume green manure crops and a previous winter rye forage crop on unfertilized (N) sorghum-sudangrass plant stand, color, and height.

Summer	Winter	Stand	Color		Height	
Crop	Crop	5/25/2012	6/12/2012	6/12/2012	6/25/2012	7/13/2012
		plant lin m^{-1}			cm	
Fallow		8.4 a[†]	2.9 a	63.1 a	100.0 a	52.5 a
Combine		8.6 a	2.9 a	65.6 a	108.1 a	54.4 a
Iron & Clay		9.8 a	2.9 a	61.9 a	94.4 a	57.5 a
Laredo		8.2 a	2.9 a	61.9 a	98.1 a	56.9 a
Vernal		8.1 a	2.6 a	65.0 a	105.6 a	51.9 a
Mungbean		7.1 a	3.3 a	64.4 a	106.9 a	58.1 a
	Fallow	8.5 a	2.7 b	64.0 a	101.9 a	58.1 a
	Rye	8.2 a	3.1 a	63.3 a	102.5 a	52.3 a
Fallow	Fallow	8.6 a	2.8 b	63.8 a	100.0 a	56.3 a
	Rye	8.3 a	3.0 ab	62.5 a	100.0 a	48.8 a
Combine	Fallow	8.1 a	2.6 b	68.8 a	110.0 a	51.3 a
	Rye	9.1 a	3.1 ab	62.5 a	106.3 a	57.5 a
Iron & Clay	Fallow	10.1 a	2.5 b	61.3 a	91.3 a	65.0 a
	Rye	9.5 a	3.3 ab	62.5 a	97.5 a	50.0 a
Laredo	Fallow	7.9 a	3.0 ab	66.3 a	105.0 a	56.3 a
	Rye	8.5 a	2.8 b	57.5 a	91.3 a	57.5 a
Vernal	Fallow	8.6 a	2.4 b	65.0 a	108.8 a	58.8 a
	Rye	7.5 a	2.8 b	65.0 a	102.5 a	45.0 a
Mungbean	Fallow	7.8 a	2.8 b	58.8 a	96.3 a	61.3 a
	Rye	6.5 a	3.8 a	70.0 a	117.5 a	55.0 a

[†] Different letters within column are significant at $P = 0.05$ level.

Table 12. Effect of five warm-season legume green manure crops and a previous winter rye forage crop on unfertilized (N) sorghum-sudangrass forage yields.

Summer	Winter	Harvest Date			
Crop	Crop	6/25/2012	8/15/2012	9/25/2012	Total
		t DM ha^{-1}			
Fallow		2.53 a[†]	4.85 a	8.61 a	15.99 a
Combine		2.53 a	4.72 a	8.07 a	15.32 a
Iron & Clay		2.08 a	3.78 a	8.24 a	14.10 a
Laredo		1.97 a	4.41 a	7.66 a	14.04 a
Vernal		2.30 a	5.34 a	8.81 a	16.45 a
Mungbean		2.38 a	5.82 a	8.36 a	16.57 a
	Fallow	2.10 a	4.92 a	8.34 a	15.35 a
	Rye	2.50 a	4.72 a	8.25 a	15.47 a
Fallow	Fallow	2.28 a	4.84 a	7.38 cd	14.50 a
	Rye	2.79 a	4.86 a	9.84 a	17.49 a
Combine	Fallow	2.25 a	4.36 a	7.85 abcd	14.45 a
	Rye	2.82 a	5.08 a	8.30 abcd	16.19 a
Iron & Clay	Fallow	1.72 a	4.06 a	8.85 abcd	14.63 a
	Rye	2.44 a	3.51 a	7.63 bcd	13.57 a
Laredo	Fallow	1.90 a	5.49 a	8.09 abcd	15.47 a
	Rye	2.05 a	3.34 a	7.23 d	12.61 a
Vernal	Fallow	2.47 a	5.17 a	8.14 abcd	15.78 a
	Rye	2.14 a	5.50 a	9.47 abc	17.11 a
Mungbean	Fallow	1.96 a	5.61 a	9.71 ab	17.27 a
	Rye	2.80 a	6.04 a	7.01 d	15.86 a

[†] Different letters within column are significant at $P = 0.05$ level.

of sorghum-sudangrass over winter rye or winter fallow on June 12, which is consistent with N fertilization of forage crops (**Table 13**). Cool-season legumes had no effect on forage yield of cuts one or two; however, sorghum-sudangrass following winter rye yielded higher ($P = 0.05$) than any of the legume treatments for cut three, except for hairy vetch, which was not different (**Table 14**).

Cut three had a summer crop x winter crop interaction ($P = 0.02$). In this case, winter fallow rotation preceded by mungbean was 32% higher for sorghum-sudangrass yield (9.71 t DM ha^{-1}) compared to winter fallow plots preceded by summer fallow (7.38 t DM ha^{-1}). Strangely, the opposite was true in plots that received winter rye as a winter treatment. Under this rotation, fallow (9.84 t DM ha^{-1}) and Vernal soybean (9.47 t DM ha^{-1}) treatments yielded approximately 26% more forage than Laredo soybean (7.23 t DM ha^{-1}) or mungbean (7.01 t DM ha^{-1}) treatments. Summer fallow-winter rye and Vernal soybean-winter rye rotations had very low or no N contributions compared to mungbean, which contributed 167 kg N ha^{-1} to the soil the previous summer. Soil water usage by mungbean may have contributed to this yield depression as sorghum-sudangrass exhausted soil water supplies during the summer months. A winter rye crop may have prevented sufficient recharge of soil moisture over the winter months compared to winter fallow. Winter rye did not affect mungbean

Table 13. Effect of eight cool-season legume green manure crops on unfertilized (N) sorghum-sudangrass plant stand, color, and height.

Winter	Stand	Color	Height		
Crop	5/25/2012	6/12/2012	6/12/2012	6/25/2012	7/13/2012
	plant lin m^{-1}			cm	
Fallow	8.6 a[†]	2.8 c	63.8 a	100.0 a	56.3 a
Rye	8.3 a	3.0 c	62.5 a	100.0 a	48.8 a
Apache	4.6 a	4.9 a	63.8 a	103.8 a	51.3 a
AWP	6.8 a	4.9 a	76.3 a	133.8 a	53.8 a
Blackhawk	7.5 a	3.6 bc	68.8 a	111.3 a	52.5 a
Caleypea	6.6 a	4.9 a	68.8 a	111.3 a	60.0 a
Dixie	5.5 a	4.5 ab	68.8 a	125.0 a	57.5 a
Hairy	5.0 a	4.5 ab	72.5 a	122.5 a	51.3 a
Rose	6.3 a	4.3 ab	66.3 a	113.8 a	57.5 a
Whistler	7.3 a	4.6 a	72.5 a	115.0 a	56.3 a

[†] Different letters within column are significant at $P = 0.05$ level.

Table 14. Effect of eight cool-season legume green manure crops on unfertilized (N) sorghum-sudangrass forage yields.

Winter	Harvest Date			
Crop	6/25/2012	8/15/2012	9/25/2012	Total
		t DM ha^{-1}		
Fallow	2.28 a[†]	4.84 a	7.38 bc	14.50 a
Rye	2.79 a	4.86 a	9.84 a	17.49 a
Apache	3.52 a	2.97 a	8.13 bc	14.62 a
AWP	4.12 a	5.73 a	7.82 bc	17.95 a
Blackhawk	2.18 a	5.04 a	8.10 bc	15.33 a
Caleypea	3.54 a	5.15 a	7.36 bc	16.05 a
Dixie	3.67 a	5.92 a	7.12 c	16.70 a
Hairy	3.68 a	5.50 a	8.90 ab	18.09 a
Rose	3.57 a	6.37 a	7.76 bc	17.70 a
Whistler	4.07 a	5.11 a	8.20 bc	17.38 a

[†] Different letters within column are significant at $P = 0.05$ level.

residue decomposition. Thus, N mineralization and overall contribution of N to the soil by mungbean residue was the same regardless of winter treatment.

4. Conclusions

Commencing this study after killing a perennial, fertilized grass pasture created a scenario where a large SOC pool was tilled and subsequently mineralized, which released substantial amounts of N into the soil. Though some legumes produced large amounts of biomass with high N concentrations, this contribution had little to no effect on forage yields of winter rye or sorghum-sudangrass despite favorable growing conditions for winter rye and sorghum-sudangrass. In fact, sometimes the effect was negative due to depleted soil moisture prior to rye and sorghum-sudangrass growth and establishment.

Despite the effect of field history, some information from this study can enhance our knowledge of using green manures in East Texas. Warm-season legumes endured a severe drought and heavy deer browse in 2011. Under these conditions, mungbean proved to be the most superior legume with largest biomass yield (6.24 t DM ha^{-1}) and total N contribution to the soil (157 kg N ha^{-1}). Both cowpea varieties showed excellent drought tolerance as well yet had lower yields due to selective deer browsing. Despite its apparent advantages, mungbean depressed winter rye yields by 36% and N concentrations by 5% in cut one but had no effect on the four subsequent cuttings. This detriment can likely be attributed to depletion of soil water by mungbean compared to other WSLs. When WSLs were followed by winter fallow, mungbean increased sorghum-sudangrass forage yield on cut three compared to plots left fallow year-round. However, the opposite was true for mungbean followed by winter rye instead of winter fallow.

Favorable weather conditions in winter of 2011-2012 led to optimum growth of CSLs. Austrian winter pea outperformed other CSLs by producing an estimated 310 kg N ha^{-1}. Still, cool-season legume green manures had limited impact on sorghum-sudangrass forage yields. Soil moisture was not limiting for sorghum-sudangrass following CSLs since soil water was near field capacity at the time of spring incorporation. Certain WSLs (mungbean, Iron-and-Clay cowpea, and Combine cowpea) showed short term improvement in SOC and soil N, but effects were less after eight months. Winter rye proved superior in enhancing SOC over CSLs after one season; however, approximately 682 kg C ha^{-1} still remained in Dixie crimson clover residue 23 weeks after incorporation and might improve long term SOC levels if included in rotations regularly.

Overall, no rotation appeared to outperform another in total forage yield production. However, on intensively cropped agricultural land with limited N, Austrian winter pea would clearly be superior in total N production over all other legumes included in this experiment. Warm-season legumes, such as mungbean, can potentially produce substantial amounts of N to supplement forage crop requirements, but these crops create more production risk because of less dependable summer rainfall and moisture competition.

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Conflicts of Interest

All authors declare no conflicts of interest regarding the publication of this paper.

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