Journal of Environmental Protection, 2010, 1, 73-84
doi:10.4236/jep.2010.12010 Published Online June 2010 (http://www.SciRP.org/journal/jep)

Growing Cover Crops to Improve Biomass Accumulation and Carbon Sequestration: A Phytotron Study

Qingren Wang[1,2*], Yuncong Li[1,2], Ashok Alva[3]

[1]Tropical Research and Education Center, Homestead, USA; [2]Department of Soil and Water Science, University of Florida, Gainesville, USA; [3]USDA, ARS, Vegetable and Forage Crops Research, Prosser, USA.
Email: qrwang@ufl.edu

Received March 10th, 2010; revised April 13th, 2010; accepted April 14th, 2010.

ABSTRACT

Cover crop system has shown a potential approach to improving carbon sequestration and environmental quality. Six of each winter and summer cover crops were subsequently grown in two soils, Krome gravelly loam soil (KGL), and Quincy fine sandy soil (QFS), in phytotrons at 3 *temperatures* (10/20, 15/25, 25/30°C *for winter/summer cover crops*) *to investigate their contributions for carbon* (*C*) *sequestration. Among winter cover crops, the highest and the lowest amounts of C accumulated were by bellbean* (*Vicia faba L.*), 597 g/m^2 *and white clover* (*Trifolium repens*), 149 g/m^2, *respectively, in the QFS soil. Among summer cover crops, sunn hemp* (*Crotalaria juncea L.*) *accumulated the largest quantity of C* (481 g/m^2), *while that by castorbean (Ricinus communis*) *was* 102 g/m^2 *at* 30°C *in the KGL soil. The mean net C remained in the residues following the* 127 d *decomposition were* 187 g/m^2 *of C* (73% *of the total*) *and* 91 g/m^2 (52% *of the total*) *for the winter and summer cover crops, respectively. Following a whole cycle of winter and summer cover crops grown, the mean soil organic C* (*SOC*) *increased by* 13.8 *and* 39.1% *in the KGL and QFS soil, respectively, compared to the respective soils before. The results suggest that triticale, ryegrass, and bellbean are the promising winter cover crops in the QFS soil, while sunn hemp, velvetbean* (*Mucuna pruriens*), *and sorghum sudangrass* (*Sorghum bicolor* × *S. bicolor*) *are recommended summer cover crops for both soils under favorable temperatures.*

Keywords: *Carbon to Nitrogen Ratio* (*C:N*), *Greenhouse Gas* (*GHG*), *Krome Gravelly Loam* (*KGL*), *Quincy Fine Sand* (*QFS*), *Soil Organic Carbon* (*SOC*)

1. Introduction

Soil carbon (C) sequestration by terrestrial vegetation, as one of the main approaches for greenhouse gas (GHG) mitigation, has long been identified by the Intergovernmental Panel on Climate Change [1]. Terrestrial ecosystems associated with land use and soil management play an important role in the global C budget [2]. For example, the current global terrestrial sink for C is estimated to hold 550-700 Pg of C in vegetation and 1200-1600 Pg in soil organic matter [3]. Soil is the largest terrestrial C pool, constitutes at 2500 Pg of total C (organic and inorganic) within one meter depth [4]. This soil C pool is approximately two-thirds of the total C in ecosystems [5]. The former is about 3.3-fold greater than the atmospheric C pool (760 Pg), and 4.5-fold greater than the biotic C pool (560 Pg) [6]. In addition, soil organic carbon (SOC) pools have the slowest turnover rates in general terrestrial ecosystems [7], therefore C sequestrated in soils has a great potential to mitigate CO_2 emission to the atmosphere [3].

Increased fixation of atmospheric CO_2 with terrestrial vegetation, and in turn, contributing to enhanced SOC leads to a reduction in GHS emissions and related negative effects on the environment. However, the efficiency of C sequestration by various vegetations differs largely as influenced by differences in their physiological characteristics, growth rates, biomass accumulation rates, etc., and by many environmental factors, such as the soil type, temperature, etc.

Maximizing biomass production by optimizing input use is a major goal in agro-ecosystems. Conversion of plant sequestered C to SOC is important since the latter is very stable with long residence time, *i.e.*, hundreds and even thousands of years [8]. Agricultural soils under ap-

propriate management can contain substantial amounts of soil C in the forms of soil organic matter (SOM). Excluding carbonated rocks, soils constitute the largest surface C pool, approximately 1500 Gt, which is equivalent to almost three fold greater than the quantity stored in the terrestrial biomass and twice the amount stored in the atmosphere [9].

Cover crops provide an effective practice to enhance SOC [10-13] in addition to their role in improving soil and water conservation [14]. Cover crops can also enhance soil fertility and productivity for a sustainable agricultural production [15,16]. A linear relationship has been reported between the amount of C sequestered in the soil and C input as plant biomass or residues by a number of researchers [17-19]. Removal of cover crop tops from the soil greatly decreased soil C [20]. The growth rates and amounts of cover crop biomass as well as sequestered CO_2 C differed among different cover crop species and environmental factors [3].

In a wide range of agroclimatic regions, winter cover crops are generally grown during fall through spring. Summer cover crops facilitate conserving soil and water during the rainy summer season, improving soil fertility, leading to increased yields and quality of the subsequent cash crops [14-16,21]. In Canadian prairies, growing summer cover crops instead of fallow sequestered approximately 1.5 Tg CO_2 per year from the atmosphere [22].

To improve C sequestration efficiency, plant sequestered C in organic forms need to be transferred to stable forms, such as recalcitrant SOC via humification or carbonization processes. The stability of organic C in plant residues or in soil depends on the cover crop species used in the production system in addition to effects of environmental factors, including soil type, temperature, and moisture. Organic C in plants comprises active and inactive components, which also refer to as labile and recalcitrant pools [23]. The active organic C consists of four fractions; *i.e.*, decomposable organic C, resistant organic C, microbial biomass organic C and humified organic C [24]. The relative distribution of organic C in the above fractions depends on the physiological and chemical characteristics of plant residues, *i.e.*, C:N ratio and lignin content. Most of the previous studies on the role of cover crops on C sequestration or SOC accumulation are exclusively related to agricultural practices: such as tillage, cropping systems, crop rotation, land use or shifting cultivation, fertilization, etc. [9,12,13,19,20,25,26]. Information is lacking on the influence of different cover crop species on the efficacy of soil C sequestration. In addition, it is hard if it is not impossible to evaluate both winter and summer cover crops under filed conditions. Therefore, the objective of the current research was, under the controlled environment, to elucidate effects of soil and temperature conditions on the quantities of C accumulation, biomass production, mineralization rates and efficiency of C sequestration among different winter and summer cover crops typically grown in the temperate and subtropical regions.

2. Materials and Methods

2.1 Soils and Cover Crops

A Krome gravelly loam (KGL) soil (*loamy-skeletal, carbonatic, hyperthermic Lithic Udorthents*) from Miami Dade County, FL, and a Quincy fine sandy soil (mixed, mesic Xeric Torripsamments) from Benton County, WA, were used in this study. Some characteristics of the above soils are shown in **Table 1**. The above soils sampled at 0-15 cm depth were sieved to remove large rocks and plant residues. Plastic pots, 25 cm diameter, 23 cm high, 11.3 liters in volume with a capacity of 8 kg soil per pot, were used. Six each winter and summer cover crops, including three each legumes and nonlegumes were evaluated.

The winter cover crops used in the experiment were in the order of: triticale (*Triticale hexaploide* Lart.), ryegrass (*Lolium perenne* ssp. Multiflorum), mustard (*Brassica juncea*, ssp. Indian gold), bell beans (*Vicia faba* L.), purple vetch (*Vicia benghalensis* L.), and white clover (*Trifolium repens*). The summer cover crops included in the order of: sorghum sudangrass [*Sorghum bicolor* × *S. bicolor* var. *sudanense* (Piper) Stapf.], okra (*Abelmoschus esculentus* L.), castor bean (*Ricinus communis*), sunn hemp (*Crotalaria juncea* L. cv. Tropic Sun), velvetbean [*Mucuna pruriens* var. utilis (Wall. ex Wright) Baker ex Burck], and cowpea (*Vigna unguiculata* L., cv. Iron Clay).

Table 1. Selected characteristics of the two soils used in this study

	pH[†] (water)	EC[‡] (μS/cm)	Organic C (g/kg)	$CaCO_3$ equivalent (g/kg)	Total N (g/kg)	Total P (g/kg)	KCl extractable	
							NH_4-N (mg/kg)	NO_3-N (mg/kg)
KGL soil[±]	7.8	148.0	14.2	571.7	0.69	0.26	26.3	8.1
QFS soil	7.6	78.8	2.1	ND[≠]	0.01	0.12	31.7	6.6

[†]Soil pH was measured in a ratio of 1:2.5 (soil: water).
[‡]Soil electrical conductivity (EC) was measured in a ratio of 1:2 (soil: water).
[±]KGL = Krome gravelly loam, and QFS = Quincy fine sand.
[≠]ND: not detected.

2.2 Experimental Design, Phytotron Setup and Management

A nested factorial design was adopted with temperature as a main factor, soil types and 6 cover crop species (for either winter or summer cover crops) were nested as sub-factors. The experiment was conducted in three individual phytotrons (Conviron 8601, Conviron Products Company, Winnipeg, Canada) to simulate different temperatures but kept other parameters, e.g., light intensity, relative humidity and day length, etc. the same to reproduce the growth conditions for the winter and summer cover crops with a respective fallow. For winter cover crops (November 20th, 2007 through March 7th, 2008), temperatures were: 10/8, 15/10, and 20/15°C (day/night, d/n), following the seed germination at 20°C across all 3 treatments above. Light intensity was gradually increased or decreased 40% per hour with ramp procedure with 10 h day length. The light intensity was 0.294×10^3 μmol s^{-1} m^{-2}, calibrated by a light intensity sensor (LI-COR, Quantum with LI-1000 datalogger), and relative humidity of 50/75% (d/n).

The temperatures for summer cover crops (April 9th through June 25th, 2008) were 20/15, 25/20, and 30/25°C (d/n), the day length of 14 h. Light intensity was same as that used for the winter cover crops, with relative humidity of 75/85% (d/n). Plant density was 10 per pot for okra, bellbean, purple vetch, sorghum sudangrass and sunn hemp; 30 for white clover, ryegrass and triticale; while 3 -5 per pot for castor bean, velvetbean, mustard and cowpea. Three gram of fertilizer (10 N-4.3 P-8.3 K) was applied per pot. No inoculation was applied to legumes. All plants were irrigated through drip line to adjust a flow rate of 2 L/h, the frequency and duration were determined based on plant growth stages for quantities of water required.

With a separate experiment, cover crop decomposition rates were preliminarily evaluated in an extra phytotron with the single (KGL) soil individually for both winter and summer cover crops. In this experiment, the same cover crop species as in the previous study were grown and harvested at the same temperature in the same (KGL) soil, the aboveground biomass was cut into approximately 1-cm pieces, the fresh weight and moisture content were determined with subsamples and those subsamples were also used for chemical analysis. The certain amount of fresh cover crop residues was evenly distributed on the soil surface of the same pot used for respective cover crop growth. Residue surface application instead of soil incorporation was to extend the residue residence time in a similar field approach of no tillage practice. Water content of the soil was maintained at 75% of the field capacity for the respective soil by weighing the pots once a week. Temperatures maintained at 15°C for winter and 25°C for summer cover crops, and the same lighting conditions that described above for the winter and summer cover crop growth studies were adapted. At the end of 127 d mineralization study, the remaining plant residues were carefully removed from each pot, dried and weighed, and subsamples were taken again for chemical analysis. The mass weight loss of plant residues due to decomposition was calculated based on the difference between the amount of residues applied and the amount remained after decomposition. The total amount of C decomposed was calculated based on the residue weight loss and the residue C concentrations determined in the subsamples. The concentrations of SOC and total N were determined before and after the decomposition experiment.

2.3 Sampling and Chemical Analysis

Soil samples were collected from the center of each pot at 0-10 cm depth prior to and one month after cover crop growth. Soil samples were air dried and ground to pass through a < 1 mm mesh sieve for chemical analysis. The experiment was terminated at the time when any one of these cover crops was flowering, which was about 90 days for both winter and summer cover crops under the experimental conditions. The aboveground plant biomass was harvested, and fresh and dry weights (at 75°C for 7 d) of biomass were recorded. A subsample of the aboveground biomass was ground to pass through a < 0.5 mm mesh sieve for chemical analysis.

Total C and nitrogen (N) contents in the soil and cover crops were analyzed using CNS Auto-analyzer (Vario Max Elementar, Hanau, Germany). Soil inorganic C was determined via pressure calcimeter method and the organic C was calculated by subtracting the inorganic C from the total C [27].

2.4 Statistical Analysis of the Data

The data were subjected to analysis of variance (ANOVA) using SAS [28] with nested design and a general linear model. For the ANOVA with the nested design in the experiment, three different error structures were conducted to compare mean squares of different sources of variation. The main factor was tested against the main factor error, where the sub-treatment was tested against the interaction of replicates (or block) × sub-treatment and the interaction between the main factor and the sub-factor were tested against the sub-factor error [29]. Further analysis was conducted for each individual factor to separate means with the single factor or combination of the factors for the interaction effects using Duncan test at $p = 0.05$, as needed.

3. Results and Discussion

3.1 Cover Crop Biomass, and C and N Contents

Total C and N as well as biomass production of both winter and summer cover crops were significantly influ-

enced by cover crop species and growth temperatures (**Table 2**). The soil type had no significant influence on the above parameters for the summer cover crops, while in the case of winter cover crops, it significantly influenced the biomass production and the total N. Also, significant interaction effects were found for temp × crop for both winter and summer cover crops on total C and N, and soil × crop for winter cover crops for all three evaluation parameters.

Result implies that soil types have strong influence on the biomass production and total quantity of N accumulation for the winter cover crops rather than the summer cover crops. The growth temperatures rather than soil types influence the biomass production and the C:N ratio for the summer cover crops rather than the winter cover crops and a significant interaction effect (temp × crop) occurred.

3.2 Total C in Aboveground Biomass

Winter cover crops: Total C in the aboveground biomass varied among the winter cover crops (**Table 3**). In the QFS soil, total biomass C (mean across all temperatures) was greater in bellbean as compared to that in the remaining species, except triticale. In the KGL soil, total biomass C decreased in the order: triticale > ryegrass > bellbean = mustard = purple vetch = white clover. Overall biomass total C was significantly greater in the QFS soil as compared to that in the KGL soil for all cover

Table 2. Analysis of variance (ANOVA) for biomass production and total biomass C and N for winter and summer cover crops

	df	*F*-value			
		Carbon	Nitrogen	Biomass	C:N ratio
			Winter cover crop		
Temperature (Temp)	2	14.08^{*}	8.83^{*}	38.91^{**}	38.91^{**}
Soil	1	3.24^{NS}	217.16^{**}	50.94^{*}	50.94^{*}
Cover crop (Crop)	5	41.10^{***}	49.76^{***}	23.19^{***}	23.19^{***}
Temp × Soil	2	2.90^{NS}	3.31^{NS}	4.72^{NS}	4.72^{NS}
Temp × Crop	10	16.95^{***}	5.34^{***}	2.07^{NS}	2.07^{NS}
Soil × Crop	5	6.26^{**}	113.77^{***}	14.42^{**}	14.42^{***}
Temp × Soil × Crop	10	1.35^{NS}	6.11^{***}	4.46^{**}	4.46^{**}
			Summer cover crop		
Temperature (Temp)	2	9.31^{*}	10.90^{*}	10.45^{*}	0.89^{NS}
Soil	1	2.06^{NS}	0.72^{NS}	2.10^{NS}	521.69^{**}
Cover crop (Crop)	5	17.45^{***}	17.96^{***}	16.89^{***}	90.94^{***}
Temp × Soil	2	2.49^{NS}	0.90^{NS}	2.60^{NS}	1.03^{NS}
Temp × Crop	10	5.28^{***}	3.40^{**}	5.27^{***}	4.60^{**}
Soil × Crop	5	0.75^{NS}	2.21^{NS}	0.79^{NS}	6.75^{**}
Temp × Soil × Crop	10	2.12^{NS}	2.89^{*}	2.02^{NS}	5.41^{**}

*Significant at $p \leq 0.05$; ** significant at $p \leq 0.01$; *** significant at $p \leq 0.001$; and NS: no significant difference at $p \leq 0.05$.

Table 3. Total C (g/m^2) in aboveground biomass of winter cover crops

Soil[†]	Temp	Triticale	Ryegrass	Bellbean	Mustard	Purple vetch	White clover
QFS soil	25ºC	369^{b*}	342^{b}	597^{a}	247^{bc}	378^{b}	149^{c}
	15ºC	411^{a}	393^{a}	418^{a}	390^{a}	282^{ab}	139^{b}
	10ºC	384^{a}	297^{b}	291^{b}	261^{bc}	194^{c}	80^{d}
KGL soil	25ºC	266^{a}	228^{ab}	161^{b}	160^{b}	144^{b}	232^{ab}
	15ºC	317^{a}	260^{ab}	233^{bc}	179^{cd}	132^{d}	139^{d}
	10ºC	303^{a}	267^{a}	169^{b}	168^{b}	183^{b}	80^{c}
Means							
QFS soil		388^{Aab}	344^{Abc}	435^{Aa}	299^{Ac}	285^{Ac}	122^{Ad}
KGL soil		295^{Ba}	252^{Bb}	188^{Bc}	169^{Bc}	153^{Bc}	150^{Ac}
	25ºC	317^{Aab}	285^{Aab}	379^{Aa}	204^{Ab}	261^{Aab}	191^{Ab}
	15ºC	364^{Aa}	326^{Aa}	326^{ABa}	284^{Aab}	207^{Abc}	139^{Bc}
	10ºC	344^{Aa}	282^{Ab}	230^{Bc}	214^{Ac}	189^{Ac}	80^{Cd}

[†]KGL= Krome gravelly loam; and QFS = Quincy fine sand.
[*]Values followed by different letter (s), lower case within the same row, and upper case within the same column of a subset (either the soil or temperature), represent significant difference at $p \leq 0.05$.

crops except white clover. Temperature effect was significant only in bell bean and white clover species. The greatest amount of biomass C (597 g/m^2) was obtained in bellbean grown in the QFS soil at 25^{o}C. At 10^{o}C in the QFS soil, biomass C was greater by triticale than that by the other cover crops. In the KGL soil at 25^{o}C, the biomass C was greater in triticale than that in either purple vetch, mustard or bellbean. At 15 and 10^{o}C, the biomass C in triticale and ryegrass were greater than that in the remaining cover crops.

Summer cover crops: In the QFS soil at 30^{o}C, biomass C in sunn hemp was significantly greater that by castorbean, okra, and cowpea (**Table 4**). At 25^{o}C, sunn hemp biomass C was significantly greater than that by the remaining five cover crops. At 20^{o}C, cowpea biomass C was significantly lower than that by the other cover crops. Similarly, in the KGL soil, the relative ranking of biomass C response among the six cover crop species was different at different temperatures. Soil type influence (mean across all temperatures) was significant on biomass C only in sorghum sudangrass. Biomass total C was significantly greater at 30^{o}C as compared to that at either 20 or 25^{o}C for sunn hemp, velvetbean, and sorghum sudangrass. In general, biomass C accumulation was greater in the winter than in the summer cover crops under the experiment conditions (**Tables 3** and **4**).

3.3 Aboveground Biomass and Total N in Various Cover Crops

The aboveground biomass and total N response followed somewhat similar pattern as total C accumulation among various cover crops (**Table 5**). The mean biomass production and total N of winter cover crops were generally greater in the QFS than those in the KGL soil. No significant difference was observed between these two soils for summer cover crop biomass and/or total N but these summer cover crops accumulated more biomass and N at high temperature than at low temperature. This result has confirmed that the soil type had greater influence on the growth and accumulation by the winter cover crops. Temperature appeared to have a dominant influence on the above response variables of the summer cover crops. Among the summer cover crops, sunn hemp produced the greatest amount of biomass (**Table 5**), equivalent to 11 Mg ha^{-1} at 30^{o}C. This agrees with results of our parallel field studies [21,30], which showed 15-20 Mg ha^{-1} of aboveground biomass by sunn hemp.

Nitrogen under some growth conditions is a dominant factor to limit the biomass production and C accumulation. Therefore, legume cover crops, by virtue of their ability to fix atmospheric N, can overcome this limitation, thus are able to produce greater amount of biomass as compared to that by nonlegume cover crops [12,30]. Some winter cover crops, such as bellbean and purple vetch, accumulated 30-35 g/m^2 of N under the optimal conditions (25^{o}C) in the QFS soil (**Table 5**). All winter cover crops, except white clover, accumulated greater amount of N while grown on the QFS soil than that on the KGL soil. A similar trend was also observed with respect to accumulation of organic C (**Table 3**).

Table 4. Total C (g/m^2) in aboveground biomass of summer cover crops

Soil[†]	Temp	Sunn hemp	Velvetbean	Castorbean	Sorghum sudangrass	Cowpea	Okra
QFS soil	30^{o}C	480^{a*}	264^{ab}	164^{b}	347^{ab}	146^{b}	157^{b}
	25^{o}C	365^{a}	170^{b}	102^{b}	137^{b}	75^{b}	133^{b}
	20^{o}C	178^{a}	114^{ab}	137^{ab}	183^{a}	44^{b}	117^{ab}
KGL soil	30^{o}C	481^{a}	376^{a}	102^{b}	164^{b}	121^{b}	126^{b}
	25^{o}C	157^{a}	147^{a}	43^{b}	113^{ab}	81^{ab}	90^{ab}
	20^{o}C	183^{a}	160^{a}	45^{b}	130^{a}	33^{b}	198^{a}
Means							
QFS soil		338^{Aa}	183^{Abc}	134^{Abc}	222^{Ab}	89^{Ac}	136^{Abc}
KGL soil		274^{Aa}	228^{Aa}	63^{Ab}	136^{Bb}	78^{Ab}	138^{Ab}
	30^{o}C	481^{Aa}	320^{Ab}	133^{Ac}	255^{Abc}	134^{Ac}	142^{Ac}
	25^{o}C	257^{Ba}	159^{Bb}	72^{Ac}	125^{Bbc}	78^{ABbc}	112^{Abc}
	20^{o}C	181^{Ba}	137^{Bab}	91^{Abc}	157^{Bab}	39^{Bc}	157^{Aab}

[†]KGL= Krome gravelly loam; and QFS = Quincy fine sand.
[*]Values followed by different letter (s), lower case within the same row, and upper case within the same column of a subset (either the soil or temperature), represent significant difference at $p \leq 0.05$.

Table 5. Total aboveground biomass and N (g/m^2) in winter and summer cover crops

		25°C/30°C[†]		15°C/25°C		10°C/20°C	
		QFS[≠]	KGL	QFS	KGL	QFS	KGL
Winter cover crops							
Biomass	TC[±]	917^{b‡}	640^{a}	982^{a}	736^{a}	907^{a}	709^{a}
(g/m^2)	RG	880^{b}	571^{ab}	980^{a}	577^{ab}	7287^{b}	640^{b}
	BB	1392^{a}	402^{bc}	974^{a}	546^{b}	705^{b}	414^{b}
	MT	607^{bc}	424^{abc}	970^{a}	442^{bc}	630^{bc}	422^{b}
	PV	903^{b}	326^{cd}	691^{ab}	326^{cd}	495^{cd}	428^{b}
	WC	485^{c}	587^{ab}	387^{b}	359^{c}	347^{d}	220^{c}
N (g/m^2)	TC	9^{b}	4^{b}	7^{c}	5^{b}	9^{a}	9^{a}
	RG	15^{b}	5^{b}	8^{bc}	5^{b}	9^{a}	6^{a}
	BB	35^{a}	6^{b}	24^{a}	6^{ab}	10^{a}	8^{a}
	MT	7^{b}	5^{b}	10^{bc}	5^{b}	8^{a}	6^{a}
	PV	30^{a}	5^{b}	18^{ab}	3^{b}	12^{a}	8^{a}
	WC	10^{b}	17^{a}	10^{bc}	9^{a}	6^{a}	6^{a}
Summer cover crops							
Biomass	SH	1131^{a}	1111^{a}	834^{a}	368^{a}	427^{a}	432^{ab}
(g/m^2)	VB	615^{ab}	885^{a}	397^{b}	335^{a}	274^{ab}	369^{ab}
	CB	391^{b}	249^{b}	247^{b}	106^{b}	334^{ab}	110^{c}
	SS	802^{ab}	395^{b}	331^{b}	267^{ab}	431^{a}	307^{b}
	CP	353^{b}	302^{b}	180^{b}	191^{ab}	108^{b}	77^{c}
	OK	401^{b}	331^{b}	338^{b}	227^{ab}	286^{ab}	502^{a}
N (g/m^2)	SH	17^{a}	21^{a}	12^{a}	8^{ab}	5^{a}	10^{a}
	VB	11^{ab}	21^{a}	9^{ab}	12^{a}	4^{ab}	8^{a}
	CB	4^{b}	2^{b}	2^{c}	1^{b}	3^{ab}	2^{b}
	SS	3^{b}	4^{b}	3^{bc}	2^{b}	3^{ab}	4^{b}
	CP	6^{b}	5^{b}	4^{bc}	5^{b}	1^{b}	2^{b}
	OK	5^{b}	3^{b}	3^{bc}	2^{b}	2^{b}	4^{b}

[†]The first temperature was for winter and the second for summer cover crops.
[±]TC: triticale, RG: ryegrass, BB: bellbean, MT: mustard, PV: purple vetch, WC: white clover, SH: sunn hemp, VB: velvetbean, CB: castorbean, SS: sorghum sudangrass, CP: cowpea, and OK: okra.
[‡]Values followed by different letters within the same column of a subset (by winter or summer cover s and by each response parameter) represent significant difference at $P \leq 0.05$.

3.4 Concentrations of C and N in Cover Crop Biomass

Among the winter cover crops, C concentration was significantly lower in white clover (36%) as compared to that in the remaining five winter cover crops (40-43%) (**Figure 1**). Biomass N concentrations were in the range of 1.8-2.5% for legumes, which was significantly greater than the range of 0.9-1.1% for the nonlegumes. The C:N ratio varied from 13.9 (white clover) to 52.4 (triticale) among these six winter cover crops. The mean C concentration as well as C:N ratio across all winter cover crops were greater for the KGL than those for the QFS soil, while the converse was observed for N concentrations. The temperature effect was not significant on concentrations of C and N across all winter cover crops and soil types but the C:N ratio was significantly lower at 10°C than that at other temperatures (**Figure 1**).

The C concentrations in the summer cover crop biomass were significantly greater for sunn hemp, velvetbean, sorghum sudangrass and cowpea followed by castorbean and okra (**Figure 2**). The N concentration was the greatest for velvetbean, while the lowest for sorghum sudangrass. As a result, the C:N ratio followed the pattern: sorghum sudangrass > castorbean = okra > sunn hemp = velvetbean = cowpea. Overall, there was no significant difference found between soil types for the C concentration but plants grown in KGL soil had a greater N concentration than those in the QFS soil, which resulted in a greater C:N ratio of plant biomass in the latter than that in the former soil. The temperature effect was non-significant on the biomass C and N contents as well as C:N ratio. This result agrees well with the previous studies. For instance, the C concentrations in various winter cover crops remained constant but the N concentrations differed greatly between legume and nolegume cover corps, which resulted in a large variation in C:N ratio in different cover crop biomass [11,32].

3.5 Residue Decomposition and C Sequestered

The rate of decomposition of crop residues over 127-d under similar conditions as those adapted during the respective cover crop growth period varied among both winter and summer cover crops. The total C remained in the soil following 127 d of decomposition varied from 53 to 79% and 18-58% of total C accumulated in the respective winter and summer cover corps (**Table 6**). This agrees with the reports of Dossa *et al*. [33], *i.e.* 59-81% of the C added as shrub residue was mineralized in 118 d.

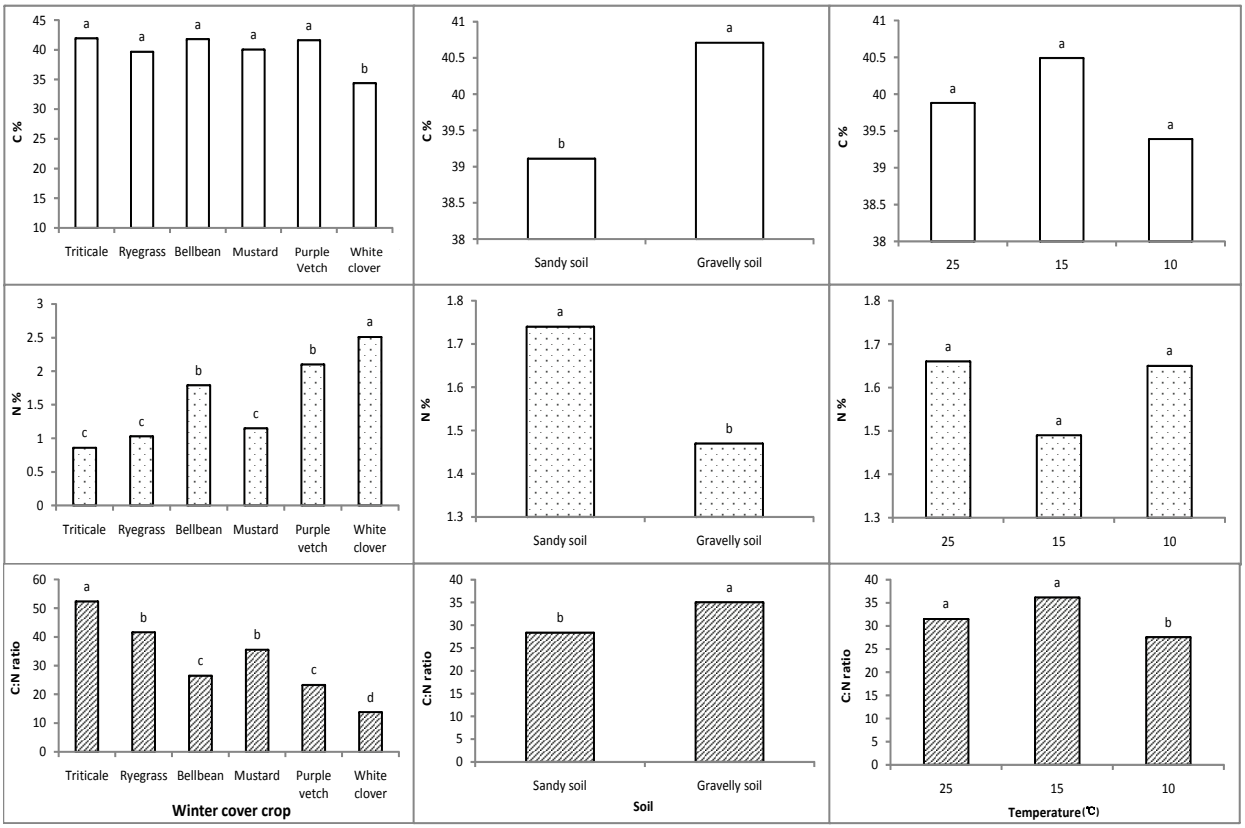

Figure 1. Concentrations of C, N and C:N ratio in winter cover crop biomass

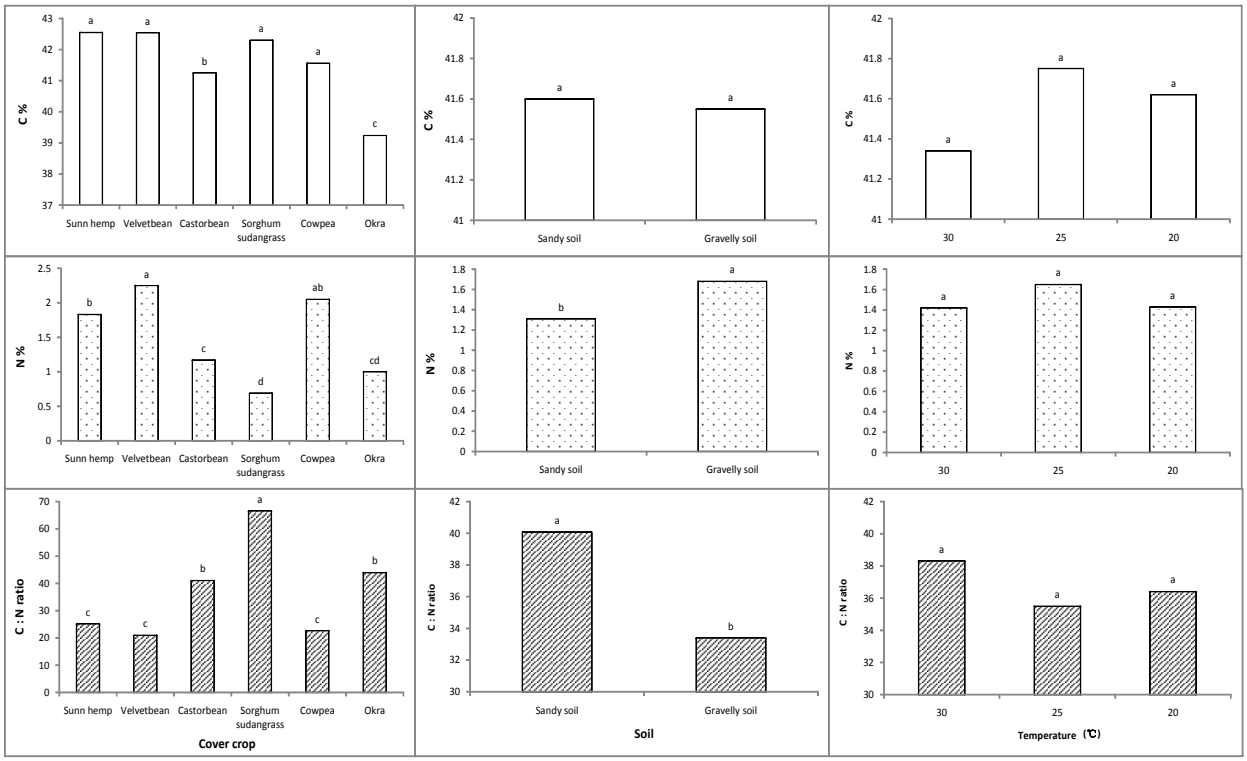

Figure 2. Concentrations of C, N and C:N ratio in summer cover crop biomass

Table 6. Carbon accumulation in cover crop aboveground biomass and that retained in the soil following 127-d decomposition

Cover crop	Total C input (g/m^2)	Total C decomposed (g/m^2)	Amount of C left in residues (g/m^2)	% of C retained in residues
Winter cover crops				
Triticale	341.6[a*]	75.4[a]	266.2[a]	78[a]
Ryegrass	292.2[a]	62.6[ab]	229.7[a]	79[a]
Bellbean	311.4[a]	79.0[a]	232.5[a]	75[a]
Mustard	234.2[ab]	55.8[b]	178.4[b]	76[a]
Purple vetch	218.9[b]	74.8[a]	144.1[bc]	66[b]
White clover	136.1[c]	64.3[ab]	71.8[c]	53[c]
Mean	**255.7**	**68.7**	**187.1**	**73**
Summer cover crops				
Sunn hemp	305.9[a]	127.4[a]	178.5[a]	58[ab]
Velvetbean	205.2[ab]	98.1[ab]	107.1[b]	52[b]
Castorbean	98.8[c]	28.1[c]	70.7[c]	72[a]
Sorghum sudangrass	179.1[ab]	78.5[b]	100.6[b]	56[ab]
Cowpea	83.4[c]	68.4[b]	15.0[d]	18[c]
Okra	137.0[bc]	61.7[b]	75.3[bc]	55[b]
Mean	**168.2**	**76.6**	**91.2**	**52**

[*]Values followed by different letter (s) within the same column of a subset (winter or summer cover crops) represent significant difference at $p \leq 0.05$.

Among the winter cover crops, total C input as well as the amount of C left in the residues after decomposition were greater for triticale, ryegrass and bellbean than that by the remaining three cover crop species (**Table 6**). White clover ranked the lowest for both parameters although its amount of leftover was not significantly different from purple vetch. Among the summer cover crops, sunn hemp ranked the highest and cowpea the lowest for the total C left in the residues. The percent of C retained in the residues was significantly greater by castorbean, sunn hemp and sorghum sudangrass than that by cowpea. Percent of C retained in the soil was greater for castorbean (72%) as compared to that for velvetbean, okra and cowpea (**Table 6**).

The N concentration associated with C:N ratio is often an important factor to determine the biomass quality [34-36] and biomass decomposition [11,13,33,37-39], which is closely related to the C sequestration efficiency. The current study showed that the decomposition rate (**Table 6**) is related to the N concentration or the C:N ratio, as in the cases of sunn hemp and velvetbean compared to castorbean or of bellbean and purple vetch compared to mustard with various C:N ratios (**Figure 1** and **2**). The quantities of C decomposed following 127 d were quite high for both triticale and sorghum sudangrass (**Table 6**), which had high C:N ratios, 52 and 67, respectively. Therefore, the biomass C:N ratio is an important trait of biomass quality that influences decomposition rate. In addition, some biochemical properties, such as lignin, polyphenolic and tannin contents also influence residue decomposition rate [38].

3.6 Soil Organic Carbon Changes with Cover Crops and Temperatures

After winter cover crops grown, concentrations of SOC in either the QFS or the KGL soil showed no significant difference regardless of different cover crops grown in comparison with fallow (data not shown). After summer cover crops grown, compared to fallow, no any significant change in SOC was observed in the QFS soil at all temperatures, and it seemed hardly to observe such a change in the KGL soil due to a considerable fluctuation even the concentration of SOC in one treatment was significantly greater than that in the other (**Table 7**). Short duration of cover crop growth approved to have very little influence on the SOC changes in the soil. However, since the winter cover crop residues were returned to the soil (soil surface applied) and subsequently the summer cover crops were grown, the SOC at the termination of summer cover crop growth showed some changes among the cover crop species though such changes were fluctuated and not significant. Therefore, a long term trial is needed to monitor SOC changes with cover crops in the agricultural system. The fluctuation changes in SOC have been observed by other researchers [13]. Our results agree with that of Lal [2] who concluded that the use of cover crops as a short-term green manure may not necessarily enhance the SOC pool.

However, increases of SOC occurred after cover crops grown as compared to the respective soils before the experiment. For instance, the SOC content (mean across all winter cover crops and temperatures) increased by 0.9 and 4.8% in the KGL and QFS soils, respectively, as compared to the respective soils prior to the experiment. The increases in the SOC content following the growth of the summer cover crops vs. winter cover crops were 13.7 and 25.9% for the respective soils. The corresponding increases after the summer cover crops (including winter cover crop residues returned to the soil) compared to the SOC prior to the experiment were 13.8 and 31.9% (**Table 8**). The SOC content of the QFS soil was signifi-

Table 7. Concentrations of SOC (g/kg) after summer cover crops grown in different soils at various temperatures

Soil†	Temp	Sunn hemp	Velvetbean	Castorbean	Sorghum sudangrass	Cowpea	Okra	Fallow
QFS soil	30°C	3.1^{a*}	3.3^{a}	3.3^{a}	2.7^{a}	3.4^{a}	2.2^{a}	2.3^{a}
	25°C	2.4^{a}	2.2^{a}	2.9^{a}	2.7^{a}	2.9^{a}	2.6^{a}	2.0^{a}
	20°C	2.9^{a}	3.1^{a}	1.9^{a}	4.2^{a}	2.7^{a}	2.8^{a}	2.7^{a}
KGL soil	30°C	21.9^{a}	12.6^{c}	12.8^{c}	15.2^{bc}	23.0^{a}	13.5^{c}	21.2^{ab}
	25°C	13.4^{b}	12.7^{b}	12.2^{b}	17.1^{ab}	14.5^{ab}	10.3^{b}	22.0^{a}
	20°C	14.4^{cd}	11.1^{d}	17.2^{abc}	20.0^{a}	19.3^{ab}	19.4^{ab}	15.6^{bc}
Means								
QFS soil		2.8^{Ba}	2.8^{Ba}	2.7^{Ba}	3.2^{Ba}	3.0^{Ba}	2.5^{Ba}	2.3^{Ba}
KGL soil		16.6^{Aab}	12.1^{Ac}	14.0^{Abc}	17.4^{Aab}	18.9^{Aa}	14.4^{Abc}	19.6^{Aa}
	30°C	12.5^{Aab}	7.9^{Ac}	8.1^{Ac}	8.9^{Bbc}	13.2^{Aa}	7.9^{ABc}	11.7^{Aabc}
	25°C	7.9^{Aab}	7.5^{Aab}	7.5^{Aab}	9.9^{ABab}	8.7^{Aab}	6.5^{Bb}	12.0^{Aa}
	20°C	8.7^{Abc}	7.1^{Ac}	9.5^{Aabc}	12.1^{Aa}	11.0^{Aab}	11.1^{Aab}	9.1^{Babc}

†KGL = Krome gravelly loam; and QFS = Quincy fine sand.
*Values followed by different letter (s), lower case within the same row, and upper case within the same column of a subset (either the soil or temperature), represent significant difference at $p \leq 0.05$.

Table 8. The overall changes of SOC (g/kg) before and after cover crops grown in different soils

Soil†	Prior to growing cover crops	After winter cover crops grown	After summer cover crops grown	Net change (winter cover crops vs. prior)	Net change (summer vs. winter cover crops)	Net change (winter + summer cover crops vs. prior)
QFS soil	2.10	2.20	2.77	4.8%	25.9%	31.9%
KGL soil	14.21	14.34	16.16	0.9%	13.7%	13.8%

†KGL = Krome gravelly loam; and QFS = Quincy fine sand.

cantly lower than that of the KGL soil regardless of cover crop species or fallow soil, and the former soil rather than the latter soil had more SOC increase after cover crops grown as compared to the respective soils before the cover crop growth. This result agrees with a previous report that soil with low SOC usually has more potential to regain organic C than soil with high SOC [2].

Accumulation of SOC is a slow and long-term process. Sainju [19] reported that to observe differences in SOC under field conditions even with substantial C inputs by cover crops requires more than two years. Our previous study [16] with two years of cover crops grown in the field (KGL soil), showed no SOC increase as compared to that of the fallow soil. Increased cropping intensity in crop rotations by reducing the frequency of bare fallow can increase crop production and C inputs to the soil [24]. Kuo and Jellum [11] also indicated that concentrations of C and N in the surface soil (0-15 cm) increased with increasing total C input from cover crops because sol accumulation of C and N is a function of the total input of organic C [40].

Bordovsky *et al*. [41] found that the surface (0-5 cm) SOC concentration increased with time in their 11-year field experiment following continuous cultivation of grain sorghum [*Sorghum bicolor* (L.) Moench] and wheat (*Triticum aestivum* L.) in the Miles fine sandy loam soil in Texas. In Georgia cotton (*Gossypium hirsutum* L.) production region with winter cover cropping system, SOC in the Dothan sandy loam at 0-10 cm increased by 6-8% over a period of 3 years with winter cover crops, such as rye (*Secale cereal* L.) and hairy vetch (*Vicia villosa* Roth). The rate of SOC sequestration was 233-300 kg C ha^{-1} yr^{-1} while the rate of loss was 167 kg C $ha^{-1}yr^{-1}$ in the soil without these cover corps [13]. Conversely, changing crop-fallow to continuous monoculture or rotation cropping, or increasing the number of crops in a rotation system was less effective in sequestering SOC as compared to shifting to no till practice [26].

Integrated agricultural practices, including cover crops with no tillage or at least with conservation tillage, are needed to improve soil C sequestration. Tillage or incorporation of plant residues into the soil increases SOC mineralization [2,42]. In strip- and chisel-tilled plots, the SOC decreased by 3-17% and 4-17% in 0-10 cm and 10-30 cm depth, respectively, but in no till treatments, SOC increased by 6-8% with winter cover crops at 0-10 cm and by 0.4% with rye and 3% with biculture of vetch and rye at 0-30 cm [13].

The beneficial effects of growing cover crops in enhancing SOC pool have been reported from around the world [43-45]. Furthermore, the enhancement of C sequestration by growing cover crops associated with conservation tillage has been reported by a number of researchers [12,16,43,46,47]. For example, Sainju *et al*. [32]

observed that hairy vetch under no till can improve SOC, and cover cropping associated with N fertilization can have effects in storing SOC in no tilled soils due to the reduction in mineralization rates of crop residues and soil organic matter. Metay *et al*. [46] found that no till with cover crop (*Crotalaria*) increased the storage of C in the topsoil layer (0-10 cm) compared to disc tillage, with the latter only less than 10% of cover crop residues returned to the soil.

No tillage or conservation tillage can conserve crop residues but cannot increase the soil C or biomass input. The SOC accumulation or C sequestration requires an increase in organic matter or crop residue inputs along with a decrease in decomposition rate of soil organic matter [2,3,48]. Paustian *et al*. [49] observed that SOC increases linearly with increased addition of crop residues. Cover crops or cover cropping systems not only serve a large sink to remove the atmospheric CO_2 but also increases the biomass input into the soil. Therefore, cover cropping system combined with the conservation tillage has shown a great advantage in improving C sequestration and sustainable development in agriculture. The contribution of cover crops to SOC or carbon sequestration via assimilating atmospheric CO_2 into SOC has great potential in reducing the CO_2 concentration from the atmosphere. This potential may last at least a few decades because the SOC has been depleted over the world in arable land and may reach a new equilibrium in 50-100 years [3,26].

4. Conclusions

The total amounts of C accumulated by aboveground biomass varied greatly among both winter and summer cover crops. Therefore, choice of cover crops species is important for increased efficiency in biomass production and carbon sequestration. Soil and temperature influenced the biomass production and C accumulation under some circumstances. Biomass production and C accumulation of most winter cover crops, except white clover, were greater in the QFS soil than those in the KGL soil. Such difference was not evident with respect to the summer cover crops. When the aboveground cover crop biomass was returned to the soil for decomposition with over 127 days, about 73 and 52% of the aboveground biomass C was retained from the winter and summer cover crop residues, respectively. After a year rotation summer cover crops following winter cover crops, SOC increased by 13.8 and 31.9% in the KGL and QFS soil, respectively, compared to the respective soils prior to the experiment. This study has demonstrated improved SOC accumulation by sequestration of atmospheric C following the growth of cover crops.

5. Acknowledgements

The research was founded by USDA-ARS with a collaboration research program. We sincerely thank Dr. Thomas Davenport, Mr. Robert Stubblefield, Jorge Vergel, Jacob Hall, Ms. Guiqin Yu, and Laura Rosado at TREC, University of Florida for their supports with phytotron facilities and/or help in sample collections and chemical analyses.

REFERENCES

[1] R. T. Watson, I. R. Noble, B. Bolin, N. H. Ravindranath, D. J. Verardo and D. J. Dokken, "Land Use, Land Use Change and Forestry," Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2000.

[2] R. Lal, "Soil Carbon Sequestration to Mitigate Climate Change," *Geoderma*, Vol. 123, No. 1-2, 2004, pp. 1-22.

[3] K. Paustian, O. Andrén, H. H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiessen, M. Van Noordwijk and P. L. Woomer, "Agricultural Sols as a Sink to Mitigate CO_2 Emissions," *Soil Use and Management*, Vol. 13, No. 4, 1997, pp. 230-244.

[4] H. Eswaran, P. R. Reich, J. M. Kimble, F. H. Beinroth, E. Padammabhan and P. Moncharoen, "Global Carbon Stocks," In: R. Lal, J. M. Kimble, H. Eswaran and B. A. Steward, Eds., *Global Climate Change and Pedogenic Carbonates*, Lewis Publishers, Boca Raton, 2000, pp. 15-25.

[5] D. S. Schimel, B. H. Braswell, E. A. Holland, R. McKeown, D. S. Ojima, T. H. Painter, W. J. Parton and A. R. Townsend, "Climatic, Edaphic, and Biotic Controls over Storage and Turnover of Carbon in Soils," *Global Biogeochemical Cycles*, Vol. 8, No. 3, 1994, pp. 279-293.

[6] R. Lal, "Carbon Sequestration in Soils of Central Asia," *Land Degradation & Development*, Vol. 15, No. 6, 2004, pp. 563-572.

[7] S. E. Trumbore, "Potential Responses of Soli Organic Carbon to Global Environmental Change," *Proceedings of the National Academy of Sciences*, Vol. 94, No. 16, 1997, pp. 8284-8291.

[8] R. Lal, J. Kimble, R. F. Follet and B. A. Stewart, (Eds.) "Management of Carbon Sequestration in Soil," CRC Press, Boca Raton, 1998.

[9] M. Bernoux, C. C. Cerri, C. E. P. Cerri, M. S. Neto, A. Metay, A. S. Perrin, E. Scopel, T. Razafimbelo, D. Blavet, M. de C. Piccolo, M. Pavei and E. Milne, "Cropping Systems, Carbon Sequestration and Erosion in Brazil, a Review," *Agronomy and Sustainable Development*, Vol. 26, No. 1, 2006, pp. 1-8.

[10] K. A. McVay, D. E. Radcliff and W. L. Hargrove, "Winter Legume Effects on Soil Properties and Nitrogen Fertilizer Requirements," *Soil Science Society of American Journal*, Vol. 53, No. 6, 1989, pp. 1856-1862.

[11] S. Kuo, U. M. Sainju and E. J. Jellum, "Winter Cover Crop Effects on Soil Organic Carbon and Carbohydrate," *Soil Science Society of American Journal*, Vol. 61, No. 1, 1997, pp. 145-152.

[12] U. M. Sainju, W. F. Whitehead and B. P. Singh, "Agricultural Management Practices to Sustain Crop Yields and Improve Soil and Environmental Qualities," *The Scientific World*, Vol. 3, 2003, pp. 768-789.

[13] U. M. Sainju, B. P. Singh, F. W. Wayne and S. Wang, "Carbon Supply and Storage in Tilled and Nontilled Soils as Influenced by Cover Crops and Nitrogen Fertilization," *Journal of Environmental Quality*, Vol. 35, No. 4, 2006, pp. 1507-1517.

[14] Q. Wang, Y. Li and W. Klassen, "Influence of Summer Cover Crops on Retention of Soil Nitrogen and Phosphorus in a Subtropical Area," *Journal of Soil and Water Conservation*, Vol. 60, No. 1, 2005, pp. 58-63.

[15] Q. Wang, Y. Li, W. Klassen and Z. Handoo, "Influence of Cover Crops and Soil Organic Amendments on Okra (*Abelmoschul esculentus* L.) Production and Soil Nematodes," *Renewable Agriculture and Food Systems*, Vol. 22, 2007, pp. 41-53.

[16] Q. Wang, W. Klassen, Y. Li and M. Codallo, "Cover Crops and Organic Mulch to Improve Tomato Yields and Soil Fertility," *Agronomy Journal*, Vol. 101, No. 2, 2009, pp. 345-351.

[17] P. E. Rasmussen and W. J. Parton, "Long-Term Effects of Residue Management in Wheat-Fallow: I. Inputs, Yield, and Soil Organic Matter," *Soil Science Society of American Journal*, Vol. 58, No. 2, 1994, pp. 523-536.

[18] D. R. Huggins, G. A. Buyanovsky, G. H. Wagner, J. R. Brown, R. G. Darmody, T. R. Peck, G. W. Lesoing, M. B. Vanotti and L. G. Bundy, "Soil Organic C in the Tallgrass Prairie-Derived Region of the Corn Belt: Effects of Long-Term Crop Management," *Soil & Tillage Research*, Vol. 47, No. 3, 1998, pp. 219-234.

[19] U. M. Sainju, H. H. Schomberg, B. P. Singh, W. F. Whitehead, P. G. Tillman and S. L. Lachnicht-Weyers, "Cover Crop Effect on Soil Carbon Fractions under Conservation Tillage Cotton," *Soil & Tillage Research*, Vol. 96, No. 1-2, 2007, pp. 205-218.

[20] S. Kuo and E. Jellum, "Influence of Winter Cover Crop and Residue Management on Soil Nitrogen Availability and Corn," *Agronomy Journal*, Vol. 94, No. 3, 2002, pp. 501-508.

[21] Q. Wang, Y. Li and W. Klassen, "Summer Cover Crops and Soil Amendments to Improve Growth and Nutrient Uptake of Okra (*Abelmoschus esculentus* L.)," *Horticultural Technology*, Vol. 16, 2006, pp. 328-338.

[22] R. L. Desjardins, W. N. Smith, B. Grant, H. Janzen, S. Gameda and J. Dumanski, "Soil and Crop Management and the Greenhouse Gas Budget of Agroecosystems in Canada, Sustaining the Global Farm," In: D. E. Stott, R. H. Mohtar and G. C. Steinhardt, Eds., *Selected Papers from the* 10*th International Soil Conservation Organization Meeting*, Purdue University, West Lafayette, 2001, pp. 478-480.

[23] K. K. McLauchlan and S. E. Hobbie, "Comparison of Labile Soil Organic Matter Fractionation Techniques," *Soil Science Society of American Journal*, Vol. 68, No. 5, 2004, pp. 1616-1625.

[24] J. J. Hutchinson, C. A. Campbell and R. L. Desjardins, "Some Perspectives on Carbon Sequestration in Agriculture," *Agricultural and Forest Meteorology*, Vol. 142, No. 2-4, 2007, pp. 288-302.

[25] L. Janik, L. Spouncer, R. Correl and J. Skjemstad, "Sensitivity Analysis of the Roth-C Soil Carbon Model," *National Carbon Accounting System Technical Report No*. 30, CSIRO Land and Water and Mathematical and Information Sciences, Australian Greenhouse Office, Canberra, 2002.

[26] T. O. West and W. M. Post, "Soil Organic Carbon Sequestration Rates by Tillage and Crop Rotation: A Global Data Analysis," *Soil Science Society of American Journal*, Vol. 66, No. 6, 2002, pp. 1930-1946.

[27] Q. Wang, Y. Li and Y. Wang, "Optimizing Weight Loss on Ignition Methodology for Organic and Carbonate Carbon Determination in Sediments from Various Sources," *Water Resource Research*, in press, 2010.

[28] SAS Institute, "SAS," Version 9.1.3, Cary, 2004. http://support.sas.com/documentation/onlinedoc/91pdf/index_913.html

[29] D. Montgomery, "Design and Analysis of Experiments," 6th Edition, John Wiley & Sons, Inc., Hoboken, 2005.

[30] Q. Wang, Y. Li and A. Alva, "Growing Cover Crops to Improve Carbon Sequestration," *Oral Presentation*, *ASA*, *CSA, SSSA and GSA International Joint Meetings*, Houston, 5-9 October 2008.

[31] W. L. Hargrove, "Winter Legumes as a Nitrogen Source for No-Till Grain Sorghum," *Agronomy Journal*, Vol. 78, No. 1, 1986, pp. 70-74.

[32] U. M. Sainju, B. P. Singh and W. F. Whitehead, "Long-Term Effects of Tillage, Cover Crops, and Nitrogen Fertilization on Organic Carbon and Nitrogen Concentrations in Sandy Loam Soils in Georgia, USA," *Soil Tillage Research*, Vol. 63, No. 3-4, 2002, pp. 167-179.

[33] E. L. Dossa, M. Khouma, I. Diedhiou, M. Sene, F. Kizito, A. N. Badiane, S. A. N. Samba and R. P. Dick, "Carbon, Nitrogen and Phosphorus Mineralization Potential of Semiarid Sahelian Soils Amended with Native Shrub Residues," *Geoderma*, Vol. 148, No. 3-4, 2009, pp. 251-260.

[34] D. A. Martens, "Plant Residue Biochemistry Regulates Soil Carbon Cycling and Carbon Sequestration," *Soil Biology and Biochemistry*, Vol. 32, No. 3, 2000, pp. 361-369.

[35] D. A. Martens, "Management and Crop Residue Influence Soil Aggregate Stability," *Journal of Environmental Quality*, Vol. 29, No. 3, 2000, pp. 723-727.

[36] S. B. Mirsky, L. E. Lanyon and B. A. Needelman, "Evaluating Soil Management Using Particulate and Chemically Labile Soil Organic Matter Fractions," *Soil Science Society of American Journal*, Vol. 72, No. 1, 2008, pp. 180-185.

[37] C. S. Jarvis, E. A. Stockdale, M. A. Shepherd and D. S. Powlson, "Nitrogen Mineralization in Temperate Agricultural Soils: Processes and Measurement," *Advances in Agronomy*, Vol. 57, 1996, pp. 187-235.

[38] B. Vanlauwe, O. C. Nwoke, N. Sanginga and R. Merckx, "Impact of Residue Quality on the C and N Mineralization of Leaf and Root Residues of Three Agroforestry Species," *Plant and Soil*, Vol. 183, No. 2, 1996, pp. 221-231.

[39] P. R. Kemp, J. F. Reynold, R. A. Virginia and W. J. Whitford, "Decompositionof Leaf and Root Litter of Chihuahuan Desert Shrubs: Effect of Three Years of Summer Drought," *Journal of Arid Environment*, Vol. 53, No. 1, 2003, pp. 21-39.

[40] W. E. Larson, C. E. Clapp, W. H. Pierre and Y. B. Marachan, "Effects of Increasing Amounts of Organic Residues on Continuous Corn: II. Organic Carbon, Nitrogen, Phosphorus, and Sulfur," *Agronomy Journal*, Vol. 64, No. 2, 1972, pp. 204-208.

[41] D. G. Bordovsky, M. Choudhary and C. J. Gerard, "Tillage Effects on Grain Sorghum and Wheat Yields in the Texas Rolling Plains," *Agronomy Journal*, Vol. 90, No. 5, 1998, pp. 638-643.

[42] E. G. Gregorich, K. J. Greer, D. W. Anderson and B. C. Liang, "Carbon Distribution and Losses: Erosion and Deposition Effects," *Soil & Tillage Research*, Vol. 47, No. 3-4, 1998, pp. 291-302.

[43] M. A. Fullen and K. Auerswald, "Effects of Grass Ley Set-Aside on Runoff, Erosion and Organic Matter Levels in Sandy Soils in East Shropshire, U.K.," *Soil & Tillage Research*, Vol. 46, No. 1-2, 1998, pp. 41-49.

[44] A. E. Johnston, "The Effects of Ley and Arable Cropping Systems on the Amount of Organic Matter in the Rothamstead and Woburn Ley-Arable Experiments," *Rothamstead Experimental Station*, *Report for* 1972, Part 2, 1973, pp. 131-159.

[45] L. G. Nilsson, "Data of Yield and Soil Analysis in the Long-Term Soil Fertility Experiments," *Journal of the Royal Swedish Academy of Agriculture and Forestry Supplement*, Vol. 18, 1986, pp. 32-70.

[46] A. Metay, J. A. A. Moreira, M. Bernoux, T. Boyer, J. M. Douzet, B. Feigl, C. Feller, F. Maraux, R. Oliver and E. Scopel, "Storage and Forms of Organic Carbon in a No-Tillage under Cover Crops System on Clayey Oxisol in Dryland Rice Production (Cerrados, Brazil)," *Soil & Tillage Research*, Vol. 94, No. 1, 2007, pp. 122-132.

[47] B. R. Singh, T. Borresen, G. Uhlen and E. Ekeberg, "Long-Term Effects of Crop Rotation, Cultivation Practices and Fertilizers on Carbon Sequestration in Soils in Norway," In: R. Lal, J. M. Kimble, R. F. Follett and B. A. Stewart, Eds., *Management of Carbon Sequestration in Soil*, CRC Press, Boca Raton, 1998, pp. 195-208.

[48] R. F. Follett, J. M. Kimble and R. Lal, "The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect," Lewis Publishers, Boca Raton, 2001.

[49] K. Paustian, C. V. Cole, D. Sauerbeck and N. Sampson, "CO_2 Mitigation by Agriculture: An Overview," *Climate Change*, Vol. 40, No. 1, 1998, pp. 135-162.

