Advances in Agricultural Science

Volume 6 (2018), Issue 04, 60-71

Journal homepage: www.aaasjournal.org

ISSN: 2588-3801

Research Article

Open Access

Long–term straw retention drives carbon sequestration and crop productivity in dryland soils

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ARTICLE INFO

Article history:

Received: April 30, 2018
Revised: June 18, 2018
Accepted: July 15, 2018
Available online: December 15, 2018

Keywords:
C balance
C input and output
Grain yield

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ABSTRACT

Higher population densities in rural areas and climate change have necessitated technical change in crop production. Intensification without causing degradation is required to cope with changing population dynamics. A study was conducted to assess the influence of tillage systems on crop yield and soil carbon balance in a long-term spring wheat−field pea rotation in a rain–fed semiarid Loess Plateau environment. Experimental work included the following treatments: conventional tillage with straw removed (T), no till with straw removed (NT), no till with straw retention (NTS) and conventional tillage with straw incorporated (TS). Straw treated soils resulted in decreased soil temperature and increased soil moisture compared to soils with straw removed. No tillage with straw retained treatments produced the highest average grain yield of 1809 kg ha^{-1} on average than that of conventional tillage with straw removed (1280 kg ha^{-1}) and no till with straw removed (1337 kg ha^{-1}). No tillage with straw retained and conventional tillage with straw incorporated had positive soil C balance, but the effect was greater on no tillage plots. The lower C inputs under treatments witht straw removed translated into negative soil C balance. NTS farming practices demonstrated sustained increases in soil quality and crop productivity, whiles treatments with straw removed reduced carbon inputs in dryland cropping system.

1. Introduction

Soils play an important role in climate change mitigation by storing carbon and decreasing global greenhouse gas emissions in the atmosphere (Lal, 2004). Crop residues are precursors of the soil organic C pool, and returning more crop residues to the soil is associated with increases in organic C concentration (Lal, 2004; Russell *et al.*, 2009). According to Lal, (2009) conservation tillage offer many benefits like increasing organic matter content and carbon sequestration. The adoption of sound soiland crop residues management strategies could increase soil C sequestration and crop productivity. These strategies can be achieved by increased input of crop residues while minimizing C loses by erosion, decomposition and carbon emission. Whiles conservation agriculture systems have been noted to improve soil and crop productivity

(Andruschkewitsch *et al.*, 2013), conventional plough-based (mouldboard ploughing at 20 cm and harrowed) farming systems could accelerate carbon mineralization and thus reduce soil C content.

The adoption of conservation agriculture principles, in combination with other sustainable soil management practices has been reported to increase crop productivity and carbon inputs (Huang *et al.*, 2008). Conservation tillage retains more plant residue on the soil surface and has greater near–surface soil C contents than conventional tillage (Lal and Pimentel, 2009). The decomposition of plant residue is slower in conservation tillage due to the low contact between the plant materials and the soil compared to conventional tillage which buries plant materials (Wu *et al.*, 2016). According to Yeboah *et al.* (2016) the potential to increase C inputs to soils is associated with high yield agriculture. In this context, the ability to develop and implement innovative soil management practices play an important role in maintaining or improving the productive capacity of soils and enhancing the resilience of the agroecosystem, which is a key priority for crop production. The mechanism and potential of C sequestration in soil are still not well understood, and predictions made for world-wide carbon (C) balance remain uncertain (Rustad, 2006).

This study hypothesized that less soil disturbances coupled with adequate residue retention could improve soil quality and as a result enhance crop productivity and increase C inputs. Soil temperature and moisture influence both below and above ground biomass especially in arid and semi-arid areas and therefore is expected to impact on carbon inputs. Therefore, the objective of this study was to determine the impact of different tillage and straw management practices on crop productivity, and to estimate the C balance in soil through C input and C output.

2. Materials and method

2.1 Study site

The study was conducted at the Rainfed Agricultural Experimental Station (35°28′N, 104°44′E, elevation 1971-m above-sea-level) of Gansu Agricultural University, Gansu Province. The station is located in the semi–arid Western Loess Plateau, which is characterized by step hills and deeply eroded gullies. This area has Aeolian soils of sandy–loam with low fertility, locally known as Huangmian soils (Chinese Soil Taxonomy Cooperative Research Group, 1995), which equate to *Calcaric Cambisols* based on the FAO (1990) description. This soil type is primarily used for cropping and is the dominant soil in the district. Long–term (annual) rainfall records for the Rainfed Experimental Station (Dingxi) show an average of 391 mm per year and annual evaporation of 1531 mm. These conditions are representative of those commonly found in semi–arid agricultural environments. Daily rainfall recorded during the course of the study is presented in Figure 1.

2.2 Experimental design

Cropping during the study included a spring wheat (*Triticum aestivum*) and field pea (*Pisum sativum*) double sequence rotation (referred to as W→ P→W and P→ W→P sequence). The data reported here were collected on the spring wheat plots alone. The study was conducted during the 2014 and 2015 cropping seasons. Table 1 show the detailed treatment description used in the experiment. The experiment was established in 2001 and prior to this flax (*Linum usitatissimum* L.) was cultivated. In straw–amended plots, the wheat straw from the previous crop was returned to the original plots immediately after threshing. Chopped wheat straw (6750 kg ha^{-1}) was applied in all straw treated plots in 2001. Tillage treatments were arranged in a randomized complete block design with three replicates. Each plot was 4 m wide x 17 m long in block 1and 21 m long in blocks 2 and 3. Spring wheat was sown in mid–March at a seeding rate of 187.5 kg ha^{-1} using a no–till seeder at 20 cm row spacing. The crop was harvested in late July to early

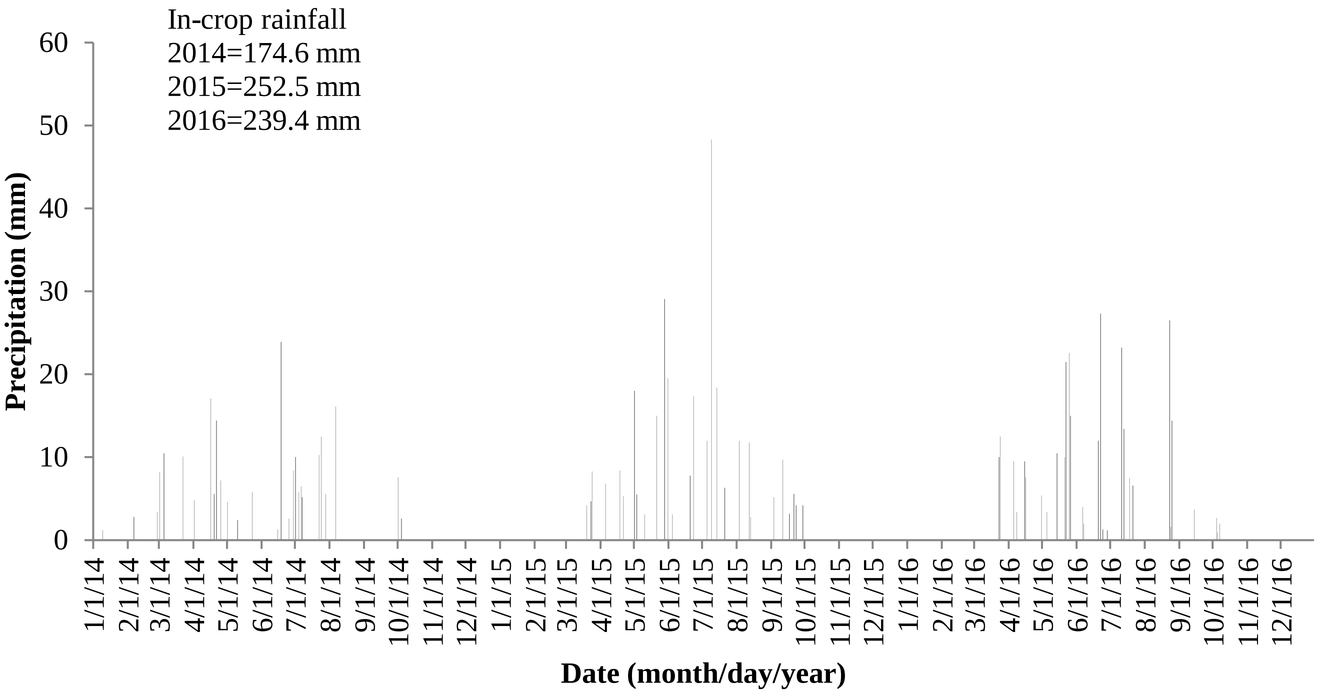

Figure 1. Daily rainfall records for the 2014, 2015 and 2016 season.

Table 1. Detailed description of treatments used in this experiment

Treatment code	Tillage	Straw	Description
	Conventional tillage		
T		No straw	Conventional tillage with straw removed All straw was removed after harvesting
TS		Straw	Conventional tillage with straw incorporated. All straw was returned after threshing
	No tillage		
NT		No straw	No–till with straw removed. All straw was removed after harvesting
NTS		Straw	No–till with the ground covered with straw. All straw was returned after threshing

August. Phosphorus fertilizer was applied at 45.9 kg P ha^{-1} as ammonium dihydrogen phosphate and nitrogen fertilizer was applied at 100 kg ha^{-1}. The phosphorus and nitrogen fertilizer were applied at sowing using the same no–till seeder and incorporated into the soil to about 20 cm deep.

2.3 Treatment description

2.3.1 Conventional tillage with straw removed (T)

The field was ploughed 3 times and harrowed twice after harvesting. The first plough was conducted in August immediately after harvesting; the second and third ploughs were in late August and September respectively. The plough depths were 20 cm, 10 cm and 5 cm, respectively. The field was harrowed after last cultivation in September and re-harrowed in October before the ground is frozen. This is the typical conventional tillage practice in Dingxi Region.

2.3.2 Conventional tillage with straw incorporating (TS)

The field was ploughed and harrowed exactly as that of T treatment (3 ploughs and 2 harrows), but with straw incorporated at the first plough. All the straw from the previous crop was sent back to the original plot immediately after threshing and then incorporated into soil.

2.3.3 No- till with no straw (NT)

No-till was conducted throughout the experimental period. Seed sowing and fertilization was performed with seeding-machine at the same time

2.3.4 No- till with straw (NTS)

No–till with the ground covered with straw. All straw was returned after threshing.

2.4 Determination of soil temperature and moisture

Soil temperature (Ts) at 5, 10 and 15 cm was determined bi-weekly each plot using a thermo–couple (JM624, Tianjin Jinming Instrument Co. Ltd., China) . Soil moisture at 0–5, 5–10 and 10–30 cm depth intervals was determined bi-weekly by taking a 5 cm diameter soil core and drying the soil at 105°C for 24 h. Gravimetric water content at the three depths was multiplied by soil bulk density (Blake and Harge, 1986) to obtain the volumetric water content, which is expressed in $cm^3\ cm^{-3}$.

2.5 Grain yield and total aboveground biomass

Plots were harvested by hand using sickles. The crop was cut 5cm abovetheground and the outer edges (0.5 m) from each plot were discarded. Grain yield and aboveground biomass were determined.

2.6 Determination of total carbon and total nitrogen

Plant samples were milled to pass through a 1–mm sieve for analysis. The plant samples were collected at maturity to determine total carbon and total nitrogen content. Total carbon in the whole above ground plant, excluding the grain was determined with a C and N analyzer (analytikjena; multi N/C, 2100S, Germany).The average total C was the mean of three replicates of each treatment. Total nitrogen in the whole above ground plant material, excluding the grain was determined by the Kjeldahl distillation and titration method using the mean of three replicates of each treatment.

2.7 Calculation of C inputs

The C inputs (C_i) were estimated using the method of Bolinder et al. (2007). If all the proportions of the plant are returned, the total C input was calculated using the equation:

$$\mathrm{C_i} = \mathrm{C_S} + \mathrm{C_R} + \mathrm{C_E}\, n \qquad (1)$$

where C_i is the C input, C_S is the C input of aboveground biomass excluding the grain, C_R is the C input of belowground biomass (roots) and C_E is the C input of rhizodeposition. The C input of these fractions can be calculated if the C amount of the crop yield is known. The quantity of straw applied in 2001 (6750kg ha^{-1}) and the C content in the straw (0.39 g g^{-1}) was used for the 2002 C_i calculation. In the preceding years, field measured harvest index, grain yield (kg ha^{-1}), total C in the whole aboveground plant, excluding grain (in g g^{-1}) were used in the calculation of C_i.

If the aboveground biomass is removed, the amount of carbon added to soil is estimated as:

$$C_i = C_R + C_E \quad (2)$$

The carbon in straw (C_S), root (C_R) and rhizodeposition (C_E) was determined as follows:

$$C_S = \frac{Y_P(1-HI)}{HI} \times P_C \quad (3)$$

$$C_R = \frac{Y_P}{(S:R \times HI)} \times P_C \quad (4)$$

$$C_E = C_R \times Y_E \quad (5)$$

where Y_P is the grain yield (kg ha^{-1}), HI is the harvest index, P_C is the plant C in the whole aboveground plant, excluding the grain, S:R the shoot: root ratio, and Y_E is the extra–root C (rhizodeposition C), expressed as factor relative to recoverable roots. The S:R and Y_E values were 5.6 and 0.65, respectively as indicated by Bolinder et al. (2007). Harvest index (HI) was determined using the definition of Donald (1962), where grain yield (Y_P) is expressed as a proportion of total–aboveground biomass (B_Y). Thus:

$$HI = \frac{Y_P \ (\text{kg ha}^{-1})}{B_Y \ (\text{kg ha}^{-1})} \quad (6)$$

2.7 Carbon balance

Soil C balance was calculated as:

$$\text{Soil Carbon Balance} = \text{C input in soil} - \text{C output from soil} \quad (7)$$

2.8 Statistical analysis

Statistical analyses were undertaken with the Statistical Product Services Solution “22.0’ (IBM Corporation, Chicago, IL, USA) with the treatment as the fixed effect and year as random effect. Differences between the means were determined using Duncan’s Multiple Range Test. Significances were declared at $P = 0.05$, unless otherwise stated.

3. Results

3.1 Variations in mean soil temperature and moisture

Soil temperature was averaged across the sampling period in all treatments to determine the mean temperature in the 5, 10 and 15 cm soil layers. Tillage, straw and year had significant effect ($P<0.05$) on soil temperature at 5-10 cm soil depth, in some cases, but their interactions were not significant (Table 2). The average soil temperature over the entire study period was significantly different ($P<0.05$) among treatments (Table 3). Tillage, straw and year had significant effect ($P<0.05$) on soil temperature at 5-10 cm soil depth, but their interactions were not significant (Table 2). The lowest mean temperature was obtained in NTS (14 °C), followed by TS (15°C) and NT (15 °C) whereas T (16 °C) was the highest over the two years of the study (Table 3). Mean soil temperature decreased with depth. The average soil moisture was highest ($P<0.05$) in the NTS treatment (18 cm^3 cm^{-3}) and to a lesser extent in TS (17 cm^3 cm^{-3}) compared to T. Generally, soil moisture increased at 0–5 to 5–10 cm soil depths, but decline slightly at 10–30 cm (Table 4). The highest soil moisture was observed at the 5–10 cm depth, followed by 10–30 cm, with the lowest soil moisture at 0–5 cm depth.

3.2 Stubble and grain yield

There was no significant tillage and straw interaction on stubble yield, but tillage, straw and year individually had a significant effect on stubble yield (Table 5). No tillage (NT and NTS) treatments were 18%, 7 % and 8% more stubble yield compared to soils under tillage treatments, respectively (Table 6). On average, the NTS and TS treatments significantly increased ($P<0.05$) stubble yield compared to T treatment. Interaction between straw

Table 2. Analysis of variance for straw, tillage and year effects and their interaction

Source	Soil temperature (°C)			Soil moisture (cm^{3}cm^{-3})		
	0–5	5–10	10–30	0–5	5–10	10–30
	………………………………… (cm)………………………………………					
Tillage (T)	3.65 n.s.	7.34*	2.63 n.s.	14.19*	14.71**	0.87 n.s.
Straw (S)	2.87 n.s.	45.22**	9.54*	28.89**	27.56**	0.65 n.s.
Year (Y)	8.98*	21.65**	0.13 n.s.	98.34**	105.01**	6.08 n.s.
T x S	0.02 n.s.	0.74 n.s.	0.68 n.s.	0.21 n.s.	3.05 n.s.	0.39 n.s.
T x Y	0.01 n.s.	0.10 n.s.	0.69 n.s.	0.03 n.s.	2.67 n.s.	0.00n.s
S x Y	0.20 n.s.	2.42 n.s.	0.00 n.s.	0.02 n.s	3.86 n.s.	0.179 n.s.

The values represent F–statistic.

Table 3. Soil temperature as affected by depth and different tillage treatments

Treatment	Soil Temperature (°C)						
	0–5			5–10			10–30
	………………………………………….. (cm)……………………………………........						
	2014	2015	Mean	2014	2015	Mean	Mean
T	17a	21a	19a	16a	14a	15a	12a
TS	15c	18b	17a	13b	12ab	13bc	11b
NT	16b	19ab	17a	14ab	13ab	14ab	11ab
NTS	14d	17b	16a	13b	12b	12c	11b

Values with different letters within a column are significantly different at $P < 0.05$.

T – conventional tillage with straw removed; TS – conventional tillage with straw incorporated; NT – no-till with straw removed; NTS – no-till with straw retained

Table 4. Soil moisture as affected by depth and different tillage treatments

Treatment	Soil Moisture (cm^3 cm^{-3})						
	0–5			5–10			10–30
	………………………………………….. (cm)…………………………………………..						
	2014	2015	Mean	2014	2015	Mean	Mean
T	8b	10b	9b	16b	19 b	18b	16a
TS	9a	12a	10ab	17ab	20b	19ab	18a
NT	9ab	11ab	10ab	17ab	20b	18ab	18a
NTS	10a	12a	11a	18a	23a	20a	18a

Values with different letters within a column are significantly different at $P < 0.05$.

T – conventional tillage with straw removed; TS – conventional tillage with straw incorporated; NT – no-till with straw removed; NTS – no-till with straw retained

Table 5. Analysis of variance for tillage, straw and year effects and their interaction

Source	Stubble yield	Grain yield	Plant C	Plant N
Tillage (T)	19.01**	6.87*	115.16**	6.33*
Straw (S)	153.28**	117.85**	305.75**	96.67**
Year (Y)	248.19**	51.45**	1.11 n.s.	10.01**
T x S	3.08 n.s.	0.30 n.s.	1.01 n.s.	2.33 n.s.
T x Y	1.30 n.s.	0.29 n.s.	2.42*	0.01 n.s.
S x Y	5.58*	18.71*	1.37 n.s.	6.21*

The values represent F–statistic.

Table 6. Stubble and grain yield of spring wheat as affected by different tillage treatments

Treatment	Stubble yield				Grain yield			
	2014	2015	2016	Mean	2014	2015	2016	Mean
	………………………………………….. ($kg\ ha^{-1}$)…………………………………							
T	2802c	4485c	4096b	3794b	1075c	1275b	1490c	1280b
TS	3613b	6028b	4150b	4597ab	1458a	1980a	1673b	1704a
NT	3091bc	4782c	4026b	3966b	1269b	1346b	1397d	1337b
NTS	4507a	6442a	4898a	5282a	1528a	2074a	1824a	1809a

Values with different letters within a column are significantly different at $P<0.05$.

Table 7. Total carbon and nitrogen of spring wheat as affected by different tillage treatments

Treatment	Plant C			Plant N		
	2014	2015	Mean	2014	2015	Mean
	………………………………………. ($g\ kg^{-1}$) …………………………………..					
T	382c	380b	381c	4.41c	4.31b	4.36b
TS	392b	392a	392ab	5.64ab	5.11a	5.37a
NT	386bc	390ab	388b	4.80bc	4.76ab	4.78b
NTS	399a	398a	398a	5.82a	5.24a	5.53a

Values with different letters within a column are significantly different at $P<0.05$.

and year was significant ($P<0.05$) in affecting grain yield; tillage, straw and year independently affected grain yield (Table 5). The grain yield recorded in plots with straw returned was the greatest; an increase of 27%, 55 % and 21% compared to plots with straw removed plots was observed over the 3-years. No tillage with straw retained (NTS) treatments produced the greatest average grain yield of 1809 kg ha^{-1}, representing a significant increase of 41.25% and 35.23% compared to T and NT treatments, respectively. The TS treatments increased grain yield in 2014 (by 36 % and 15 %), 2015 (by 55% and 47%) and 2016 (by 12% and 20 %) compared to T and NT treatments, respectively.

3.3 Total C and N of spring wheat

No tillage with straw retained (NTS) soils recorded the greatest total C and N though differences were not always significant ($P<0.05$, Table 7). The no tillage with straw retained (NTS) treatment had higher N content compared to conventional tillage

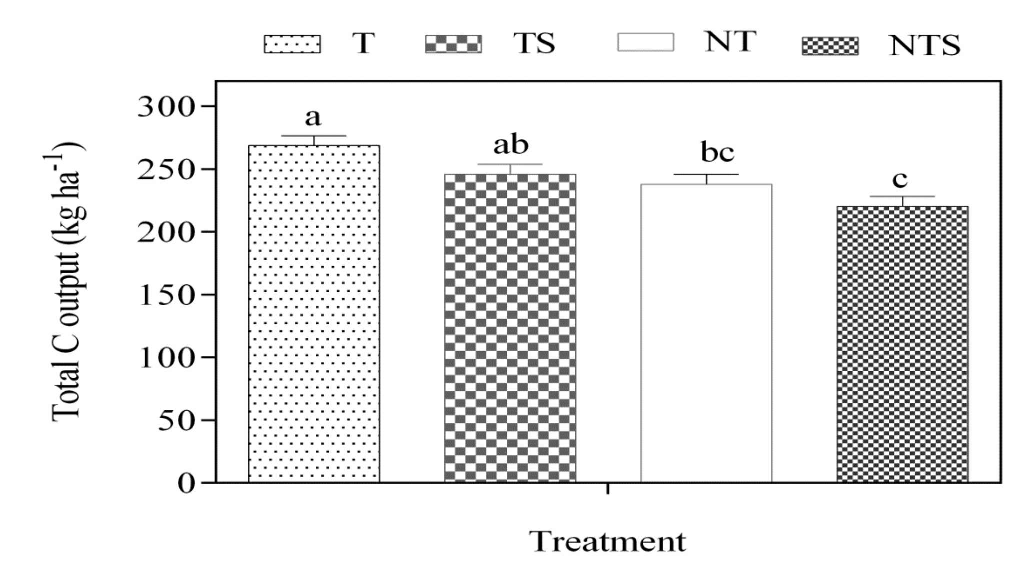

Figure 2. Total C output for spring wheat as affected by different tillage treatments. *Different letters* denote statistically different values at $P<0.05$. Error bars represent the standard error (SE) (n = 3).

Table 8. Analysis of variance for tillage, straw and year effects and their interaction

	C input	C balance
Tillage (T)	2.65 n.s.	69.84**
Straw (S)	6.77 n.s.	1464.15**
Year (Y)	10.87**	106.32**
T x S	0.19 n.s.	10.20**
T x Y	8.10**	0.95 n.s.
S x Y	18.46**	14.96**

The values represent F–statistic.

with straw removed (T), which corresponded in all cases to significant differences ($P<0.05$). Conventional tillage with straw incorporated (TS) treatments also had significant effect on total C and N of the plant compared to T treatments . The mean value of total C and N of the plants under straw application either with no tillage or conventional tillage was significantly higher than no tillage with straw removed. The mean total C value was higher under the NT treatment than the T treatment.

3.4 Total C output

No tillage on straw treated plots caused a significant reduction in total C output by 22 % whiles no tillage on straw removed plots reduced total C output significantly by 12% relative to straw removed on conventional tilled plots (Figure 2). In all, no tillage treatments decreased total C output compared to conventional tillage with straw removed.

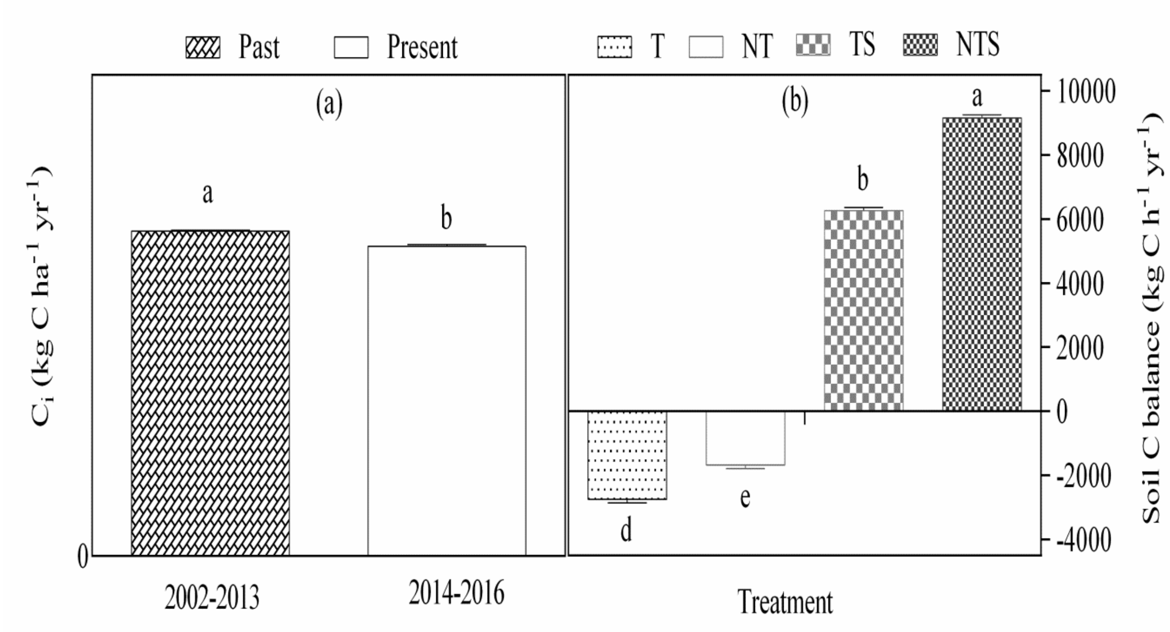

Figure 3. Average carbon input (C_i) and soil C balance under different tillage treatments . *Different letters* denote statistically different values at $P<0.05$. Error bars represent the standard error (SE) (n = 3).

3.5 Carbon inputs and soil C balance

A summary of the analyses of variance indicating the effect of treatment factors on C inputs is presented in Table 8. Interaction between tillage and year, and straw and year affected C inputs, but with the exception of year, the treatment factors individually had no significant influence ($P<0.05$) on C inputs. The trend of C inputs was similar in all treatments; straw treated plots under both conventional tillage and no tillage had the highest C inputs, but the effect of no tillage was the greatest (Table 9). The total C inputs from 2002 to 2016 were higher in NTS and least in T treatments.

The average C inputs (Figure 3a) was higher during the past period (2002 to 2013) compared to the present period C inputs (2014 to 2016). As shown in Table 8, the treatment factors independently had a significant effect ($P<0.05$) on soil C balance. The interaction between tillage and straw, and straw and year significantly affected soil C balance. The balance between input and output of C from soil was negative for conventional tillage with straw removed and no tillage with straw removed (Figure 3b). The positive balance was recorded in no tillage with straw retained (NTS) and conventional tillage with straw incorporated (TS) where input of C exceeded the output of C from soil.

4. Discussion

Soil temperature and moisture content, particularly in the 0–30 cm depth interval is important for crop production in dry areas. In this study, straw application influenced soil temperature and moisture in both tillage and no tillage plots, but the greatest effect occurred in till plots. Previous studies have shown that no–till with straw residue may lower soil temperature (Li *et al*., 2011; Yeboah *et al*., 2017). Increased soil moisture in no tillage plots under straw application was in agreement with Li *et al*. (2011) and Yeboah *et al*., (2016). Stubble retention is also mentioned in several studies (e.g., Huang *et al*., 2008; Yeboah *et al*., 2016) to improve soil water holding capacity in dry land cropping systems. The soil moisture data showed that, tillage systems with less soil disturbance could improve soil moisture. The significance of retaining crop

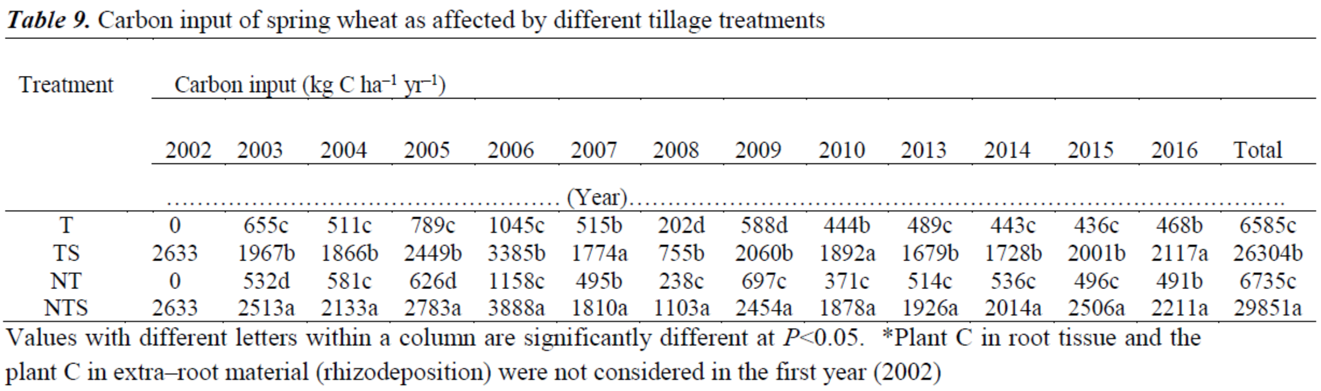

Table 9. Carbon input of spring wheat as affected by different tillage treatments

Treatment	Carbon input (kg C ha^{-1} yr^{-1})													
	2002	2003	2004	2005	2006	2007	2008	2009	2010	2013	2014	2015	2016	Total
	……………………………………………(Year)……………………………………………………………………………													
T	0	655c	511c	789c	1045c	515b	202d	588d	444b	489c	443c	436c	468b	6585c
TS	2633	1967b	1866b	2449b	3385b	1774a	755b	2060b	1892a	1679b	1728b	2001b	2117a	26304b
NT	0	532d	581c	626d	1158c	495b	238c	697c	371c	514c	536c	496c	491b	6735c
NTS	2633	2513a	2133a	2783a	3888a	1810a	1103a	2454a	1878a	1926a	2014a	2506a	2211a	29851a

Values with different letters within a column are significantly different at $P<0.05$. *Plant C in root tissue and the plant C in extra–root material (rhizodeposition) were not considered in the first year (2002)

residues was emphasized in this study by the difference of soil temperature and soil moisture under straw treated soils, particularly under no tillage treated soils.

The higher biomass and grain yield obtained on the straw amended soils is attributed to the fact that in drier environment. Surface crop residues reduce the soil temperature, conserve water, and improve soil quality, resulting in better growth and hence yield (Zou *et al*., 2016). Increasing soil water availability enhances wheat growth and therefore yield. The lowest yield recorded on the non-straw treated soils throughout this study may be related to the removal of all the aboveground biomass at the end of the cropping season. Zhang *et al*. (2008) showed that inadequate carbon inputs to arable soils, as occurs when straw is removed and manure is not added deplete soil organic carbon and reduce crop productivity. Therefore, when crop residues were removed, it had immediate adverse effects on biomass and grain yield and yield reductions became evident in the study area.

Lower C losses in no tillage soils, particularly with residue retention in comparison to conventionally treated soils, were consistent with results from other studies (Regina and Alakukku, 2010;Yeboah *et al*., 2016). The lower C output could be attributed to the straw that was returned to the soil and to some extent by increased biomass production.. Conservation tillage enhances residue cover on the soil surface results in higher upper surface soil C contents than conventional tillage; the decomposition of plant residue is slower in conservation tillage due to the limited soil–residue contact (Lal, 2009). Management strategies in agroecosystems may influence C balance in soil through differences in soil C input and soil C output. In agricultural system when C input to the soil exceeds the C output from the soil, a positive imbalance occurs which subsequently results in C sequestration in soil (Ghoshal and Singh, 2010). In this study, the difference between C input and C output was found to be positive in all straw treated plots ; C balance was found to be negative for all plots that had straw removed . The results indicated that straw application significantly enhanced the annual C inputs and soil C balance. Some studies (e.g., Zhang *et al*., 2012) have highlighted the beneficial role of straw returned for C sequestration. When C inputs and outputs are in balance with one another, there is no net change in soil C levels. In this study, straw treated plots had higher C sequestration potential in terms of soil C balance particularly when residue retention was combined with no tillage techniques. On the other hand, soils without carbon inputs with or without tillage treatment had negative C balances . The increase in annual C inputs could translate into higher C storage in terms of soil C build–up and thus enhanced C sequestration. The input of C in the straw treatments translated to higher crop productivity, which was more pronounced in no tillage treated soils.

5. Conclusion

No tillage with straw retention decreased soil temperature, and increased soil moisture content. Straw application in no tillage farming practices increased stubble and grain yield due to improved soil quality. Straw amended soils had positive soil C balance whilst non–straw amended soil had negative soil C balance. Sustainable future food production targets can be met with improved soil management technologies in semi–arid rainfed areas. It is therefore recommended that adoption of tillage with residue retention could be considered to improved soil and crop productivity in rainfed spring wheat cropping under semi–arid conditions

Acknowledgments

This research was supported by the National Natural Science Foundation of China (31571594 and 41661049), The "National Twelfth Five–Year Plan" Circular Agricultural Science and Technology Project (2012 BAD14B03) and Gansu Provincial Key Laboratory of Aridland Crop Science open fund project (GSCS – 2013–13).

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