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Soil respiration and net ecosystem production under different tillage practices in semi-arid Northwest China

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ABSTRACT

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In semi-arid areas, increasing CO_2 emissions are threatening agricultural sustainability. It is unclear whether different tillage practices without residue returned could help alleviate these issues while increasing crop productivity. This study aimed to quantify soil respiration under conventional tillage (CT); rotary tillage (RT); subsoiling (SS) and no-till (NT), all without residue returned in the Western Loess Plateau. The results showed that SS and NT significantly decreased soil respiration compared to CT, but the effects of SS was the greatest. As a result, SS decreased carbon emission by 22% in 2014 and 19% in 2015 versus CT. The trends of net ecosystem production under different tillage systems were as follows: CT > RT > NT > SS. No-till increased net ecosystem production by 33% in 2014 and 12% in 2015 relative to CT. The SS treatment increased average grain yield by 27% and 23% over CT and RT, and enhanced water use efficiency by an average of 43%. On average, SS increased carbon emission efficiency by 60% and 43% compared to CT and RT, respectively. Thus, subsoiling management strategy is a promising option for the development of sustainable agriculture in semi-arid areas.

Keywords: greenhouse gas; no tillage; carbon sequestration; crop productivity

Global surface temperature has increased by 0.8°C in the last 100 years (Hansen et al. 2010). This warming has probably been caused by increased anthropogenic emissions of long-lived greenhouse gases (GHGs) such as carbon dioxide (CO_2). The concentration of CO_2 increases at a rate of approximately 3 ppm per year (Tans and Keeling 2012). Further increase will have large effects on natural cycles and ecosystems and, as a consequence, human activities. Therefore there is a strong incentive to mitigate further increases in temperature by reducing CO_2 emissions.

Reduced tillage or no-till have been increasingly used worldwide due to their environmental advantages and lower labour inputs (Kirkegaard et al. 2014) over conventional systems. Most studies declared that no-till decreases soil disturbance (Alletto et al. 2010), and lowers CO_2 emission

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from the soil (Fuentes et al. 2011). Nevertheless, some other demonstrated no significant differences between no-till and conventional tillage, or even opposite (Govaerts et al. 2009). Some recent reports also addressed faithful question on the potential of no-till in reducing greenhouse gas emissions, increasing C-sequestration (Kirkegaard et al. 2014) and improving crop water use efficiency (Fan et al. 2012). Straw retention under no-till would be somewhat valid solution to sustain lesser CO_2 emission (Fuentes et al. 2011), and in some cases to increase C-sequestration (Alletto et al. 2010) and improve soil structure (Zhang et al. 2013).

Although well established in other parts of China, conservation agriculture, particularly the combination of no tillage and stubble retention, is rarely practiced on the Loess Plateau. This is because both farmers and local extension agents hold strong beliefs that crop residues are in demand as livestock feed and as fuel for heating or cooking (Lal 2007). The exhaustion of soil organic matter and the continued removal of crop residues is of major concern. Our study hypothesized that tillage practices with reduced C inputs to the soil would enhance soil physical properties and raise the potential to reduce CO_2 emissions. Given this context, the objectives of the present study were to: (1) assess the effects of different tillage practices on grain yield and water use efficiency, and (2) quantify CO_2 emissions and net primary production under different tillage systems.

MATERIAL AND METHODS

Study site. The field experiments were conducted in 2014 and 2015 growing seasons under rainfed conditions at the Dingxi Experimental Station (35°28'N, 104°44'E and elevation 1971 m a.s.l.), Gansu province, northwestern China. The site had sandy loamy soil with pH of 8.3, soil organic carbon below 7.63 g/kg and Olsen P below 13.3 mg/kg. The long-term annual rainfall at the experimental site averages 391 mm ranging from 246 mm in 1986 to 564 mm in 2003 with about 54% received between July and September. Annual accumulated temperature > 10°C is 2239°C. Total rainfall recorded during the course of the study was 280 mm and 274 mm in 2014 and 2015, respectively.

Experimental design and treatment description. The experiments were conducted in a randomized complete block design with three replicates of four treatments. The treatments were: conventional tillage (CT); rotary tillage (RT); subsoiling (SS) and no-till (NT). Conventional tillage (CT) was the local farming practice, which included mouldboard ploughing to a depth of 20 cm, followed by harrowing. The rotary tillage was done to a depth of 15 cm. A roller was used to firm the soil after CT and RT to reduce water loss. Subsoil tillage was performed to 35 cm depth. There were a total of twelve plots; each plot was 46 m^2 (4 m × 11.5 m) in size with narrow ridges (15 cm high × 40 cm wide) alternated with wide ridges (10 cm high × 70 cm wide). All the ridges were covered with plastic film to increase soil temperature and speed-up germination, and also to reduce evaporative losses. After the soil was covered with film, holes were made using a handheld device through the film in furrows to help collect and channel water from ridges to the rooting zone when raining. Soil preparation, ridging and mulching occurred at sowing. The maize (*Zea mays* L., cv. Funong 821) was sown with a hand held-dibbler in furrows between the narrow and wide ridges (Figure 1) at a density of 52 000 plants/ha. Prior to setting up ridges and plastic film, 100 kg N/ha in the form of urea (46%) and 150 kg P/ha (P_2O_5) were broadcast as basal fertilizer on each plot. 100 kg N/ha in the form of urea (46%) was top-dressed before flowering. The experiment was initiated in 2012; however, this article reports the experimental data for the 2014 and 2015 cropping seasons.

Measurement and calculation

Soil sampling. Concurrently with soil respiration, gravimetric soil water content in the 0–5 cm and 5–10 cm depth was determined based on the method described by Jia et al. (2012). Gravimetric water content at the two depth intervals was multiplied by soil bulk density to obtain the volumetric water content, which is expressed in cm^3/cm^3. Volumetric soil water content values reported correspond to the mean of the two depths (0–5 cm and 5–10 cm). Soil bulk density (BD) was determined by taking small cores, and by relating the oven-dried mass of soil to the volume of the core (Carter 1993). The soil bulk density was determined at 0–5 cm and 5–10 cm within 3 days prior

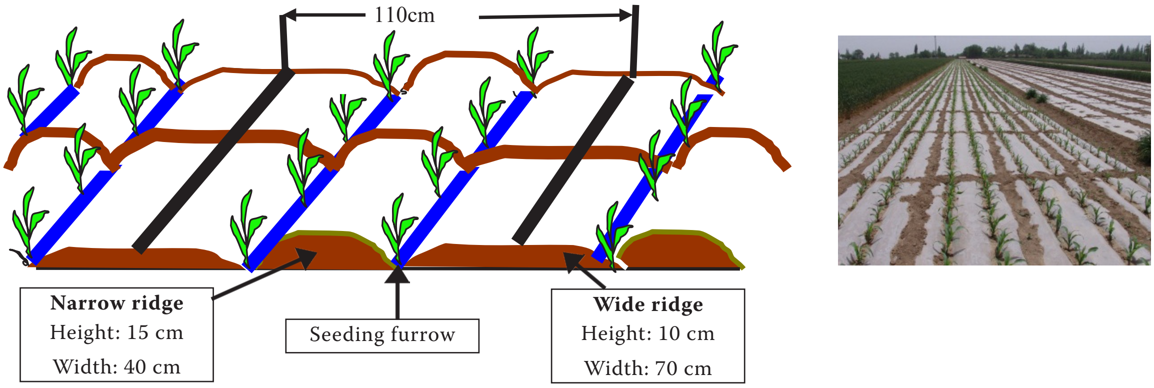

Figure 1. Field layout of furrow-planting with completely mulched alternate narrow and wide ridges

to land preparation. Two soil core samples were taken in each plot for determination of soil bulk density. Total porosity (TP) was computed from:

$$\text{Porosity} = 1 - \text{BD}/\text{p}_\text{p} \qquad (1)$$

Where: BD – soil bulk density and p_p – absolute particle density, of 2.65 g/cm^3.

Soil bulk density and gravimetric water content were used to determine the water-filled pore space (WFPS) of each soil core (Yanai et al. 2007). Soil saturated hydraulic conductivity (K_{sat}) was determined at 2 points per plot using the disc permeameter described in Xu et al. (2002). In both years, the treatments showed similar values for soil bulk density, total porosity, water-filled pore space and soil saturated hydraulic conductivity, and therefore, the values reported correspond to the mean of both years. Soil water data were taken under the plastic film mulch.

Soil respiration and carbon emission. Soil respiration (Rs) was measured using EGM-4 (British PP Systems) portable CO$_2$ analyzer from April to October. For each measurement event, gas sampling was performed between 08:00–12:00 h. Three measurements were taken from each plot at each sampling time to reduce the effects of environmental variation.

Carbon emission (CE) (kg/ha) was estimated based on soil respiration using the following equation described by Zhai et al. (2011):

$$\text{CE} = \Sigma\ [\underline{\text{Rsi} + 1 + \text{Rsi}}\ (\text{ti} + 1 - \text{ti}) \times 0.1584 \times \times 24] \times 0.2727 \times 10 \qquad (2)$$

Where: Rs – soil respiration (μmol CO$_2$/m^2/s) measured at biweekly intervals in growing season, *i* + 1 and *i* – previous and the current sampling date; t – days after sowing. 0.1584 converted μmol CO$_2$/m/s to g CO$_2$/m^2/h, 0.2727 converted g CO$_2$/m^2/h to g C/m^2/h, and 24 and 10 were to convert g C/m^2/h to kg/ha for the growing season.

To quantify grain yield per unit of carbon emission, carbon emission efficiency (CEE) was calculated (Eq. 3):

$$\text{CEE} = \text{grain yield (kg/ha)/carbon emission (kg/ha)}$$

Net primary production (NPP) and net ecosystem production (NEP). The NEP represents the C flux from the atmosphere to the soil-plant system, and was calculated by using the equation of Iqbal et al. (2009). The NPP was estimated by the equation (Eq. 4) as documented by Osaki et al. (1992):

$$\text{C (kg)} = 0.446 \times \text{DW (kg)} - 67$$

Grain yield, water use efficiency and evapotranspiration. At physiological maturity, maize plants were hand-harvested from an area of 13.2 m^2 (4 m × 3.3 m) per plot. The grains were separated, weighed and the grain yield per hectare was extrapolated.

Water use efficiency (WUE) was estimated using the equation (5) described in Wang et al. (2013):

$$WUE = \frac{Y}{ET} \qquad (5)$$

Where: WUE – water use efficiency; Y – grain yield (kg/ha); ET – total evapotranspiration over the entire growing season (mm).

Evapotranspiration (ET) was calculated using the equation (6) described in Wang et al. (2013) as follows:

$$\text{ET} = \text{P} - \Delta\text{W} \qquad (6)$$

Where: P – growing season rainfall; ΔW – change in the stored soil water for the soil profile (0–200 cm depth) before sowing and at harvest.

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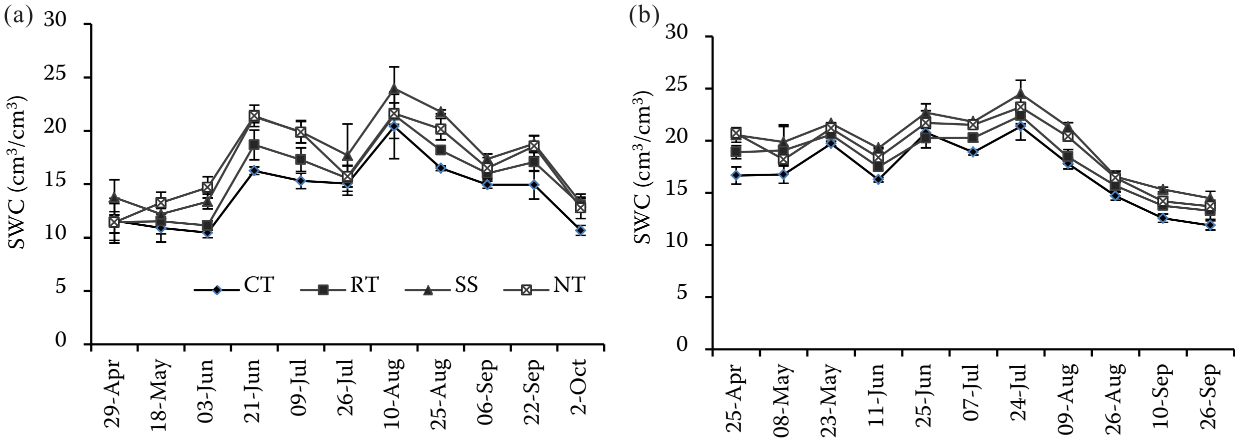

Figure 2. Diurnal soil water content in (a) 2014 and (b) 2015 under different tillage practices. Vertical bars represent the standard error (SE). Mean values ± SE from three replicates. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

The soil water content was measured at nine depth intervals as follows: 0–5, 5–10, 10–30, 30–50, 50–80, 80–110, 110–140, 140–170 and 170–200 cm for the calculation of water use efficiency and evapotranspiration. The volumetric soil water content (cm^3/cm^3) in the 10–200 cm depth was measured with Trime-Pico IPH (Precise Soil Moisture Measurement, IMKO Micromodul technik GmbH, Ettlingen, Germany). Soil water storage was estimated from the volumetric soil water content by multiplying it with the layer depth. Previous studies conducted at the study site reported no significant runoff or drainage during the growing season (Huang et al. 2008).

Statistical analyses. The data were analysed with the analysis of variance (ANOVA) at ($P < 0.05$) using the Statistical Package for the Social Sciences 22.0 (IBM Corporation, Chicago, USA). The differences between the means were determined using the Tukey's honest significance test (*HSD*) test.

RESULTS AND DISCUSSION

Soil attributes. Compared with CT and RT plots, SS treatments had 23.2% and 12.8% higher soil water content, respectively, in 2014 and 16.4% and 9.0% higher soil water content in 2015, respectively (Figure 2). Soil water content also increased under NT soils compared with CT soils, but the effect was lower than that in SS soils. This result is consistent with previous studies of Cai et al. (2014) who reported increased soil water in subsoiling. The average water-filled pore space was highest ($P < 0.05$) in the SS (18%) and NT (13%) compared with CT (Table 1). Significant differences ($P < 0.05$) were found in soil bulk density, total porosity and soil hydraulic conductivity (Table 1 and Figure 3). Compared to the CT plots, SS treatment decreased soil bulk density by 9% and increased total porosity and soil saturated conductivity by 7% and

Table 1. Soil bulk density (BD), total porosity (TP) and water-filled pore space (WFPS) measured at different soil depths (cm) under different tillage practices

Treatment	BD (g/cm^3)		TP (%)		WFPS (m/m^3)	
	0–5	5–10	0–5	5–10	0–5	5–10
CT	1.18 ± 0.01^a	1.23 ± 0.02^a	55.41 ± 0.25^b	53.67 ± 0.67^b	0.22 ± 0.00^b	0.26 ± 0.00^b
RT	1.15 ± 0.02^a	1.18 ± 0.02^{ab}	56.71 ± 0.89^b	55.65 ± 0.83^{ab}	0.25 ± 0.02^{ab}	0.28 ± 0.01^{ab}
SS	1.07 ± 0.02^b	1.13 ± 0.03^b	59.74 ± 0.79^a	57.46 ± 1.06^a	0.27 ± 0.01^a	0.30 ± 0.01^a
NT	1.13 ± 0.51^{ab}	1.16 ± 0.02^{ab}	57.50 ± 0.52^{ab}	56.35 ± 0.67^{ab}	0.25 ± 0.01^{ab}	0.30 ± 0.01^a

Mean values ± standard error (SE) from three replicates. Values with different letters within a column are significantly different at $P < 0.05$. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

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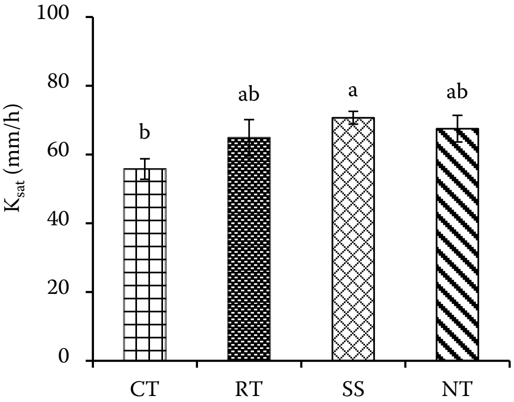

Figure 3. Soil saturated hydraulic conductivity (K_{sat}) under different tillage practices. The different letters in the figure are statistically different at $P < 0.05$. Vertical bars represent the standard error (SE). Mean values ± SE from three replicates. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

27%, respectively. Abu-Hamdeh (2003) reported improved topsoil structure and characteristics under subsoiling. Govaerts et al. (2009) noted that high bulk density resulting in reduced aeration is associated with compaction by tillage implements, but Zhang et al. (2013) noted that, the effect depends on depth and method of tillage.

Soil respiration and carbon emission. The diurnal soil respiration had similar patterns for the 2014 and 2015 growing seasons (Figure 4). The highest emission peak occurred on 25 August 2014 (Figure 4a) and on 9 August 2015 (Figure 4b). The emission values for the peak ranged from 0.73–0.94 μmol/m^2/s in 2014 and 0.77–0.90 μmol/m^2/s in 2015. The results of this study are consistent with the findings of Meng et al. (2006) who demonstrated that soil respiration of maize changed with crop growth, peaked in July and then declined gradually. Significant effects ($P < 0.05$) on soil respiration were observed on five occasions in 2014 and on seven occasions in 2015 when the lowest diurnal soil respiration were observed for the SS and NT treatments and the highest emissions occurred from the RT and CT plots.

Subsoiling significantly decreased average soil respiration by 22% and 15% in 2014 compared to CT (Figure 5), similar values were 19% and 13% in 2015 (Figure 5). In a lesser magnitude, NT decreased average soil respiration compared to CT. Subsoiling and NT, consequently, decreased carbon emissions significantly, compared to CT (Figure 6). The significant soil respiration decreased in SS and NT may be related to the improvement in soil properties as seen in the increases in porosity and saturated conductivity. Govaerts et al. (2009) observed significant reduction in CO_2 emission with improvement in soil properties. It was shown that soil compaction plays an important role in microbial activity since the increase in soil density leads to decreased pore space and lower soil respiration due to reduced oxygen availability for microbial respiration (Tan et al. 2005). Generally, the soil in this study may not be compacted so much that it could limit oxygen availability, which interferes with soil organisms' ability to respire. In this study, soil respiration significantly correlated with soil water content, soil bulk density and saturated hydraulic conductivity (Figure 8), suggesting a greater extent of effects of soil physi-

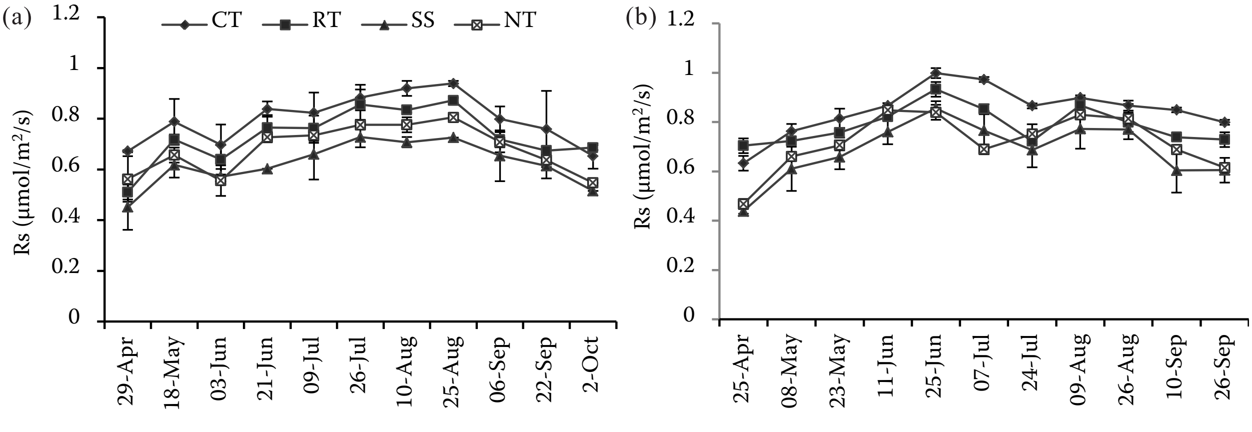

Figure 4. Diurnal soil respiration (Rs) in (a) 2014 and (b) 2015 under different tillage practices. Vertical bars represent the standard error (SE). Mean values ± SE from three replicates. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

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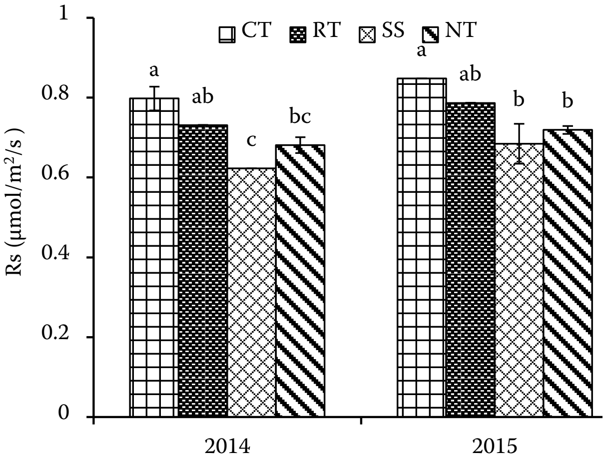

Figure 5. Average soil respiration (Rs) in 2014 and 2015 under different tillage practices. The different letters in the figure are statistically different at $P < 0.05$. Vertical bars represent the standard error (SE). Mean values ± SE from three replicates. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

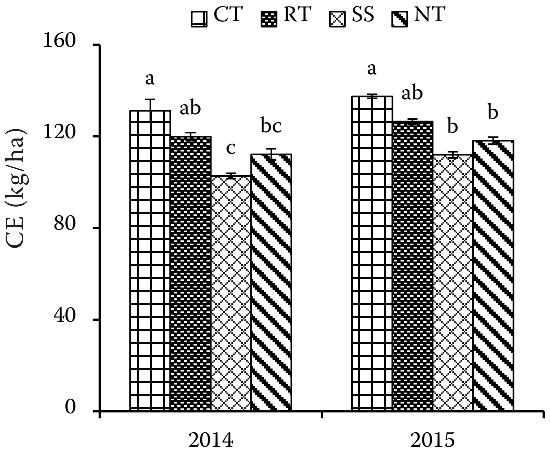

Figure 6. Average carbon emission (CE) in 2014 and 2015 under different tillage practices. The different letters in the figure are statistically different at $P < 0.05$. Vertical bars represent the standard error (SE). Mean values ± SE from three replicates. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

cal parameters on soil respiration. These results are consistent with previous studies of Yeboah et al. (2016). These findings imply that SS practice is unlikely to increase soil respiration from semiarid agricultural soils, and therefore may have the potential to act as a C sink.

Net primary production and net ecosystem production. In the present study, both SS and NT showed significant ($P < 0.05$) benefits in sequestering carbon (Table 2), but the effect of SS was the greatest. The NPP in 2014 was greatest ($P < 0.05$) in the SS (29%) and NT (27%), followed by RT (23%) compared to CT (Table 2). The corresponding values for NEP in 2014 were 37% in SS, 33% in NT and 28% in RT. SS increased NPP along with NEP in 2015 (by 22% and 29%) compared to CT. In a lesser magnitude, NT increased NPP and NEP compared to CT. An increase in grain yield and C inputs resulted in improved C-sequestration (Alletto et al. 2010). The findings suggest that the adoption of SS can significantly reduce potentially negative impacts of farming on the environment.

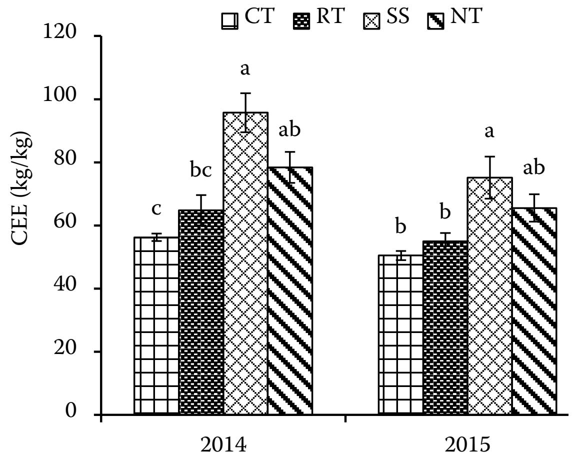

Figure 7. Carbon emission efficiency (CEE) in 2014 and 2015 under different tillage practices. The different letters in the figure are statistically different at $P < 0.05$. Vertical bars represent the standard error (SE). Mean values ± SE from three replicates. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

Carbon emission efficiency. Carbon emission efficiency determined how much grain yield was associated per unit of carbon emitted. SS had CEE of 95.73 kg/kg in 2014 and 75.14 kg/kg in 2015, or 70% and 49% more compared to CT (Figure 7). In a less magnitude, NT increased CEE by 39% in 2014 and 30% in 2015 relative to CT. Basically, an increase in CEE could be achieved through either an increase in grain yield or a decrease in soil respiration or both. In this study, the greater CEE achieved by SS could be related to the increase in grain yield and reduction in carbon emission. This finding is consistent with earlier works (e.g., Burney et al. 2010), that the net effect of higher yields offsets emissions. This result demonstrates that SS and NT tillage practices are options for maintaining environmental sustainability, without

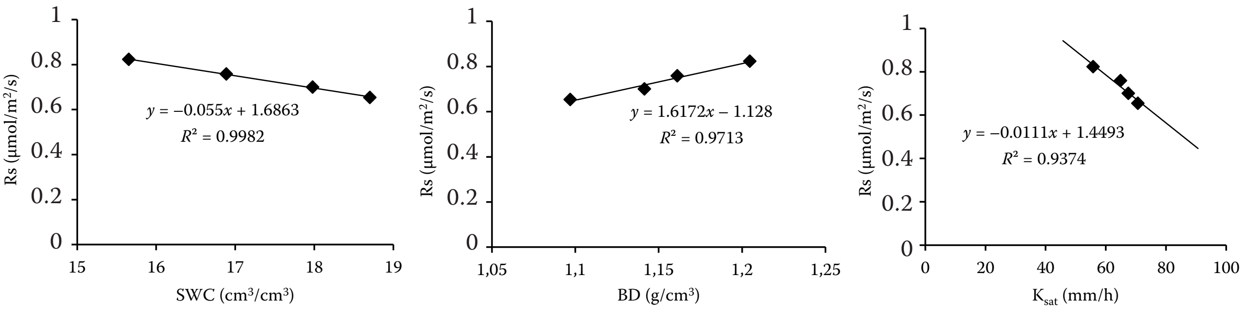

Figure 8. Relationship between average soil respiration (Rs); soil water content (SWC); soil bulk density (BD) and saturated hydraulic conductivity (K$_{sat}$)

Table 2. Net primary production (NPP) and net ecosystem production (NEP) under different tillage practices in 2014 and 2015

Treatment	NPP (g C/m^2/season)		NEP (g C/m^2/season)	
	2014	2015	2014	2015
CT	823.78 ± 5.40^{b}	813.75 ± 15.77^{c}	714.45 ± 9.45^{b}	699.11 ± 16.48^{c}
RT	1015.07 ± 24.12^{a}	837.81 ± 11.87^{bc}	915.17 ± 23.53^{a}	732.41 ± 10.91^{c}
SS	1065.65 ± 9.88^{a}	995.83 ± 7.39^{a}	980.19 ± 10.84^{a}	902.59 ± 7.90^{a}
NT	1041.41 ± 12.30^{a}	880.68 ± 1.81^{b}	948.04 ± 14.29^{a}	782.28 ± 2.95^{b}

Mean values ± standard error from three replicates. Values with different letters within a column are significantly different at $P < 0.05$. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

Table 3. Grain yield and water use efficiency (WUE) of maize under different tillage practices in 2014 and 2015

Treatment	Grain yield (kg/ha)		WUE (kg/ha/mm)	
	2014	2015	2014	2015
CT	7378.58 ± 238.92^{c}	6936.38 ± 42.56^{b}	22.51 ± 1.90^{b}	22.42 ± 0.46^{c}
RT	7786.73 ± 132.08^{c}	6948.82 ± 118.49^{b}	22.27 ± 1.05^{b}	29.10 ± 0.61^{ab}
SS	9813.24 ± 155.35^{a}	8298.86 ± 131.83^{a}	32.06 ± 2.26^{a}	30.70 ± 0.75^{a}
NT	8763.86 ± 138.16^{b}	7738.11 ± 185.89^{a}	27.05 ± 1.77^{ab}	26.27 ± 0.65^{b}

Mean values ± standard error (SE) from three replicates. Values with different letters within a column are significantly different at $P < 0.05$. CT – conventional tillage; RT – rotary tillage; SS – subsoiling; NT – no-till

confounding effect on yield in Loess Plateau area in China.

Grain yield and water use efficiency. SS and NT increased grain yield compared to CT, but the effect of SS was the greatest (Table 3). The grain yield in 2014 was greatest ($P < 0.05$) in the SS (33%) and NT (26%) compared to CT, similar values were 20% and 19% in 2015. As a result, a case study in Southern China or 42% and 40% more compared to CT (Table 3). Among tillage practices evaluated in the study, subsoiling and no till (i.e. SS and NT) conserved more water and increased grain yield. A lower water consumption (data not shown) under SS and increased grain yield, indicates improved water use by crops. These results could be attributed to optimized water balance and improved soil physical properties (Fan et al. 2012). These results imply that subsoiling can deepen the active soil layer to improve the capacity of soil water harvesting and optimization of water balance in semi-arid environments. The results clearly show that SS is an ideal practice for reducing carbon emission, increasing net ecosystem production, grain yield and carbon emission efficiency in the semi-arid environment.

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