Available online www.jocpr.com

Journal of Chemical and Pharmaceutical Research, 2015, 7(3):2353-2360

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Tillage and straw affect soil CO_2 emissions in a rain-fed corn field

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ABSTRACT

A field study was conducted to assess the effects of soil tillage practices and straw management on soil CO_2, and yield-scaled CO_2 emissions in a rain-fed summer corn field on the Loess Plateau. Tillage treatments consisted of sub-soiling tillage (CP), no tillage (NT) and moldboard plow tillage (CT). Wheat straw was removed from half of the CP, NT and CT plots after harvest, allowing us to test for interactive effects between tillage practices and straw management. Soil CO_2 emissions, soil moisture and soil temperature were recorded 12 times throughout the growing season. Across treatment combinations, the highest cumulative CO_2 emissions were recorded in CT^+, the lowest emissions were recorded in NT^-. Straw return increased cumulative CO_2 emissions to 19%–27% compared to the straw removal treatment. We concluded that conservation-focused tillage systems, i.e., no tillage, could reduce yield-scaled CO_2 emission; thus, they can produce better yields and provide environmentally friendly options.

Keywords: conservation tillage; straw management;CO_2 emission; yield-scaled

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INTRODUCTION

Carbon dioxide (CO_2) is the most important greenhouse gas in terms of its contribution to global warming [1]. During the last two centuries, arable farming has led to a worldwide decline in soil organic C (SOC) stocks[3]. About 25% of anthropogenic CO_2 emissions are due to agricultural practices [2]. Soil disturbance due to tillage operations is assumed to contribute to decrease in the physical protection of soil organic matter against microbial degradation [4, 5]. Moreover, crop fields are managed to maintain nearly neutral pH levels and drained to avoid water logging, which further increase microbial oxidation of SOC. Finally, crop fields are typically covered with vegetation for a relatively short time compared to natural ecosystems, causing lower soil C input rates [6].These issues spurred a research interest in management practices that may slow down or partly reverse C losses from crop fields [7, 8].

Reduced tillage and straw return have been suggested as management practices to increase soil C contents. Conservation agriculture has been promoted as an agricultural practice that increases agricultural productivity, reduces soil erosion, and increases soil C storage [9-12]. A number of field's studies were conducted previously to estimate the emission of CO_2 and its influence factors under different tillage systems, and they reported conservation agriculture practices have potential to sequester C and reduce CO_2 emission [13, 14]. There are, however, contrasting reports as to the potential of conservation agriculture practices for C sequestration [15-17], where they reported the similar CO_2 emission under no tillage and moldboard plow tillage or more CO_2 emission in no tillage as compared with moldboard plow. Soil temperature and moisture are two key factors for CO_2emission [18, 19]. Soil respiration of ecosystem can mainly be divided into the heterotrophic (microbes and soil animals) and autotrophic (plant root) activities and both of these factors are controlled by the environmental conditions (mainly temperature and water),

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availability of carbohydrates and substrates and others [20, 21]. Many studies have shown that seasonal variations in CO_2 emissions were mainly caused by the soil temperature, soil moisture or the combination of both these factors [22].

Rain fed fields account for about 56% of the arable area in China [23]. Summer corn (*Zea mays L.*) is a major crop, generally grown in semi-arid areas of north-west China. Most of the summer corn in this area is grown without irrigation by using intensive tillage methods *i. e.* mold board plow tillage. It is considered as one of the factors for soil erosion. However, it is not clear to what extent tillage practices and straw management affect emissions of CO_2 and crop yield in this area. Such information is essential to improve understanding of the controls over soil C dynamics and crop production under agricultural management. As the global food demand continues to increase, attempts to reduce area-scaled greenhouse gas emissions have a risk of reducing crop production [24]. Thus, to minimize the overall greenhouse gas (GHG) impact of agriculture, the amount of greenhouse gas emitted per unit of crop production needs to be considered [25].

In this study, we assessed the effect of six different tillage × straw management combinations on the grain yield, CO_2 emissions and its influence factors such as soil moisture, temperature and bacterial numbers, and yield-scaled CO_2 emissions in a rain fed corn field in Northern China. We hypothesized that tillage methods and straw levels would cause a significant difference in emissions of CO_2 and crop yield. As reduced tillage practices and straw typically increase soil moisture contents[26], we further hypothesized that the least intrusive tillage practices and straw would result in the highest crop yields in this water limited system.

EXPERIMENTAL SECTION

2.1. Study Site

The experiment was conducted on Cinnamon Loess soil at the Dry-land Experimental Station of Northwest A & F University, Yangling Town, Shaanxi province, in the Northwestern part of China (longitude 108°10´E, latitude 34°21´N, 454.8 m a.s.l.). The soils at the experimental site are classified as silt loam texture (sand 19%, silt 77%, and clay 4%) according to the USDA Texture Classification System, with a mean bulk density of 1.3g cm^{-3}. The soil in the top 20 cm had a pH of 7.3, a soil organic matter content of about 14g kg^{-1} and a total nitrogen content of 740 mg kg^{-1}. Available phosphorus was 18 mg kg^{-1}; available potassium was 129 mg kg^{-1}. Prior to our study, winter wheat was planted.

The study area is characterized by a semi-arid climate with an annual average temperature of 13 °C, annual average precipitation of 622 mm, and annual potential evaporation of 993 mm. Rainfall data and the mean monthly air temperature for the 2012 growing season at the experimental site are shown in Table 1. The last rainfall before plowing occurred on 8 June (11 mm) and the first rainfall after sowing occurred on 25–26 (combined total of 30 mm).

2.2. Design and Treatments

The experiment consisted of a randomized complete block design with three replications. The individual plots were3.2 m×15 m, with 0.5 m between plots. The treatments included three tillage systems: sub-soiling tillage (CP), no tillage (NT), and conventional tillage (CT); two levels of straw: straw retained (+), and straw removed (-). Straw was removed from half of the CP, NT and CT plots on 14th June 2012.

In the CT plots, the soil was plowed to 20–25 cm depth by using a mold board plow (Dong fanghong-LX954, China) followed by a rotavator (15 cm) for the final seed bed preparation on 16 June 2012. In the subsoil tillage plots (CP), a chisel plow with a shank spacing of about 40 cm apart and 30-35 cm depth was used. In the NT plots, no tillage was applied. Since the start of the experiment, annual tillage operations in all treatments occurred in June and October. After tillage, 375 kg ha^{-1} super-phosphate (P_2O_5 46%) was spread evenly to each plot in June and October. Summer corn (*cv.* Shan dan-609) was sown in the CT and CP plots with disk coulters to 6-8 cm depth at a rate of 30 kg ha^{-1} on 16 June 2012 by a common maize seeder. In the NT plots, corn was sown by direct drilling. The corn row space was 70 cm and plant space was 25 cm. An application of 172 kg N ha^{-1} as urea was applied to the corn crop at 5 cm depth near the plant at the 7 leaf stage and weeds were controlled according to local recommendations. Samples for grain yield were randomly selected from each treatment with three replications at crop maturity stage. In addition, components, *i.e.*, effective spikes, grain numbers per spike and 100 grain weight, were recorded. Soil bacterial numbers were recorded at the corn harvesting stage, and 5–10 cm fresh soil was taken by using the hand augur which was sterilized by 75% medicinal alcohol. Immediately, the soil bacteria content was measured by using fresh soil according to the method [27].

2.3. Soil CO_2 Measurements

Soil respiration rates were measured using the closed chamber method[28]. Soil CO_2 emissions were measured on 1, 15, 25, 30, 35, 40, 45, 55, 65, 75, 85, 110 days after planting from July 17 to October 7, 2012, resulting in a total of 12 sampling days. Chambers applied for the study were cylindrical (21 cm in diameter and 13.5 cm in height) and made of polyvinyl chloride. The chambers were randomly placed in each experimental plot and inserted about 5 cm into the soil, and remained in place during the entire monitoring period (June–October 2012). On sampling days, an infrared gas analyzer (Beijing Huayun Carbon Dioxide analyzer GXH---3010EI, Huayun, China) was attached to the chambers by using intake and outtake silicone tubes (Figure1).

The initial CO_2 concentration inside the chamber (*i.e*., X_1) was recorded without covering the chamber. The chamber was then covered by an airtight lid with a fan for three minutes, after which the CO_2 concentration was measured again (*i.e*., X_2). Soil respiration was calculated from Eq. (1):

$$F=K(X_2-X_1)\ H/\triangle t \quad (1)$$

Where F is the soil respiration value (mg m^{-2} h^{-1}), K is reduction coefficient, K=1.80 (25°C, 1Pa), H is the height of chambers, $(X_2 - X_1)/\triangle t$ is the rate of change of the CO_2 concentration inside the chamber (mg m^{-2} h^{-1}). During each CO_2 measurement, soil temperature at a depth of 10cm was recorded simultaneously at three points near the chambers by using angle stem earth thermometer. Gravimetric moisture contents in the 0-10 cm soil layer were determined in each plot by taking three soil core samples using a 50-mm-diameter steel core sampling tube. Fresh soil samples were immediately taken to the laboratory and weighed then dried in an oven at 105°C for at least 48 hours. Soil water contents were calculated from the difference between initial soil weight and weight after drying.Cumulative CO_2 emissions were calculated by using the methods described in detail by Wilson and Alkaisi [29].

$$CO_2\ (\mathrm{kgha}^{-1}) = \sum_{n=i}^{n=last} Xi + Xi + 1 * N + Xi + 2 * N + ... + Xi + Xi + n * N \quad (4)$$

Yield-scaled CO_2 emissions were calculated by dividing cumulative CO_2 emissions by crop yield.

2.4. Statistical Analysis

Mean values were calculated for each measurement and ANOVA was used to assess the effects of different tillage practices on the measured variables. When this indicated a significant F-value at Probability levels of 0.01 and 0.05, multiple comparisons of mean values were made on the basis of the least significant difference (l.s.d.). All statistical analyses were conducted using SPSS 12.0.

RESULTS AND DISCUSSION

3.1. Soil CO_2 Emissions

Soil CO_2 emission fluctuated over time, the lowest CO_2 emission was recorded at the maturity stage (day 110). Tillage and straw levels had significant effects on CO_2 emission during summer corn growth season. The emission of CO_2 reached the maximum value on 15 days (3th, July) after tillage, which was mainly due to 73.7 mm rainfall occurred on 1, July (Table 1). These CO_2 peaks just after rainfall were the greatest in all the sampling days and ranged from 97.2kg ha^{-1} day^{-1} under NT^{-} to 340.8kgha^{-1} day^{-1} under CT^{+}. The stimulatory impact on CO_2 emission after rainfall may be explained by several factors. First, seeping water could displace CO_2 in soil, restrains diffusion of CO_2 in soil pores. Rainfall could also increase CO_2 emissions by stimulating microbial activity, which is typically limited by water in arid and semi-aid ecosystems [30].

Tillage methods and straw management both significantly affected soil CO_2 emission rates ($P<0.01$) (Table 2, Table 4). In all treatments, CO_2 emission began to increase at the end of June reaching a peak at the germination stage (about 15 days after tillage). After that, CO_2 emissions declined fast, the lowest CO_2 emission rates were recorded at the maturity stage.The NT^{-}treatment showed relatively small and steady CO_2 emissions as compared with others during the entire period (Table 2). It appears from tables 2 that strawreturn increased CO_2 emission rate as compared with straw removal treatment.

Tillage, straw management and tillage×straw interactions had significant effects on the cumulative CO_2 emissions (Figure2a, Table 4), the total highest emissions were recorded for the mold board plow tillage, followed by chisel plow tillage plantingmethod, and no tillage recordedthe lowest CO_2 emissions(Figure2a, Table 4).Theseresults are consistent with soil preparation depths. Similar results have been previously reported [31, 32],these studies found that the greater the tillage depth, the higher the CO_2 emissions. Our results are in agreement with conclusions from other researchers, who reported more CO_2 released from intensive tillage owing to the greater amount of organic matter in soil pores exposed to the air resulting in accelerating the decomposition of soil organic matter by tillage methods[33].NT reduced CO_2 emission 39% as compared with CT (Table 4), which is similar to other studies [34], where they reported NT could mitigate CO_2 emission up to 50% as compared with CT.

Table 1. Mean monthly air temperature (℃) and rainfall (mm) during summer corn growing season in the experimental site

Time	**Mean air temperature(℃)**	**Rainfall (mm)**
June	25.2	41
July	26.0	103
August	24.1	116
September	18.2	105
October	13.7	18

Values in each column followed by different letters are statistically different at p<0.05 level.

Table 2. CO_2 emissions (kg ha^{-1} day^{-1}) affected by tillage and straw methods during summer corn growing season (2011–2012)

Treatments	**Days after planting (d)**											
	1	**15**	**25**	**30**	**35**	**40**	**45**	**55**	**65**	**75**	**85**	**110**
CP-	79.7b	221.6b	180.1b	117.9b	116.6cd	68.0d	120.5d	99.1e	63.5c	73.9d	56.4e	37.6d
CP+	93.3a	207.4c	154.2c	117.9b	127.0b	126.4b	156.8b	129.6c	102.4a	132.2a	99.1a	81.6ab
NT^-	21.4e	97.2e	93.3e	45.4c	60.9e	44.7e	54.4e	40.8f	40.2d	25.3e	31.1f	19.4e
NT^+	50.5c	187.9d	132.2d	117.9b	110.2d	89.4c	138.7c	120.5d	102.4a	73.9d	66.1d	55.7b
CT^-	40.8d	180.1d	156.8c	142.6a	159.4a	66.1d	140.0c	141.9b	77.8b	81.6c	77.8c	49.2c
CT^+	89.4a	340.8a	307.2a	134.8a	121.8bc	136.1a	178.8a	161.4a	66.1c	106.9b	89.4b	40.2d

Values in each column followed by different letters are statistically different at P<0.05 level

Table 3. Components of summer corn affected by tillage and straw methods

Treatments	Components of yield			
	Effective spikes	Grain numbers per spike	100 grain weight (g)	Yield (kg ha^{-1})
CP^-	48797ab	628a	29.7ab	9073a
CP^+	48809ab	611b	30.8a	9165a
NT^-	46217 b	564cd	30.4ab	7904bc
NT^+	48352 ab	560d	30.9a	8601ab
CT^-	46712 b	565c	28.0b	7397c
CT^+	50725 a	555e	28.7ab	8060bc

Values in each column followed by different letters are statistically different at P<0.05 level.

Table 4. ANOVA (Mean Square Value) of yield components, cumulative emissions of CO_2 and yield-scaled CO_2 emissions during crop season (2011-2012)

Source	**D.F**	**Effective spike**	**Grain per spike**	**100 grain weight**	**Grain yield**	**Total CO_2 emission**	**Yield scaled CO_2**	**Bacterial Numbers**
Block	2	37797	81**	36.8**	1980554**	4.4**	0.0	69**
Tillage	2	4369873	6939**	9.0*	2958749**	83.7**	1.5**	9784**
Straw	1	18968694	483**	2.7	1054560	45.9**	0.4**	2399***
Tillage×straw	2	6011606	57**	0.1	173968	1.7**	0.0	334**

*Note: * $p < 0.05$, ** $p < 0.01$.*

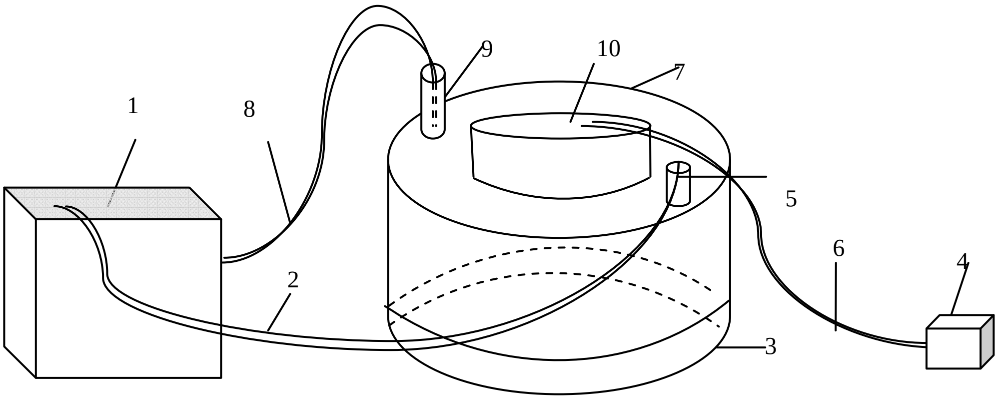
CO_2 emission was significantly influenced by straw levels. Straw return increased CO_2 emission (Table 2, Figure2a), which may be due to these reasons: straw returnin the field supported carbon and energy for soil bacterial, which increased bacterial numbers (Figure4) and activity resulting in more CO_2 emission and plant respiration. Our results were similarly to Qiang et al.[35] who reported soil respiration was increased by the straw return treatment. However, in some parts of the world, straw is removed from fields for other uses (such as fuel for heating), instead of burning crop residues, straw return in fields can be great beneficial for soil fertility [36], Edmeades[37] reported that residue return treatment can support essential nutrients to crops and reduce CO_2 emissions into the atmosphere, which resulted from the burning of the crop residues. Our results indicated that straw return with no-till treatment can reduce CO_2 emission while maintaining crop productivity.

3.2. Soil Temperature and Soil Moisture versus CO_2 Emissions

During the corn growth season, the average of soil temperature was the lowest (23.4) in NT^+, while in CT^-; the highest temperature value (25.2) was recorded. Straw return reduced soil temperature (Figure 3a). Similar to soil temperature, tillage and straw methods has an influence on soil moisture, straw return increased soil moisture contents by 0.14% in CP, by 2.60% in NT, and 1.02% in CT tillage, respectively (Figure 3b).

CO_2 emission from croplands is influenced by climate and atmospheric concentration of CO_2, management practices, nutrients, rate of residue decomposition, biological, chemical and physical soil properties[38]. Soil CO_2

concentration could be influenced by soil temperature and soil water contentby altering soil diffusivity [39, 40]. Our results indicated that NT and straw return treatments could reduce soil temperature and increase soil water content. This may be related with soil microbes and crop roots, which are influenced by soil properties.



a. Machine part

b. Airtight container part

Figure.1. Closed chamber system to measure soil respiration. gas analyzer, 1; silicon tubes (0.7 cm in diameter), 2 and 8; base ring, 3; outside lid, 7; inside lid with fan attached, 10; fan battery, 4; power line connecting battery and fan, 6;intake and outtake of gas analyzer, 5 and 9

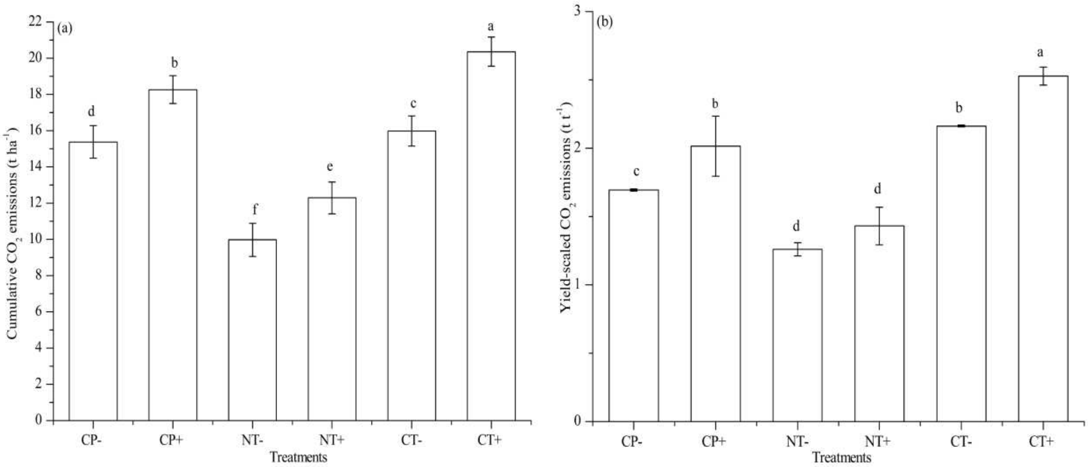


Figure.2. Cumulative CO_2 emissions and yield-scaled CO_2 emissions as affected by different tillage methods and straw levels during summer corn growth (2011-2012). (a). Emissions of cumulative CO_2emissions from different tillage methods and straw levels, (b). Yield-scaled CO_2emissions from different tillage methods and straw levels,*i. e.* CP^-, sub-soiling tillage with straw removal., CP^+, sub-soiling tillage with straw return, NT^-, no tillage with straw removal., NT^+, no tillage with straw return., CT^-, mold board plow tillage with straw removal., CT^+, mold board plow tillage with straw return

3.3. Bacterial Numbers versus CO_2 Emissions

Tillage and straw methods had significant effects on bacterial numbers from 5-10 cm soil depths; the highest bacterial numbers was recorded following CP^+ tillage (Figure 4). Higher bacterial numbers were recorded for other treatments during crop growth season as compared with CT^- (Figure. 4). The straw return treatment increased the bacterial numbers compared to the straw removal treatments (Figure4), which is similarly to CO_2 emission and the bacterial numbers order in different tillage was: CP>NT>CT. In our study, more CO_2 emissions, and soil bacterial numbers were recorded in straw return methods, this results may be helpful in the soil fertility, and soil carbon sequestration [41].

3.4. Crop Yield

There is a significant impact on crop yield related to tillage and straw levels; CP significantly increased crop yield as compared with other tillage treatments (Table 3,Table 4), this is mainly because the porosity of the soil upper layer was increased by mold board plow tillage practice by altering soil structure. This method increases the initial water infiltration into the soil, but total infiltration is often decreased by subsoil compaction; thus, a lot of rainfall as run-off and large amounts of soil may be lost through erosion [42, 43]. However, sub-soiling tillage deepens the plough layer andconserves soil water without plowing soil, which is a benefit for crop root deepening and crop production. In our study, NT^- and NT^+ increased yield by 6.8% and 16.3% relative to CT^-, respectively, in accordance with Lal [44] who reported no tillage increased corn yield by 20.63% and 18.92% as compared with plow-till for the first growing season and second season, respectively. However, lower wheat yield in NT than CP was recorded. This result can probably be explained by these reasons: it is difficult for seed to come out from the soil due to hard soil in no tillage(In our study, NT reduced effective spikes and grain numbers per spike as compared with CP). Also,greater bulk density in NT compared with CP is not good for crop growth. Moreover, in our study,NT reduced soil temperature (Figure3a) and lower temperature slowed down the crop growth. Straw return treatment reduced soil temperature due to low thermal conductivity of materials. Straw return in fields reduced soil temperature by reflecting sunshine and restraining evaporation. Low soil-surface temperatures related to residue return were recorded in our study; this result is in accord with those reported byGriffith et al. [45] and Gupta et al.[46].

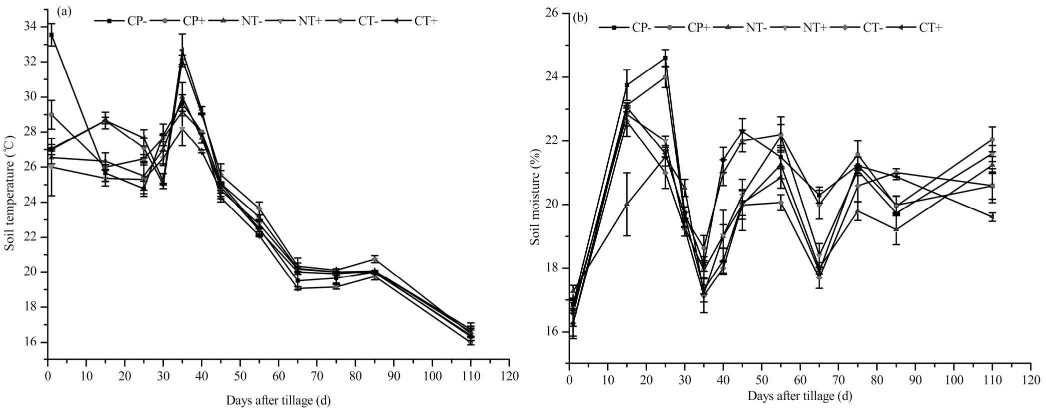


Figure.3. Soil temperature and soil moisture affected by different tillage methods and straw levels during summer corn growth (2011-2012). (a). Soil temperature from different tillage methods and straw levels. (b). soil moisture from different tillage methods and straw levels,*i.e.* CP$^-$, sub-soiling tillage with straw removal. CP$^+$, sub-soiling tillage with straw return. NT$^-$, no tillage with straw removal. NT$^+$, no tillage with straw left. CT$^-$, mold board plow tillage withstraw removal. CT$^+$, mold board plow tillage with straw return

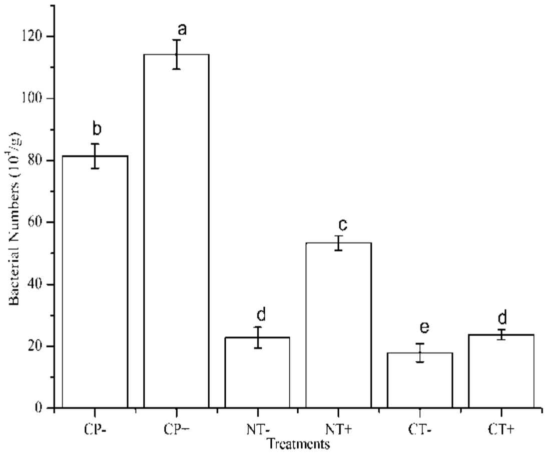


Figure.4. Bacterial numbers as affected by different treatments during corn growth season, *i.e.* CP$^-$, sub-soiling tillage with straw removal. CP$^+$, sub-soiling tillage with straw return. NT$^-$,no tillage withstraw removal. NT$^+$, no tillage with straw return. CT$^-$, mold board plow tillage with straw removal. CT$^+$, mold board plow tillage with straw return

3.5. Yield-Scaled CO_2 Emissions

Many studies evaluated CO_2 emission and its impact factors, but yield-scaled CO_2 emission was not included. In this study, we evaluated yield-scaled CO_2 emissionsby using total CO_2 emissions divide crop yield. Our results showed that yield-scaled CO_2 emissions were significantly affected by different tillage and tillage methods×straw interaction (Table 4, Figure 2b). CT$^+$ had the highest (2.53t t^{-1}), followed by CT$^-$ (2.16t t^{-1}), and NT$^-$ (1.26t t^{-1}) was the lowest as compared with others treatments. The trend of yield-scaled CO_2 for different tillage treatments was CT$^+$>CT$^-$>CP$^+$>CP$^-$>NT$^+$>NT$^-$ (Figure 2b).

CONCLUSION

This study presents data applicable for reducing soil CO_2 emission for rain fed agricultural field. We found that the cumulative CO_2 emissions were lowest in NT$^-$ (9.98 t CO_2-C ha^{-1}) as compared with other treatments. CT$^+$ has the highest cumulative CO_2 emissions (20.36 t ha^{-1}), followed by CP$^+$ (18.26 t ha^{-1}),by CT$^-$(15.98 t ha^{-1}), by CP$^-$(15.38

t ha^{-1}), by NT^{+} (12.29 t ha^{-1}). NT^{-}treatment has the lowest yield-scaled CO_2 (1.26 t t^{-1}). Besides, tillage methods, straw levels, soil temperature, soil moisture content and soil bacterial numbers had an influence on CO_2 emissions. No-till and straw return could increase soil moisture content and reduce soil temperature. Furthermore, microbial activity is greater in no-till (yet not increasing C emissions) than that of mold board plow. Therefore, no-till can help further in increasing crop yield and land productivity while also reducing CO_2 emissions, thus increasing C sequestration and soil organic matter/C levels (thus, reducing fertilizer applications because more soil nutrients are being supplied during the growing season). Future study on the interactions of tillage and straw management would be helpful in elucidating recommended agricultural managements for increasing soil fertility, and maintaining high corn yields while reducing CO_2 emissions. Additionally, future research is needed to determine the longer-term effects of no tillage on annual CO_2 emissions, C storage and crop yields on China's Loess Plateau.

Acknowledgments
We thank Kees Jan van Groenigen for language improvements. The study was supported by the National Natural Science Foundation of China (31071375, 31171506) and the Northwest Agriculture and Forestry University of Science and Technology Fundamental Research special funds for the project (PY200904).

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