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Original Research

Effect of No-Till Farming and Straw Mulch on Spatial Variability of Soil Respiration in Sloping Cropland

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Abstract

The two major techniques of conservation agriculture – no-till and straw mulch – are widely used in agricultural activities. Many studies have investigated the response of soil respiration to conservation agriculture. However, there are few studies estimating soil CO_2 emissions in sloping cropland. For this research we selected typical sloping cropland in China's semiarid Loess Plateau region. The spatial heterogeneity of soil respiration under different tillage and straw mulch was investigated using an LI-8100A soil carbon flux measuring system from October 2013 to September 2014. Soil respiration showed a strong seasonal pattern under all treatments, with the highest values in July (3.42-8.26 μmol m^{-2} s^{-1}) and the lowest in January (0.16-0.33 μmol m^{-2} s^{-1}). No-till increased soil respiration by increasing soil temperature and soil moisture, while straw mulch decreased soil moisture and had the tendency to increase annual total carbon emissions, and straw incorporation had the highest annual total soil carbon emissions (992 g C m^{-2}). The slope stage had a visible effect on soil respiration, and soil respiration rates increased in the following order: lower > middle > upper positions under different treatments. The relationship between soil respiration and soil moisture was linear under all treatments; the exponential model was more suitable for simulating the relationship between soil respiration and soil temperature. Temperature sensitivity (Q_{10}) values under different treatments ranged from 1.94 to 2.63, and the difference among tillage and straw mulch treatments as a whole was not significant. However, the Q_{10} values had a tendency to decrease from summit to foot in tillage treatments, and no-tillage would reduce spatial variability of Q_{10} values.

Keywords: no-till, straw mulch, straw incorporation, Loess Plateau, slope position

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Introduction

Soil microbial respiration, which produces approximately 80 to 100 Pg CO_2-C annually, plays an important role in the global carbon cycle [1-2]. Small changes in CO_2 emissions due to land use changes and farm management practices may have a major effect on atmospheric CO_2 concentrations [3-4]. Agricultural land represents about 40-50% of the Earth's land surface [5], and is likely to increase in the future due to increasing food demand for rapidly growing human populations [6]. Agricultural activity and farm management practices can have either a positive effect on soil quality by sequestering C in soil or enhancing the release of soil C as CO_2 into the atmosphere [7-8].

Conservation practices, including no-till and covering surface soil with crop residues (mulching), play important roles in controlling soil erosion, enhancing crop productivity and improving soil fertility [9]. Several studies have reported the effect of no-till and straw mulch on soil microbial respiration and carbon storage [4, 7, 10-12]. Some researchers have reported that tillage accelerates soil disturbance, destroys the stability of soil aggregates, and promotes CO_2 emissions [13], while others have reported no such effect of tillage management on soil CO_2 emissions [4, 14-16] or reduced soil respiration [17]. Straw mulch obviously affects soil CO_2 emissions by changing soil physical and chemical properties [18], and straw decomposition itself also release some amounts of CO_2 [19-20]. In general, straw mulch is reported to stimulate soil microbial activity and respiration, which leads to increased CO_2 emissions to the atmosphere [21-23]. On the other hand, some authors suggest that the long-term application of crop residues increase the content of small macroaggregates (>250μm) in 0-10 cm depth, which then lead to the accumulation of high carbon and nitrogen concentrations, which in turn serve as a substrate for microbial growth and subsequent CO_2 emissions [21]. However, some researchers did not see such positive effects of straw mulch on soil microbial respiration [10] or reduced soil respiration [24]. Such a lack of response of added straw on CO_2 emissions could be due to several factors: 1) straw mulch decreases soil temperature, 2) residues could serve as a barrier for CO_2 emissions from soil to the atmosphere, and 3) residue decomposition rate was low due to minimum residue-soil contact [24-25].

Soil microbial respiration is reported to be variable in space, especially in sloping land possibly due to differences in soil chemical and biological properties, plant types and community, soil moisture, and soil redistribution [12, 26-28]. Most studies have reported that soil temperature and moisture affect soil microbial respiration as first-order and second-order, respectively, meaning that each degree rise in soil temperature influences soil microbial respiration [12, 26]. Soil erosion, transportation, and deposition by water and tillage drastically affect the distribution of soil organic C, which then influences the exchange of carbon between the pedosphere and the atmosphere [28-30]. Van Hemelryck et al. [28] measured soil respiration shortly after an erosion event on depositional and comparable sites without sedimentation and found a slightly increased mineralization of soil organic carbon at depositional sites. But this effect was only important in the short term. The results correspond to the findings of a laboratory study [31] where a similar but more pronounced increase in soil microbial respiration after soil deposition due to a soil disturbance that exposed protected C in soil aggregates to microbial decomposition. In contrast to these results, Bajracharya et al. [32] and Parkin et al. [27] did not find any significant differences in soil respiration measured at different slope positions in the field. Despite these inconsistent results, soil redistribution was found to have a great effect on the spatial variability of soil respiration [26]. Tillage and application of straw as mulch can affect soil redistribution, changes in soil properties, and soil temperature and moisture [7, 10, 19, 24], which affect the spatial variability of soil respiration. However, to our knowledge there few studies have been conducted on the effect of tillage and application of straw as mulch on the spatial variability of soil respiration from sloping cropland.

The main objectives of this study were: 1) to determine and compare soil CO_2 emissions under different tillage and straw mulch treatments to better understand C dynamics in soil and 2) to investigate the influence of different tillage and straw mulch management on spatial variability of soil respiration.

Materials and Methods

Site Description and Soil Characteristics

This study was conducted at Lingbao Experimental Station of Soil Erosion and Landscape Ecology of Henan Normal University, located in western Henan Province, China (34°31′N, 110°59′E). The study site is in the Loess Plateau in northern China, with a total area of 628,000 km^2 [33]. This soil in the region has suffered serious degradation by soil erosion due to its sloping landscape and intensive agricultural activities [34]. Soil conservation practices, including minimum or zero tillage and mulching, may have the most potential to reduce soil erosion and protect carbon loss in the plateau [35]. This area is a typical Loess Plateau area with temperate continental monsoon climate of four seasons. Annual mean temperature and annual mean precipitation are 13.8°C and 640 mm. Most precipitation is distributed from July to August with an average frost-free period of 206 days.

Experimental Design

The study site was in sloping cropland with an average slope degree of 12° and with corn as the monoculture crop. Corn was planted in late April 2013 and harvested after four months in September, followed by leaving the site fallow till the next corn planting. Two tillage treatments were carried out: conventional moldboard plough tillage and no tillage. Three methods of returning corn straw were set up in a conventional moldboard plough tillage plot: no corn straw application (CT), corn straw incorporated into soil (TSI), and corn straw mulch on soil surface (TSM). In the no-till treatment, two methods of returning corn straw were set up: no corn straw application (NT) and corn straw mulch on soil surface (NTM). Each plot was about 5×30 m (along the slope direction). In each plot, the slope location was used as a subsidiary-factor and three general landscape elements with three replicates were identified (summit, shoulder, and foot position), resulting in nine locations per treatment. Following treatment applications, soil respiration was measured using an automated soil CO_2 flux system (LI-8100A, LI-COR, USA) equipped with a portable chamber (Model 8100-103). Soil CO_2 flux rates were calculated on the basis of a linear increase in CO_2 concentrations in the chamber over time. A PVC collar (20.3 cm in diameter and 10 cm in height) was inserted 8 cm into the soil surface halfway between the corn rows in each location and three days before the first measurement. Living weeds inside the collars were carefully clipped from the soil surface. The collars were removed before corn sowing and were re-inserted into soil surface after corn sowing. Soil CO_2 flux rates were measured for a one-year period from 4 October 2013 to 20 September 2014; measurements were made from twice a week to monthly, between 8:30 and 11:30 local time on each sampling day. Daily soil temperature and moisture in 0-5 cm soil depth near each collar were measured during each measurement of soil respiration using a handle thermocouple probe (Omega, USA) and frequency domain reflectometry (FDR), respectively.

Soil respiration rates from the monitoring period were fitted to soil temperature and soil water content with exponential and linear functions given in equations (1) and (2) to describe the dependence of soil respiration on soil temperature and soil water content.

$$R = a \times e^{bT} \tag{1}$$

$$R = AW + B \tag{2}$$

…where R, T, and W are soil respiration, soil temperature, and soil water content, respectively, and a, b, A, and B are constant coefficients. The Q_{10} values of soil respiration based on equation (3) were calculated as:

$$Q_{10} = \exp(10\,b) \tag{3}$$

Annual soil CO_2 emissions were calculated by interpolating the average CO_2 flux rate between sampling dates, and computing the sum of the products of the average flux rate and the time between respective sampling dates for each measurement period [3-4] as follows:

$$SR = \sum F_{m,k} \Delta t_k \tag{4}$$

… where SR is total soil CO_2 emitted in the measurement season (g C m^{-2}), $F_{m,k}$ is the average CO_2 flux rate over the interval t_{k+1}-t_k as recorded by the LI-8100A Soil CO_2 Flux System, and $\Delta t_k = t_{k+1} - t_k$ is the number of days between each field measurement within the season.

Statistical Analyses

The main and interactive effects of tillage, straw mulch and slope position treatments on soil temperature,

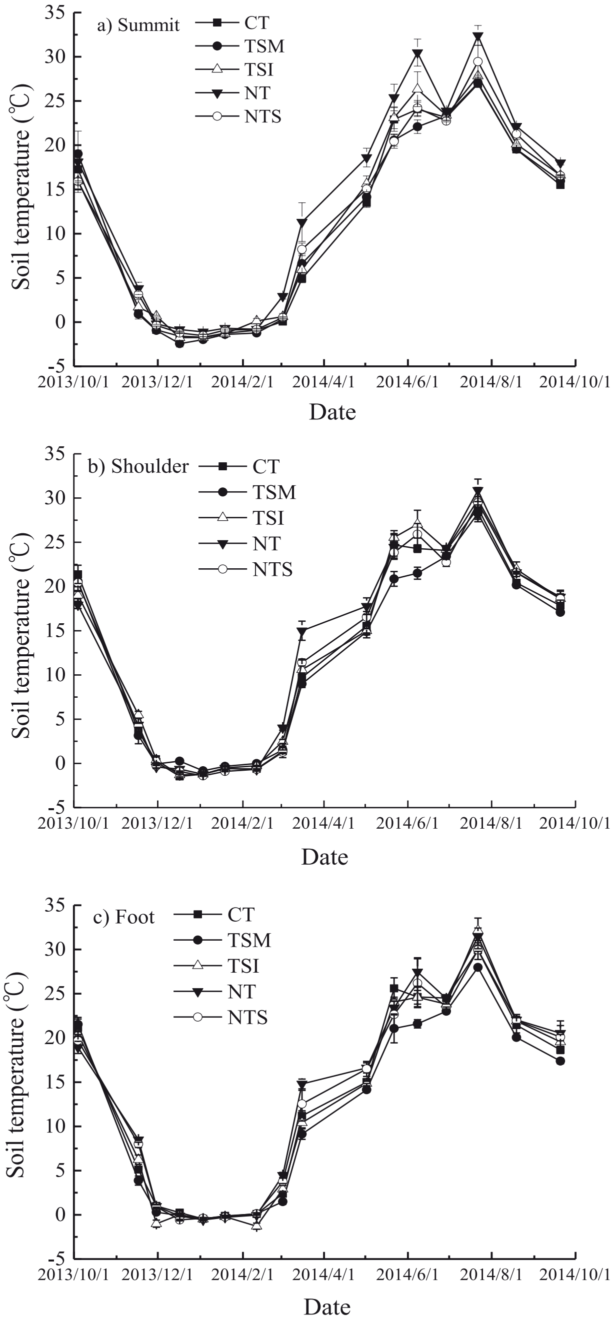

Fig. 1. The 5 cm soil temperature over the experimental period in the study site. CT = conventional moldboard plough tillage with corn straw removing; TSM = conventional moldboard plough tillage with corn straw mulching on soil surface; TSI = conventional moldboard plough tillage with corn straw incorporating into soil; NT = no-tillage with corn straw removing; NTM = no-tillage with corn straw mulching on soil surface.

soil moisture, and soil respiration were determined by repeatedly measuring analysis of variance (ANOVA). The difference in Q_{10} values under different tillage and straw mulch treatments, annual carbon emissions, and Q_{10} values under difference slope position were tested by one-way ANOVA. The correlation between soil respiration rates and soil temperature were explored using exponential regression, which was best correlated and was also used to calculate temperature sensitivity (Q_{10}). Correlations between soil respiration and soil moisture were explored by linear regression, which was best correlated. All statistical analyses were performed at a significance level of 0.05 using SPSS 16.0.

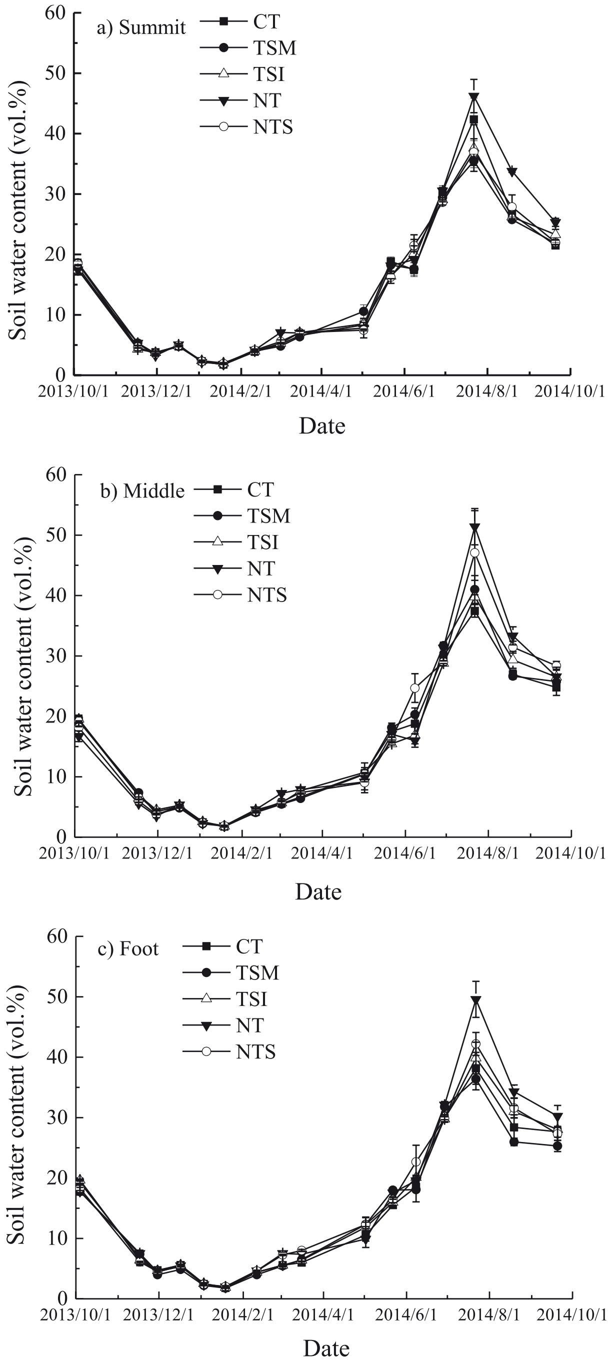

Fig. 2. The 5 cm soil water content over the experimental period in the study site. CT = conventional moldboard plough tillage with corn straw removing; TSM = conventional moldboard plough tillage with corn straw mulching on soil surface; TSI = conventional moldboard plough tillage with corn straw incorporating into soil; NT = no-tillage with corn straw removing; NTM = no-tillage with corn straw mulching on soil surface.

Results

Soil Microclimate

There was visible seasonal variability of soil temperature and moisture during the monitoring period, with the highest soil temperature and soil moisture in mid-July and the lowest soil temperature and soil moisture in early January (Figs 1-2). Slope positions had significant effects on soil temperature *(*$p<0.001$, Table 1, Fig. 1) and soil moisture ($p<0.001$, Table 1, Fig. 1) during the monitoring period. Annual average soil temperature was 0.26-2.37ºC higher in the foot position than that in the summit position under various treatments; and annual average moisture was 0.35-1.73% higher in the foot position than that in the summit position under various treatments.

Soil temperature and soil moisture in the shoulder position were lower than the foot position and higher than the summit position. The difference in soil temperature and soil moisture between shoulder position and the other slope positions also varied during the experimental period. Significantly ($p<0.001$) high soil temperature and soil moisture were recorded in no-till treatments (Table 1, Figs 1-2). Soil temperature in the summit position was higher in NT treatments than in the CT treatment (Fig. 1). Applying straw mulch showed a decreasing trend in soil temperature and soil moisture during different seasons ($p<0.001$, Table 1, Fig. 1). No significant effects of straw mulch on soil moisture were found in the experimental period. Significant interaction of slope position with tillage treatment on soil temperature ($p<0.01$) and soil moisture

Table 1. Results (F-values) of repeated measures ANOVA for average soil temperature (AST), average soil moisture (ASM), and annual total soil respiration (TSR) in monitoring periods.

Source of variation	AST	ASM	TSR
Slope position (P)	76.06^{***}	36.41^{***}	66.02^{***}
Tillage (T)	85.07^{***}	43.16^{***}	4.08^{ns}
Mulching (M)	40.83^{***}	3.22^{ns}	8.80^{**}
P×T	9.75^{**}	4.18^{*}	2.03^{ns}
P×M	4.70^{**}	2.44^{ns}	1.04^{ns}
T×M	0.03^{ns}	2.91^{ns}	0.55^{ns}
P×T×M	13.91^{***}	0.02^{ns}	4.89^{**}

*, **, ***: statistically significant at $p<0.05$, 0.01, and 0.001, respectively; ns: statistically insignificant.

($p<0.05$) were observed in the experimental period (Table 1). Tillage increased the difference between the summit and foot positions. Slope position had a strong interaction with straw mulch for soil temperature ($p<0.01$), but no such interactions were observed for soil moisture (Table 1). In addition, the significant interactive effects on soil temperature of slope position, tillage, and straw mulch were also observed ($p<0.001$, Table 1).

Annual Soil Respiration under Different Treatments

Soil respiration showed a strong seasonal pattern, with the highest microbial activity in July and the lowest in January (Fig. 3). Slope position had significant effects on soil respiration ($p<0.001$, Table 1, Fig. 3). Soil respiration rates of the three landscape positions were reduced in the following order: foot > shoulder > summit positions under different tillage and straw mulch treatments (Fig. 3), and the difference of annual soil carbon emissions between the foot and summit positions was significant (Fig. 3). Tillage alone did not have any significant effect on annual soil carbon emissions ($p>0.05$, Table 1). But NT treatment significantly increased soil respiration rates during June and September. For example, in the summit position, soil respiration rates under NT treatment were higher than CT treatments in the periods from 29 June to 20 September 2014 (Fig. 3). Straw mulch significantly increased soil respiration ($p<0.01$, Table 1). Meanwhile, straw mulch significantly decreased soil temperature ($p<0.001$) and had no significant effect on soil moisture. These results indicated that straw mulch itself led to the release of CO_2. In addition, we observed the visible interactive effects on soil respiration of slope position, tillage, and straw mulch ($p<0.01$, Table 1). In the shoulder position, soil respiration rates were lower in NTM and TSM treatments than other treatments in winter. In the foot position, soil respiration rates under NTM and NT were lower than other treatments in winter; soil respiration rates under TSI were highest in summer and autumn. Tillage and straw mulch could affect soil respiration in different slope positions by changing soil temperature, soil moisture, and soil erosion rate.

Dependence of Soil CO_2 Efflux on Soil Temperature and Soil Moisture

Soil respiration rates increased exponentially with increasing soil temperature in all treatments (Table 2). The exponential function showed a good fit for representing the dependence of soil CO_2 efflux on soil temperature. Soil temperature explained 74-92% of soil respiration using the exponential equation. Soil moisture was also an important factor controlling soil respiration, and soil moisture alone explained 61-84% of the variation in soil respiration using the linear function (Table 2).

The average Q_{10} values of soil respiration in the monitoring year were 2.07, 2.25, 2.16, 2.11, and 2.16 in the CT, TSM, TSI, NT, and NTS treatments, respectively, and the difference among different treatments was not

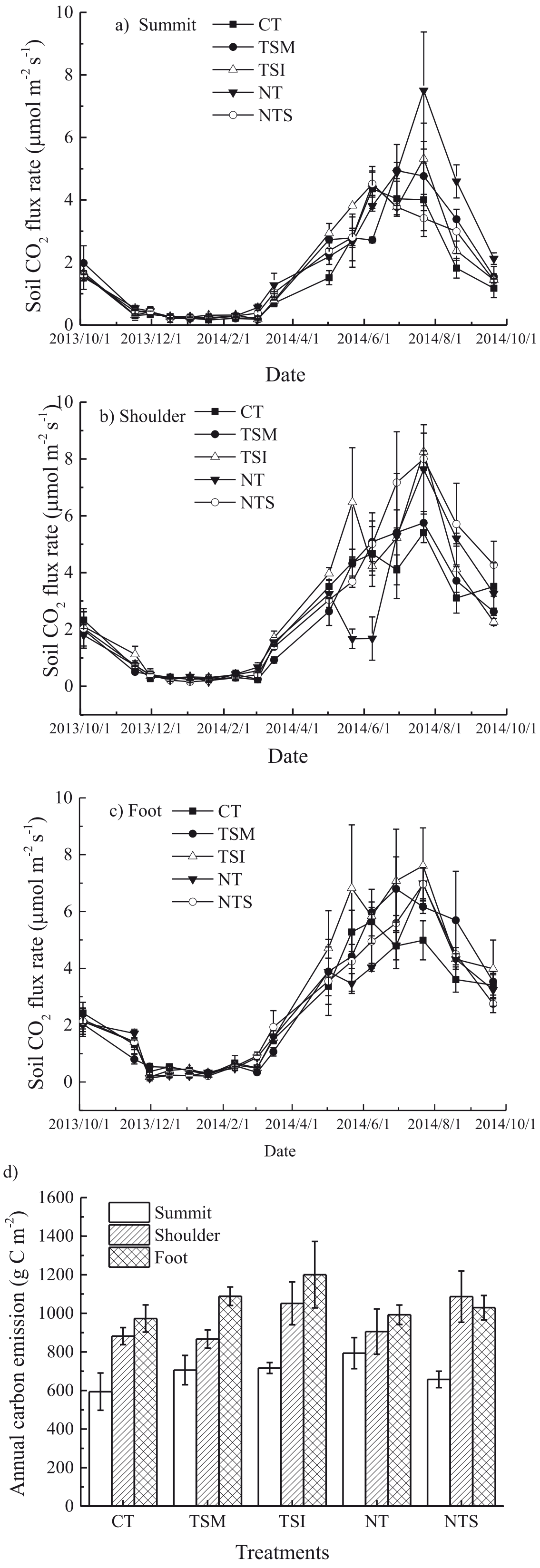

Fig. 3. Soil CO_2 fluxes over a one year period from October 2013 to September 2014. CT = conventional moldboard plough tillage with corn straw removing; TSM = conventional moldboard plough tillage with corn straw mulching on soil surface; TSI = conventional moldboard plough tillage with corn straw incorporating into soil; NT = no-tillage with corn straw removing; NTM = no-tillage with corn straw mulching on soil surface. The vertical bars indicate standard error (n = 3).

Table 2. Relationship between soil respiration and soil temperature (ºC) and soil water content (%) under different treatments.

Treatments		Estimated parameters						
		$R = a \times e^{bT}$				$R = AW + B$		
Tillage and straw mulch treatments	Topographic position	a	b	R^2	Q_{10}	A	B	R^2
CT	Summit	0.348±0.071	0.096±0.009	0.874	2.626±0.219^{e}	0.102±0.011	0.156±0.205	0.623
	Shoulder	0.709±0.107	0.073±0.006	0.863	2.078±0.084^{abc}	0.147±0.013	0.135±0.226	0.736
	Foot	0.866±0.126	0.066±0.006	0.835	1.937±0.028^{a}	0.138±0.016	0.503±0.282	0.619
TS	Summit	0.490±0.086	0.087±0.008	0.862	2.414±0.204^{cde}	0.142±0.009	-0.151±0.157	0.832
	Shoulder	0.64±0.102	0.083±0.007	0.864	2.309±0.061^{abcde}	0.155±0.011	-0.037±0.210	0.798
	Foot	0.934±0.186	0.074±0.009	0.753	2.098±0.04^{abc}	0.198±0.015	-0.041±0.260	0.792
TSI	Summit	0.463±0.064	0.088±0.006	0.924	2.507±0.386^{de}	0.131±0.013	0.058±0.227	0.673
	Shoulder	0.635±0.132	0.083±0.008	0.837	2.326±0.191^{abcde}	0.172±0.02	0.202±0.374	0.613
	Foot	1.097±0.205	0.065±0.007	0.742	1.957±0.162^{a}	0.187±0.021	0.263±0.393	0.625
NT	Summit	0.526±0.124	0.077±0.008	0.777	2.138±0.142^{abcd}	0.152±0.010	-0.151±0.191	0.833
	Shoulder	0.578±0.142	0.082±0.009	0.747	2.362±0.318^{bcde}	0.150±0.009	-0.107±0.189	0.846
	Foot	0.717±0.107	0.071±0.006	0.852	2.084±0.165^{abc}	0.133±0.010	0.301±0.202	0.799
NTS	Summit	0.666±0.01	0.066±0.006	0.796	1.959±0.122^{ab}	0.108±0.011	0.203±0.192	0.665
	Shoulder	0.723±0.166	0.081±0.009	0.782	2.327±0.205^{abcde}	0.186±0.012	-0.119±0.237	0.838
	Foot	0.754±0.122	0.074±0.006	0.84	2.210±0.279^{abcd}	0.161±0.012	0.097±0.235	0.787

R: soil respiration; T: soil temperature at 5 cm; W: soil water content at 5 cm; Q_{10}: sensitivity of CO_2 emission to a 10ºC increase in soil temperature for each treatment; Q_{10} values within a column followed by the same letter are not significantly different at $p<0.05$.

significant at $p<0.05$ (Fig. 4). Slope position affected Q_{10} values. In CT, TSM, and TSI treatments, the Q_{10} values showed a decreasing trend from summit to foot, and the difference between the summit and foot positions in CT and TSI treatment was significant ($p<0.05$). However, NT treatment increased Q_{10} values from summit to foot position, but the difference was not significant among different positions (Table 2).

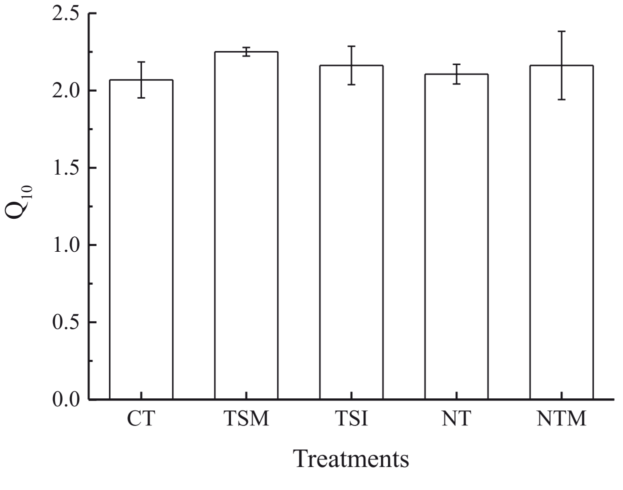

Fig. 4. The Q_{10} values in different tillage and straw mulch treatments during the monitoring period

Discussion

Effects of Tillage and Straw Mulch on Soil Respiration

Many studies have reported the effect of tillage and straw mulch on soil respiration, with no consistent trend [4, 24, 36]. These inconsistent results could be attributed to the differences in climatic conditions, soil types, farm management practices, and the timing and duration of measurements [4]. The majority of studies showed that tillage and straw mulching increase soil respiration through increased substrate (C) and soil aeration [7, 37-38]. However, in our study we found no such trend (Table 1, Fig. 3) as annual soil respiration in the summit treatment under NT treatment was higher than that in the CT treatment ($p<0.05$, Fig. 3). Our results are consistent with those of Ahamad et al. [14], Elder and Lal [15], and Glenn et al. [39], who reported a similar trend. Tillage treatment significantly affected soil temperature and soil moisture, but had no significant influence on soil respiration ($p<0.001$, Table 1). This lack of any significant effect of tillage treatment on soil respiration in our study ($p>0.05$, Table 1) could be related to the fact that no-till decreases soil microbial respiration through reduced soil physical disturbance, which then leads to increasing aggregate stability and build of SOM [13, 40]. This would offset the increase of soil respiration by changing soil temperature and soil moisture. The short-term effects of tillage result from the physical soil disturbance that occurs during plowing and the location of crop residues [41]. The magnitude of CO_2 losses from soil due to tillage practices is highly related to the intensity of soil disturbance caused by tillage. However, the effects would disappear in a short period [24, 42-43]. We did not monitor short-term effects in this study. This may underestimate the emissions in tillage treatments.

In the present study, straw input had a significant ($p<0.01$) effect on total soil respiration (Table 1). TSI treatment had the highest annual total soil respiration (992 g C m^{-2}, average annual total values of different slope positions) than other treatments, probably due to better contact between C in the added straw mulch and soil microorganisms. Kennedy and Arceneaux [41] and Yadvinder-Singh et al. [44] also reported that the incorporation of plant residues resulted in increased organic C mineralization compared with leaving them on the soil surface, where the added C is less accessible to soil microorganisms. Straw itself was an important source of C inputs, which enhance microbial biomass and thus CO_2 [19-20, 22-23], and the amount of CO_2 increased as the amount of straw increased [21]. Glenn et al. [39] has suggested that at least 25% of C in maize residues was lost due to microbial respiration during this non-growing period. Fu et al. [45] also has suggested that residue application might cause a net loss of soil carbon in agroecosystems. On the other hand, straw input treatment had a significant effect on soil temperature ($p<0.001$, Table 1), which could decrease soil respiration rates.

Effect of Slope Position on Soil Respiration

In the present study, we observed high annual soil microbial respiration rates in the foot than those in the shoulder and upper slope (Fig. 1), and the slope position had significant effects on soil respiration ($p<0.001$, Table 1). Slope position indirectly changed soil respiration by causing variability of soil temperature, soil moisture, soil microbial biomass, and plant growth, etc. [29, 31, 46]. In this study, significant correlations of soil microbial respiration with soil temperature and soil moisture at the temporal and spatial scales (Table 2) indicate that these two factors control soil microbial growth, activity, and respiration [47]. Soil temperature and soil moisture could explain 74-92% and 61-84% of the variation in soil respiration. Slope position significantly increased soil temperature and soil moisture in foot position ($p<0.001$, Table 1). This result was consistent with Van Hemelryck et al. [28], who suggested that the temperature measured at depositional positions was 0.5°C higher than that measured at eroded positions. However, some studies have shown that higher soil temperature was observed in the upper slope [29, 46]. The differences in soil temperature and soil moisture content at different positions were likely due in part to different physical and chemical properties (soil texture, bulk density, soil organic material) of soil caused by erosion [29, 48]. On the other hand, slope orientation or aspect was also an important factor affecting soil temperature and soil moisture. Our study site was located on a north-facing hillslope, and the foot position would receive more solar radiation than that of the flatter summit position. In contrast, the study sites of Xu and Wan [46] and Wei et al. [29] were located on a south-facing hillslope, and the summit position would have higher soil temperature, so more attention needs to be paid to slope orientation in future studies. Soil moisture and soil temperature were all positively correlated with soil respiration, indicating that the two factors were all limiting for soil respiration in our study site. Soil temperature and soil moisture were all higher in the foot position than in the summit position. In addition, greater carbon and nitrogen nutrient availability in the foot position caused by erosion could also directly simulate auto- and heterotrophic activities and respiration [28, 49], and this would increase the differences among slope positions. In addition, slope position also interacts with tillage and straw mulch treatments to influence soil temperature ($p<0.001$) and respiration ($p<0.01$, Table 1). Tillage and straw mulch could change soil erosion and then affect soil respiration [50]. In our study, the difference of annual soil respiration among different slope positions in CT were higher than that in NT treatment (Fig. 3), the reasons may be that tillage increased soil erosion rates and redistribution. So the effect of conservation tillage on soil erosion could be paid more attention in further studies.

Dependence of Soil CO_2 Efflux and Q_{10} on Soil Temperature and Moisture

Previous studies identified soil temperature and soil moisture as major physical factors affecting soil respiration [3, 29, 51]. Soil temperature and moisture can directly influence root and microbial activities and respiration [28, 46] and/or indirectly via altering plant growth and belowground C allocation, as well as litter decomposition [52]. Some studies have indicated that soil respiration is mainly controlled by soil temperature [3-4], while others suggest that soil moisture is also a dominant factor, especially in arid and semiarid areas [3, 11, 53]. Some studies have reported that the effect of soil moisture and soil temperature on soil respiration change during the monitoring period [29]. In our study, soil temperature and soil moisture were all important factors controlling soil microbial respiration (Table 2). The correlation between soil respiration and soil temperature was exponential, while the correlation between soil respiration and soil temperature was linear (Table 2). These results indicated that soil moisture and soil temperature may all be limited factors to affect soil respiration in our study site, and increasing soil temperature and soil moisture had a positive effect on soil respiration.

Q_{10} values ranged from 1.94 to 2.63 in this study and were similar to the range of values (1.42-2.32) reported in the plateau area [3]. Slope position had a visible effect on Q_{10}; the Q_{10} values decreased from summit to foot under CT, TSM, and TSI treatments; and the difference of Q_{10} values between summit and foot position under CT and

TSI treatments was significant ($p<0.05$, Table 2). However, the difference of Q_{10} values among slope position under NT and NTS was not visible, and the Q_{10} values even had the tendency to increase from summit to foot under NTS treatment. Those results indicated that the Q_{10} values may be changed by tillage and straw mulch treatment along the slope position. The Q_{10} value was higher at low soil moisture content [54]. Shi et al. [3] found that Q_{10} values were negatively correlated with average soil temperature and moisture. Tillage treatment significantly decreased soil temperature and increased temperature differences among slope position while decreasing soil moisture, which may partly explain the changes of Q_{10} values along the slope position. On the other hand, Wang et al. [55] found significant negative correlation between Q_{10} and C quality index. No-tillage changes the soil redistribution of labile carbon, and the nitrogen fraction may be another reason [31, 40].

Conclusion

No-till treatments enhanced soil microbial respiration mainly through increasing soil moisture and soil temperature. Residue application might cause a net increase of soil respiration by C inputs in residues itself, although straw mulch may decrease soil microbial activities by decreasing soil temperature. Slope position had significant effects on soil respiration among various tillage and straw mulch treatments, and annual total soil respiration followed a descending sequence as foot > shoulder > summit positions. Tillage and straw mulch treatments may indirectly meditate spatial variability of soil respiration by affecting soil erosion rate, soil moisture, and soil temperature. Soil temperature and soil moisture were all important in regulating spatial and temporal variability of soil respiration in semiarid cropland in the plateau. The temporal variability of soil respiration in each treatment was explained by an exponential relationship between soil respiration and soil temperature, and a linear relationship between soil respiration and soil water content. Q_{10} values showed visible spatial variability in tillage treatments, but the spatial variability disappeared in no-till treatments. These results indicated that the tillage pattern may change soil temperature sensitivity of soil respiration in sloping cropland, which should be paid more attention in future studies.

Acknowledgments

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