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Tillage effects on SOC and CO_2 emissions of Mollisols

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Abstract

A field experiment was conducted to examine the influences of 5-year no tillage without straw retaining on soil organic carbon (SOC) and carbon dioxide (CO_2) emissions from Mollisols, and to relate soil CO_2 effluxes to variations in soil temperature and moisture. A closed-chamber method was used to determine CO_2 efflux during the maize growing season in 2011. Our results showed no remarkable increase ($P>0.05$) in SOC for no tillage without straw retaining (NT), although NT practice decreased cumulative CO_2 emission during the growing season by 30% ($P<0.05$) compared with conventional tillage (CT). Annual soil CO_2 emissions were estimated at 13.34 and 9.39 Mg CO_2 ha^{-1} for CT and NT, respectively. The amount of annual lost C through CO_2 emission from NT soils could be roughly replenished by incorporation of maize straw. The log-transformed multiple regression model [$\log(f) = a + b\,T + c\log(W)$] including both soil temperature and moisture was established, which accounted for 68 and 74% of the season variations in soil CO_2 effluxes in NT and CT, respectively (both $P<0.01$). The temperature sensitivity of soil respiration was 2.39-2.75 in CT, which was higher than 2.01-2.34 in NT; soil respiration was more sensitive to soil temperature at 10 cm than at 5 cm depth. Compared with CT, NT also decreased cumulative N_2O emissions by 50% and thus total global warming potential of CO_2 and N_2O emissions. Results suggest that, considering C sequestration and global warming effect, the practice of no tillage without straw retaining is feasible in Mollisols in northeast China.

Key words: Black soil, CO_2 efflux, conventional tillage, global warming potential, northeast China, no-tillage, soil respiration, temperature sensitivity, water-filled pore space.

Introduction

Increased atmospheric carbon dioxide (CO_2) concentration has been considered as a major contributor to climate change and global warming [1, 2]. Inappropriate agricultural practices can result in C losses from soils to the atmosphere [3]. Tillage regime has been regarded as one of important factors affecting CO_2 emissions from soils [4-6]. No-till practice has been widely promoted in agricultural ecosystem due to its positive roles in improving soil fertility [7-9]; it has also been observed to increase soil organic C (SOC) content and to decrease soil CO_2 emissions by a large number of field studies [10].

No-till practice is effective in minimizing erosion losses and sequestering C, only with the use of crop residues as mulch. Whereas, no-till practice can reduce yield in poorly drained, clayey soils when springtime is cold and wet [11]. In fine-textured soils of no-till, the development of adverse physical conditions in the topsoil and a decrease in root function might reduce water and nutrient uptake by crops under no-till practice [12]. Additionally, no-till can delay soil warming in the early spring under a cold climate, and thus slower crop growth compared to conventional tillage [13]. A Mollisol is characterized by fine texture and high SOC content, and in China, it is mainly located at the northeastern China with extremely cold climate. Since clay soil-cold climate combinations are considered to be poorly suited to no-till [11, 14], we suppose that the application of no tillage without residue retaining is suitable for these regions. Then will the no tillage practice without residue retaining influence SOC stock and soil CO_2 emissions?

Influences of tillage practice on soil CO_2 emissions can be collectively controlled by environmental conditions [15], soil texture [10], and the duration of tillage [4]. Soil temperature and moisture are generally regarded as the major parameters controlling soil CO_2 emissions [15, 16]. However, there are still some uncertainties associated with the influences, especially for the relationships between soil CO_2 effluxes and the combination of soil temperature and moisture [17]. In addition, soil texture has a strong effect on CO_2 emission from soils [18]. For example, Feiziene *et al.* [10] found that the net CO_2 exchange rate was 13% more from sandy loam soil than from loam. To our knowledge, however, there exists no information about the responses of SOC and soil CO_2 emissions to no tillage practice without residues retaining in the Mollisols in northeast China, although the responses should differ from those in other soil types due to its fine texture and high C content [10].

Therefore, a field experiment was conducted: 1) to examine the influences of no tillage without straw retaining on SOC stock and soil CO_2 emissions from the Mollisols and to relate soil CO_2 effluxes with soil temperature and moisture; and 2) to evaluate the global warming potential (GWP) under no tillage without straw retaining. Although it did not retain crop straw, we hypothesized that no tillage might still decrease CO_2 emission and thus increase SOC stock, due to minimized soil disturbance.

[†] Contributed equally to this paper.

Materials and Methods

Site description: This study was conducted at Hailun National Experiment Station of Agro-ecosystem of Chinese Academy of Sciences. A detailed description of the site was in our previous study [19]. During the present growing season (in 2011), air temperature varied from 2.6 to 28.3°C with an average of 19.0°C, and total precipitation was 392.8 mm, occupying 87% of the annual precipitation.

Experimental design: A field experiment was established in 2007 including two tillage systems with three replicates: no tillage without straw retaining (NT) and conventional tillage (CT). The description of the experiment design was also shown in the previous study [19].

Soil CO_2 and N_2O efflux measurements: Soil CO_2 and N_2O effluxes were measured *in situ* using a static closed chamber method and gas chromatography. Gas sampling was conducted weekly between 9:00 and 11:00 am. Each time, four gas samples were extracted from the chamber air by a 20-ml gas-tight syringe at 0, 10, 20, and 30 min after closure, and then immediately injected into pre-evacuated 18-ml vials and taken to laboratory for analysis. Carbon dioxide concentration was determined by a gas chromatograph (GC-2010, Shimadzu Corp., Japan) equipped with a flame ionization detector (FID) using an 80/100 mesh Chromosorb 102 column. Nitrous oxide concentration was also determined with the gas chromatograph equipped with a ^{63}Ni electron capture detector (ECD) operated at 300°C.

Air temperature inside the chamber and soil temperatures at vertical depths of 5 and 10 cm were recorded *in situ* using geothermometer at the same time with gas sampling. Field soil gravimetric moisture and bulk density were determined from undisturbed soils at the neighboring locations as the gas sampling for calculation of soil water-filled pore space (WFPS) using the following equation : *WFPS* = (*gravimetric moisture* × *bulk density* × 100)/[1-(*bulk density*/2.65)].

Soil sampling and analyses: Soil samples were collected in October 2011. Eight soil cores were randomly collected from 0–20 cm soil layer in each block and mixed to form a composite for analysis. After visible roots, fauna and organic debris were removed by hand, and soil samples were sieved (<2 mm) and air dried for analyses of SOC, total nitrogen (TN) and pH. Soil bulk density was measured by the core method. Air-dried soil samples (<2 mm) were used to determine soil pH in a 1:2.5 (*w*/*v*) soil to water ratio. Soil organic C and TN were analyzed using an elemental analyzer (Vario EL III, Elementar, Germany).

Data processing and analyses: All analyses were performed with SPSS 13.0 software and the accepted significance level was $\alpha = 0.05$. Statistical significances of the differences in soil properties, plant biomass, cumulative CO_2 and N_2O emissions, and GWP between CT and NT were tested by the Student's *t*-test. Bivariate correlations were performed to examine the relationship between CO_2 efflux and soil temperatures at 5 and 10 cm depths, and soil WFPS. Regression analyses were used to depict the relationships between soil environmental parameters and CO_2 effluxes. Relationship between soil CO_2 efflux (f) and soil temperature (T) was modeled by an exponential equation: $f = a \exp(bT)$. The temperature sensitivity (Q_{10}) was calculated by the first-order exponential function as follows: $Q_{10} = \exp(10b)$. The effects of soil moisture on soil CO_2 efflux could be obscured by soil temperature [16,20], therefore, to exclude the masking effect of soil temperature, we standardized soil CO_2 efflux to a soil temperature of 10°C using the following equation [16]: $f = f_{10}\exp(\ln Q_{10} \times (T - T_{10})/10)$, where f is the soil CO_2 efflux measured in field, f_{10} is the soil CO_2 efflux at 10°C (T_{10}), Q_{10} is the change in soil CO_2 efflux with a 10°C increment in soil temperature, and T is the soil temperature at 5 cm depth.

Results

Soil properties, crop biomass and yield: Soil pH and SOC and TN stocks were not significantly affected by NT (all $P > 0.05$; Table 1). Bulk density was markedly increased by NT. The straw biomass in CT was higher than NT ($P < 0.05$), whereas the root biomass and crop grain were not significantly influenced by NT treatment ($P > 0.05$; Table. 1).

Soil temperature and moisture: Soil temperature varied from 5.0 to 32.5°C during the experiment period, with averages of 22.6 and 19.1°C at 5 and 10 depths, respectively (Fig. 1a). Generally, soil temperatures both at 5 and 10 cm depths in NT were lower than those in CT (Fig. 1a). Soil moisture at 5 cm depth averaged 35.4 and 45.9% WFPS in CT and NT, respectively (Fig. 1b). Soil WFPS in NT was profoundly higher than that in CT during the whole experiment period.

Soil CO_2 and N_2O effluxes: Temporal variations of soil CO_2 effluxes are summarized in Fig. 2. Generally, the effluxes increased gradually after sowing, reached the maximum between mid-July to mid-August, and then declined gradually until the end of September (Fig. 2). In 4 June, soil CO_2 efflux in CT dramatically increased compared with NT (Fig. 2).

Cumulative CO_2 emissions from CT and NT during the whole growing season were estimated to be 10.75±0.70 and 7.57±0.49 Mg CO_2 ha^{-1}, respectively; soils in NT emitted 30% lower CO_2 than that in CT ($P < 0.05$). Cumulative N_2O emissions from CT and NT systems during the growing season were 3.17±0.53 and 1.58±0.19 kg N_2O ha^{-1}, respectively. Cumulative soil N_2O emission in NT was significantly lower than that in CT by 50% ($P < 0.05$).

Relationships between soil CO_2 effluxes and soil temperature and moisture: During the whole growing season, correlation analyses showed poor relations between soil CO_2 efflux and soil

Table 1. Soil properties, and maize yield and biomass at harvest under conventional tillage (CT) and no tillage (NT) systems. Values are means ($n = 3$) with standard error.

Treatment	pH	Bulk density ($g\ cm^{-3}$)	SOC stock ($Mg\ ha^{-1}$)	TN stock ($Mg\ ha^{-1}$)	Root biomass ($Mg\ ha^{-1}$)	Straw biomass ($Mg\ ha^{-1}$)	Grain ($Mg\ ha^{-1}$)
CT	5.27±0.08a	0.89±0.01b	56.73±1.60a	4.02±0.13a	0.99±0.10a	10.21±0.43a	6.19±0.65a
NT	5.38±0.12a	1.04±0.02a	62.97±1.99a	4.30±0.08a	0.82±0.05a	7.04±0.40b	4.72±0.57a

Different letters within the same column indicate significant differences at $P < 0.05$.

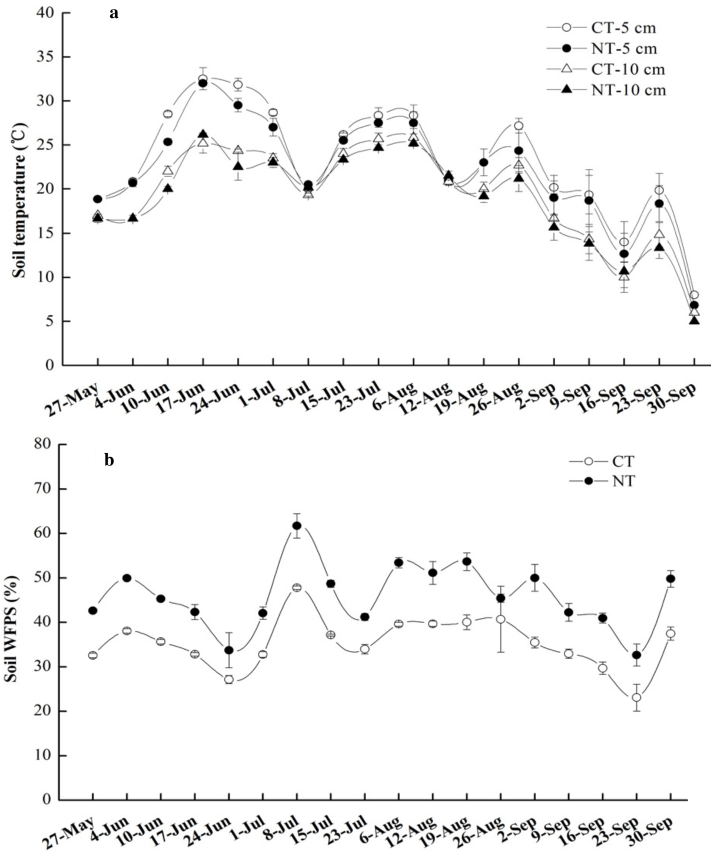

Figure 1. Temporal variations of soil temperatures at 5 and 10 cm (a) and soil water-filled pore space (WFPS) at 5 cm depth (b) during the maize growing season. Vertical bars denote the standard error of the means ($n = 3$). CT, conventional tillage, NT, no tillage.

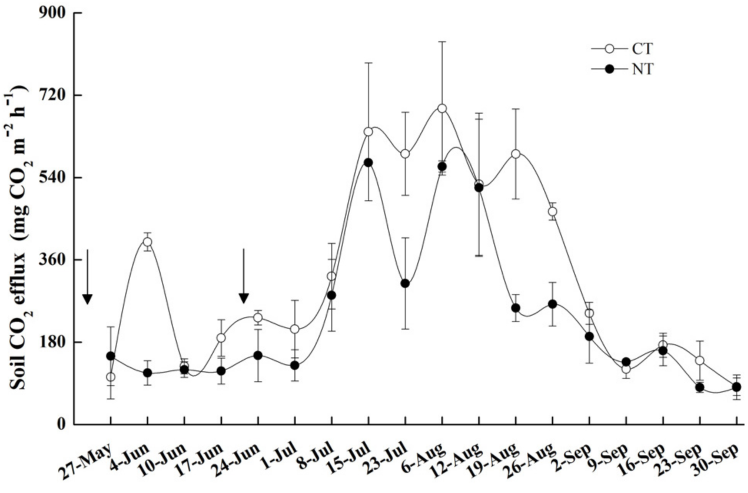

Figure 2. Soil CO_2 effluxes during the maize growing season under conventional tillage (CT) and no tillage (NT) systems. Vertical bars denote the standard error of the means (n = 3). Arrows represent the timing of fertilizer application.

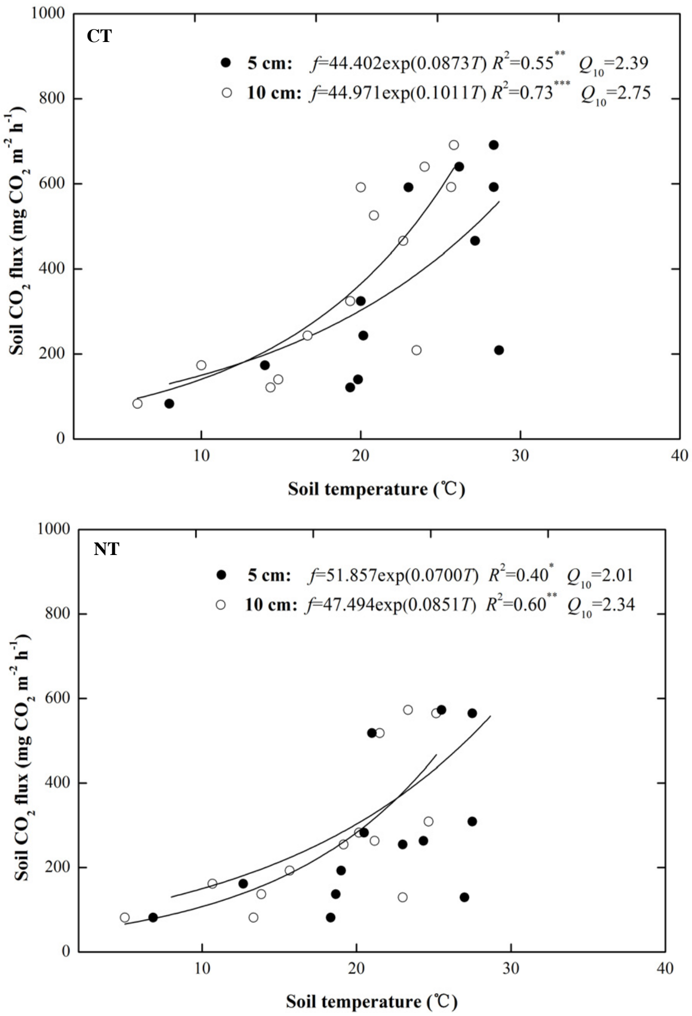

Figure 3. Relationships between soil CO_2 effluxes (f) and soil temperatures (T) at 5 and 10 cm depths under conventional tillage (CT) and no tillage (NT) systems (n = 13). *, **, and *** indicate significance at $P<0.05$, 0.01, and 0.001, respectively.

temperature at 5 cm layer ($P>0.05$, $n = 18$) and positive relations for 10 cm layer ($P<0.05$, $n = 18$) both in CT and NT. After the beginning five data sets were excluded from analyses, however, we observed greatly improved relationships between soil CO_2 effluxes and temperatures of both the two layers under the two tillage systems ($r = 0.56$-0.80, all $P<0.05$, $n = 13$). The relationships were well fitted with an exponential model (Fig. 3), accounting for 40-73% of temporal variations in soil CO_2 effluxes ($P<0.05$; Fig. 3). In addition, the Q_{10} values of soil respiration in CT and NT ranged from 2.01 to 2.75 (Fig. 3).

The regression analysis showed a poor relationship between soil CO_2 efflux with soil WFPS ($R^2 = 0.24$ and 0.28 for CT and NT, respectively, $P>0.05$; Table 2). When excluding the masking effect of soil temperature, however, the relationship between soil CO_2 efflux and soil WFPS could be well fitted by an exponential model ($R^2 = 0.34$-0.39, $P<0.05$; Table 2). Furthermore, the log-transformed multiple regression model [$\log(f) = a + b\,T + c\,\log(W)$] including both soil temperature and WFPS could explain 74% ($P = 0.001$) and 68% ($P = 0.004$) of the season variations in soil CO_2 effluxes in CT and NT, respectively, which was better than the regression model with soil temperature or soil WFPS alone (Table 3).

Global warming potential: We summed the soil-derived GWP in CO_2 equivalent for CO_2 and N_2O emissions as the total GWP. The total GWP of NT (804±54 g CO_2 m^{-2}) during the growing season was significantly lower than 1170±84 g CO_2 m^{-2} in CT ($P = 0.022$), due to the lower CO_2 GWP ($P = 0.020$) and N_2O GWP ($P = 0.047$) of NT compared with CT, which decreased by 30 and 50%, respectively (Table 4).

Table 2. Relationship between soil CO_2 efflux (f) and soil WFPS (W) in the 5 cm layer under conventional tillage (CT) and no tillage (NT) systems (n =13).

Treatment	Equation	R^2	Excluding the masking effect of temperature		
			Equation	R^2	P
CT	f=35.503exp(0.0588W)	0.24	f=19.671exp(0.0467W)	0.34	0.037
NT	f=24.000exp(0.0473W)	0.28	f=13.420exp(0.0435W)	0.39	0.023

Table 3. Relationship between soil CO_2 efflux (f) and soil temperature (T) at 5 cm depth and soil WFPS (W) in the 5 cm layer under conventional tillage (CT) and no tillage (NT) systems (n =13).

Treatment	Equation	R^2	P
CT	$\log(f) = -1.209+0.040T+1.803\log(W)$	0.74	0.001
NT	$\log(f) = -1.790+0.031T+2.107\log(W)$	0.68	0.004

Table 4. Global warming potential (GWP) of CO_2 and N_2O emissions in CO_2 equivalent as affected by conventional tillage (CT) and no tillage (NT) systems. Values are means (n = 3) with standard error.

Treatment	CT	NT	P
CO_2 GWP (g CO_2 m^{-2})	1075±70	757±49	0.020
N_2O GWP (g CO_2 m^{-2})	94±16	47±6	0.047
Total GWP (g CO_2 m^{-2})	1170±84	804±54	0.022

Units are CO_2 equivalents (g CO_2 m^{-2}) for N_2O GWP using a radiative forcing potential of 298 relative to CO_2 based on IPCC (2007). Total GWP indicates the soil-derived GWP, which was derived from soil emissions of CO_2 and N_2O. Statistical significance (P values) of the differences in GWP between the CT treatment and the NT treatment was tested by the Student's t-test.

Discussion

Effect of tillage on SOC stock: Inconsistent with many other no-till studies, our observation showed no remarkable changes in SOC stock in no-tillage treatment without straw incorporation compared with CT treatment (Table 1). The disparities between our results may be primarily originated from no incorporation of maize straw in the present study. Using a global database of 67 long-term agricultural experiments, a previous study found that SOC sequestration rate can be expected to peak in 5 to 10 years with a new equilibrium of SOC in 15 to 20 years with a change from CT to NT [21]. Thus, the negligible differences in SOC between CT and NT could partially be attributable to the short period (5 years) of NT practice and thus the delayed response of SOC, as also reported that there is little to no increase in SOC over a short period due to conservation tillage [22]. Additionally, the absence of increase in SOC in NT in the present study may be partly attributed to the relatively small or no changes in SOC induced by NT practice as compared to the large SOC background of Mollisols initially present. To detect the changes in SOC stock, therefore, it is of great importance to measure soil CO_2 emission as affected by tillage practice.

Effect of tillage on soil CO_2 emission and GWP: The lower cumulative CO_2 emission from NT than CT indicated that NT practice inhibited soil respiration in the tested Mollisols, which was in accordance with many other results on soil CO_2 emissions as affected by NT [5, 8]. About 3.3 and 5.2% of SOC stored in the surface soil (0-20 cm) was released as CO_2 during the growing season in NT and CT, respectively. Despite of the negligible change in SOC after 5-year NT, the decrease in soil CO_2 emission implies that an increase in SOC might occur in the long term. The greatly decreased soil CO_2 emission in NT compared to CT could be attributed to many factors. A primary explanation is that NT practice could reduce the mineralization of organic matter by minimizing soil disturbance [23, 24]. Although root respiration is an important contributor to influence soil respiration *in situ* [25], no significant differences in root biomass between CT and NT in the present study (Table 1) indicated that root respiration could not be the driver of the differences in soil CO_2 emissions between NT and CT. In addition, the collective effects of soil temperature and moisture affected by tillage management may partly explain the decrease in soil CO_2 emission of NT over CT. The higher R^2 between soil CO_2 efflux and soil temperature (0.40-0.55; Fig. 3) than soil WFPS (0.34-0.39; Table 2) indicated that soil temperature had a larger impact on soil CO_2 emission than soil moisture. Furthermore, consistent with other studies [26], slightly lowered soil temperature (Fig. 1a) and greatly improved soil moisture (Fig. 1b) during the growing season in NT, combined with the positive correlations between both soil temperature and moisture and soil CO_2 emission, probably resulted in the lower soil CO_2 emission of NT than CT.

The contributions of soil respirations in winter and the non-growing season to annual soil CO_2 emissions approximately averaged 6.1 and 13.3%, respectively [27], thus, the annual soil CO_2 emissions were roughly estimated at 13.34 and 9.39 Mg CO_2 ha^{-1} in CT and NT, respectively. To maintain the balance of SOC, therefore, 6.10 Mg ha^{-1} maize straw (assuming with 420 g C kg^{-1}) would be needed to be incorporated to the NT field, which are lower than the amount of harvested maize straw in NT (7.04 Mg ha^{-1}). Therefore, annual lost C through soil CO_2 emission in NT could be roughly supplemented by maize straw incorporations.

The GWP of N_2O emission was calculated in units of CO_2 equivalent over a 100-year time horizon. A radiative forcing potential of 298 was used for N_2O relative to CO_2 [28]. No tillage without straw retaining profoundly decreased soil N_2O emission during the growing season compared with CT ($P<0.05$), and thus decreased the GWP of N_2O emission, which combined with the decreased GWP of CO_2 emission indicated that NT practice could reduce the total GWP (Table 4).

Relations between soil temperature and moisture and soil CO_2 efflux: It has been widely documented that soil temperature and moisture were the dominant factors controlling the season variations of soil CO_2 effluxes [15, 29]. In this study, soil CO_2 effluxes were significantly associated with soil temperature both at 5 and 10 cm layers, with greatly improved relationships, and the exponential model [$f = a \exp(bT)$] provided a good fitting tool to depict the correlation between soil CO_2 efflux and soil temperature in the present study ($R^2 = 0.40$-0.73, $P<0.05$; Fig. 3), only when the five data sets measured neighboring two fertilization events were excluded. These results were probably resulted from the disturbance of fertilization, which could affect soil CO_2 efflux and further modify the relationship between soil temperature and CO_2 efflux [30, 31].

The Q_{10} values of soil respiration in NT were lower than those in CT for both 5 and 10 cm depths (Fig. 3), which indicated that NT practice reduced the temperature sensitivity of soil respiration. In addition, higher Q_{10} values at 10 cm than at 5 cm in both NT and

CT (Fig. 3) showed that soil respiration was more sensitive to the variation of soil temperature at 10 cm than at 5 cm depth, which is also consistent with a previous finding that the Q_{10} value increased with the depth of soil temperature measuring point [32]. This result suggests that the effects of measurement depth of soil temperature on the estimation of soil respiration sensitivity to temperature should be taken into account in modeling carbon cycle, as terrestrial carbon models generally assume a constant Q_{10} regardless of the measurement depth for a given ecosystem [33, 34].

Besides soil temperature, soil moisture is also identified as an important factor to influence soil respiration [17]. In our study, CO_2 efflux showed a poor relationship with soil moisture (Table 2). After the masking effect of soil temperature was excluded, however, soil CO_2 efflux was exponentially associated with soil moisture (Table 2). Thus, we developed a log-transformed multiple regression model including both soil temperature and WFPS to depict the relationships between CO_2 effluxes and soil temperature and moisture. Our results showed that the season variations in CO_2 effluxes were better explained by the combination of soil temperature and moisture ($R^2 = 0.68\text{-}0.74$, $P<0.01$; Table 3).

Conclusions

Although NT practice profoundly decreased cumulative CO_2 emissions by 30% during the maize growing season, 5-year NT practice did not increase SOC in the Mollisols. Annual soil CO_2 emissions were estimated at 13.34 and 9.39 Mg CO_2 ha^{-1} in CT and NT, respectively. The log-transformed multiple regression model [$\log(f) = a + b\,T + c\,\log(W)$] including both soil temperature and moisture accounted for 68-74% of the season variations in soil CO_2 effluxes in NT and CT, respectively. Compared with CT, NT also decreased cumulative N_2O emissions by 50% and thus total GWP of CO_2 and N_2O emissions. Considering C sequestration and global warming effect, our results suggest that the practice of no tillage without straw retaining is feasible in Mollisols of northeast China.

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