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# Responses of Soil Respiration and Organic Carbon to Straw Mulching and Ridge Tillage in Maize Field of a Triple Cropping System in the Hilly Region of Southwest China

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Abstract: Soil disturbance by tillage practices promotes soil respiration which is a main source of carbon dioxide emission into the atmosphere. The present study was conducted to investigate the effect of different tillage practices on soil respiration and the carbon source/sink characteristics of maize farmland ecosystems in the wheat-maize-soybean cropping system. Six tillage treatments, namely, traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS), ridge tillage + straw mulching (RS), traditional tillage + straw mulching + decomposing inoculants (TSD), and ridge tillage + straw mulching + decomposing inoculants (RSD), were used to measure the soil respiration and its hydrothermal factors. The results showed that the intensity of soil respiration increased initially and decreased afterwards throughout the growth period of maize ranging from 1.011 to 5.575  $\mu$ mol (m<sup>2</sup>·s)<sup>-1</sup>. The soil respiration rate under different treatments varied remarkably presenting a trend of RSD > TSD > TS > RS > T > R. Ridge tillage reduced the soil respiration rate of maize farmland while straw mulching improved it. Meanwhile, ridge tillage and straw mulching increased the soil temperature sensitivity index of soil respiration, but the addition of decomposing inoculants reduced this trend. The soil moisture response threshold under ridge tillage was lower, while the straw mulching was found to increase it, compared with the control. Moreover, there was a positive correlation between trapped soil fauna and soil respiration. Compared with the control, ridge tillage and straw mulching were beneficial to the carbon sink of the farmland ecosystem as shown by the maize field for the entire growing season.

**Keywords:** soil respiration; carbon balance; straw mulching; ridge tillage; maize; soil temperature; southwest region



## 1. Introduction

Global climate change with the frequency and intensity of extreme weather events has had a devastating impact on human activities, especially in agricultural farmlands around the world. The concentration of atmospheric carbon dioxide has increased by 32%, from  $2.8 \times 10^{-4}$  to  $3.69 \times 10^{-4}$  since the Industrial Revolution [1]. Farmland ecosystems are an important part of terrestrial ecosystems, accounting for 10.5% of the total land around the world. Among the greenhouse gases released by human activities, carbon dioxide emissions account for 21% to 25% [2]. In the entire terrestrial ecosystem, the farmland ecosystem is the most active carbon pool which can be adjusted by humans in the shortest time. Soil respiration, a major source of carbon cycle in agricultural soils, contributes usually up to two-thirds of the total carbon exchange as both a source and sink of CO<sub>2</sub> within the entire ecosystem [2]. Consequently, it is essential to deeply study the mechanism of soil respiration in farmland ecosystems for global carbon reduction.

The factors affecting soil respiration are complex and vary with agricultural practices. However, previous studies have noticed and simulated the hydrothermal factors of soil respiration [3], and reported a clear correlation between soil respiration and soil temperature. The relationship between soil temperature and soil respiration enhancement when the temperature rises 10 °C [4,5]. Furthermore, no obvious linear relationship exists between soil respiration and soil moisture under the small range of soil moisture changes, and the influence on soil respiration caused by changes in moisture may be masked by other factors or systematic errors [6]. Strictly speaking, soil respiration refers to all the metabolic effects when carbon dioxide is produced by disturbed soil, including biological processes (plant root respiration, soil microbial respiration, soil organic matter decomposition and soil animal respiration) and a non-biological process (chemical oxidation of carbonaceous material) [7]. Generally, plant root respiration and soil microbial respiration plays a more important role in soil respiration compared with the soil organic matter decomposition and soil animal respiration cannot be neglected especially in farmland ecosystems because invertebrates are often known to play a decisive role in soil respiration [8].

With the growing global changes, most studies have been conducted on carbon sequestration and reduction in agro-ecosystems. Agricultural soils are considered to have great potential for reducing atmospheric CO<sub>2</sub> concentrations and mitigating the greenhouse effect [9,10]. For the reduction of soil carbon emissions, it is important to study the dynamic changes of soil respiration under the main farmland management model in different regions [11]. It will help understand the carbon emission and provide scientific basis for clarifying carbon tax obligations. The maize farmland in summer is a sink for atmospheric CO<sub>2</sub> absorption [12]. Li et al. studied the carbon balance of the farmland ecosystem in the Loess Plateau and concluded that the net carbon input of the millet farmland system was 1408 kg ha<sup>-1</sup> [13]. Zhang et al., while studying the carbon balance under different fertilization methods in arid areas of cotton fields, reported that the carbon source is only present in the seedling stage of cotton, while carbon sinks are present in the rest of the period, and compound fertilizer and organic fertilizer have the greatest effect on farmland carbon sink [11]. Under normal conditions, the soil–plant system of CO<sub>2</sub> exchange from farmland behaves as a sink of atmospheric CO<sub>2</sub> and different farming methods just change the degree of sinking [14].

Conservation tillage is an important agricultural management measure that has recently been popularized and applied for reducing soil erosion, improving soil organic matter, saving water and protecting and increasing rice yield [15]. Recently, the research on soil fauna has mainly focused on the classification of soil fauna and the distribution characteristics of the communities in farmland ecosystems [16]. The research on the interaction between soil fauna and the environment has become increasingly important with the growing global climate changes [17]. Furthermore, the relationship between soil fauna and global climate change has gradually aroused concern, and as a result researches have been successively conducted about the response of soil fauna to soil pollution, land-use species invasion, soil disturbances, etc. [18–28]. Soil fauna are largely involved in the original process of soil respiration. However, the current research is mainly focused on a few groups such as earthworms,

ants, and nematodes. The number of soil animals is too small to reflect the real situation. [29] Therefore, it is necessary to expand the taxa of soil animals and explore their relationship with soil respiration.

The present study was aimed to elucidate the responses of soil respiration and soil organic carbon to straw mulching and ridge tillage, keeping in view the soil temperature, soil moisture and soil fauna in maize farmland.

# 2. Materials and Methods

## 2.1. Experimental Site

The experiment was conducted at the experimental farm of the College of Agronomy and Biotechnology, Southwest University, Chongqing, China (longitude 106°26′02′′ E, latitude 29°49′32′′ N, and altitude 220 m) during spring 2012. This region has a subtropical monsoon humid climate with 87,108 kJ·cm<sup>-2</sup> annual average gross radiation intensity, 1276.7 h annual average sunshine duration, 18 °C mean annual temperature, 40 °C maximum summer temperature, up to 359 frost-free days, 1133.7 mm average annual precipitation which accounts for 25.5%, 41.4%, 27.9%, and 5.5% in spring, summer, autumn, and winter, respectively, and with 1181.1 mm evaporation capacity and 93% drought frequency. The experimental land was purple soil with gentle slope and even fertility. Purple soils are classified as orthic entisols in the Chinese Soil Taxonomic System, Regosols in FAO (The Food and Agriculture Organization) Taxonomy or Entisols in USDA (United States Department of Agriculture) Taxonomy, developed from the fast physical weathering of sedimentary rocks of the Triassic–Cretaceous system. Before the experiment, physical and chemical properties of the upper layer of soil (0–20 cm) were analyzed by sampling from five locations (Table 1).

Table 1. Basic physical and chemical properties of soil.

Soil Bulk	Soil pH	Soil Organic	Total	Total	Total	Alkaline	Available	Available
Density		Matter	Nitrogen	Phosphorus	Potassium	Hydrolysis	Phosphorus	Potassium
(g cm <sup>-3</sup> )		(g kg <sup>-1</sup> )	(mg kg <sup>-1</sup> )	(mg kg <sup>-1</sup> )	(mg kg <sup>-1</sup> )			
1.21	6.47	28.00	1.68	1.46	34.54	38.23	18.13	170.13

# 2.2. Treatments and Experimental Design

In the first two years, straw mulching and ridge tillage was started in the cropping pattern of wheat-maize-sweet potato, while in the third year, a wheat-maize-soybean pattern was adopted with the same tillage treatments (Figure 1). The date of planting of these crops was early November, early April and late May, respectively. The maize was transplanted when it was in three leaf stage. Six treatments were arranged in a random block design replicated three times, and each block covered an area of 8 m  $\times$  3.6 m (Figure 2). The winter wheat (waxy wheat No.1, 45 kg per hectare), maize (Xidan No.1, 88,933 plants per hectare) and soybean (Yu Beans No.1, 115 kg per hectare) were used in this experiment. The winter wheat was planted into three rows with 17 plants in each row (the distance between the rows was 25 cm and the distance of the plants within the row was 20 cm), with a basal dose of calcium phosphate which contained  $P_2O_514\%$  (390 kg ha<sup>-1</sup>) and urea which contained N 46.67%  $(152 \text{ kg ha}^{-1})$ . The maize was planted in two rows with eight plants in each row, and a compound fertilizer which contained N 30%,  $P_2O_5$  5%,  $K_2O$  5% (148 kg ha<sup>-1</sup>) and urea which contained N 46.67%  $(74 \text{ kg ha}^{-1})$  were applied as basal fertilizer. The soybean was planted into three rows with 12 plants in each row, and a compound fertilizer which contained N 30%,  $P_2O_5$  5%, and  $K_2O$  5% (300 kg ha<sup>-1</sup>) were applied to each treatment of the soybean. Maize and wheat stalks were cut into 10 cm after harvesting and used for uniformly straw mulching with 42.7 kg of straw in each block (equivalent to  $24,000 \text{ kg ha}^{-1}$ ). For stalk rot treatment in TSD (traditional tillage + straw mulching + decomposing inoculants) and RSD (ridge tillage + straw mulching + decomposing inoculants), we used special strains for composting; the ingredients were compound probiotics with viable probiotics  $\geq 109$  cfu·g<sup>-1</sup> provided by Guangzhou Nongguan Biotechnology Co. Ltd., Taiwan. Additionally, decomposing

inoculants, whose dosage was 0.2% of the straw cover, were uniformly sprayed to the straw after being dissolved in water with no proportion required. The role of decomposing inoculants, which consists of lignin's thermophilic, heat-resistant bacteria, fungi, actinomycetes and bioenzymes, is reflected in the strong decomposition of cellulose and hemicellulose. Under suitable conditions, carbon, nitrogen, phosphorus, potassium, sulfur, etc. can be quickly decomposed and mineralized to form simple organic matter, which can be further decomposed into nutrients that can be absorbed by crops. On the whole, straw fast-rot agents mainly play the role of regulating available soil nutrients, fully decomposing straw and increasing organic matter, and its composition is non-toxic, easy to decompose, cheap, simple to apply, and worthy of promotion [30].



Figure 1. Wheat-maize-soybean cropping system in the hilly region of southwest China.

There were six treatments—traditional tillage (T): traditional farming throughout the experimental period; ridge tillage (R): before seeding (transplanting) ridges (20 cm high) were built up, and seeds or seedlings were sown or transplanted on the ridges; traditional tillage + straw mulching (TS): traditional tillage with crop straw left in the field as mulching; ridge tillage + straw mulching (RS): ridge tillage

with crop straw left in the field as mulching; traditional tillage + straw mulching + inoculants (TSD): traditional tillage with crop straw left in the field as mulch amended with straw decomposing agent; ridge tillage + straw mulching + inoculants (RSD): ridge tillage with crop straw left in the field as mulch amended with straw decomposing agent.



**Figure 2.** Treatment descriptions and field test layout. Traditional tillage (T): traditional farming throughout the experimental period. Ridge tillage (R): before seeding (transplanting) ridges (20 cm high) were built up, and seeds or seedlings were sown or transplanted on the ridges. Traditional tillage + straw mulching (TS): traditional tillage with crop straw left in the field as mulching. Ridge tillage + straw mulching (RS): Ridge tillage with crop straw left in the field as mulching. Traditional tillage + straw mulching + inoculants (TSD): traditional tillage with crop straw left in the field as mulch amended with straw decomposing agent. Ridge tillage + straw mulching + inoculants (RSD): ridge tillage with crop straw left in the field as mulch amended with straw decomposing agent.

# 2.3. Determination of Soil Respiration

Soil respiration was measured by the LI-6400 portable photosynthesis system connected with 6400-09 respiratory chamber. Each treatment was fixed in the positions of inter-line, inter-strand and band edge (Figure 3). A PVC (polyvinyl chloride) ring with an area of 80 cm<sup>2</sup> and height of 5 cm was inserted 2 cm below the soil in order to reduce soil disturbance. Each PVC ring was measured once, and each treatment was repeated three times. The average presented in the PVC was regarded as the

daily average respiration rate of the soil. It was measured once after every half month throughout the growth period of maize unless it was raining. All the data regarding soil respiration were recorded from 9:00 a.m. to 11:00 a.m.



**Figure 3.** Installed position of soil collars in measurement plots: the small circles in the figure represent the PVC rings arranged in a compartment. From left to right, there are inter-line, inter-strand and band edge.

# 2.4. Determination of Soil Hydrothermal Factors

The soil temperature was measured by a soil temperature probe connected to the LI6400-09 at a depth of 10 cm of soil. The soil moisture was measured by drying at 105 °C for 24 h, and the sample was taken at the same time of measuring soil respiration from five locations at the depth of 0–5 cm soil before being mixed together in an aluminous box.

# 2.5. Determination of Soil Fauna

In the period of maize transplanting to harvesting, the soil fauna within 5 cm of the soil layer was taken by the five-point sampling method every two weeks and separated by the Tullgren apparatus. Meanwhile, the ground soil fauna was captured by trapping methods once a month which was classified by the "Retrieval of Chinese Soil Animals" [29].

# 2.6. Calculation of Carbon Balance in Farmland Ecosystem

The net ecosystem productivity (NEP) represents the ecosystem carbon balance and was calculated according to Sun et al. [22]. NEP =  $0.4 \times \text{NPP} - 1.0368 \times \text{R}_{\text{m}} = \text{NPP} - 1.0368 \times (\text{R}_{\text{s}}-\text{R}_{\text{d}}) \times 115$ , where, NPP is the sum of the aboveground and underground biomass (g·m<sup>-2</sup>). To calculate NPP, we took destructive sampling for the aboveground biomass, initially dried at 105 °C for 24 h followed by 80 °C until the constant weight was achieved. Then the weight difference between successive samples were divided by the number of days between them. In this case, the unit of NPP was g·m<sup>-2</sup>. The underground biomass was calculated by the root–crown ratio, which is 0.1. R<sub>m</sub> is heterotrophic soil respiration (µmol·(m<sup>2</sup>·s)<sup>-1</sup>), R<sub>s</sub> is total soil respiration (µmol·(m<sup>2</sup>·s)<sup>-1</sup>) and R<sub>d</sub> is soil autotrophic respiration (µmol·(m<sup>2</sup>·s)<sup>-1</sup>), which accounts for 50% of total soil respiration. The carbon content of the maize plant (%) is 0.4 and there are 115 days in the maize growth period;  $1(\mu mol(CO_2) \cdot (m^2 \cdot s)^{-1}) = 1.0368g(C) \cdot (m^2 \cdot d)^{-1}$ .

# 2.7. Statistical Analysis

The collected data were statistically analyzed following one-way analysis of variation (ANOVA) and means were separated according to the least significant difference (LSD) test at a probability level of 0.05. Correlation analysis was used to analyze the relationship between soil temperature, soil moisture, soil animal numbers and soil respiration; linear regression was used to analyze the relationship among soil respiration rate, soil temperature and soil moisture. All the collected data was analyzed by Microsoft Excel 2003 and SPSS 13.0.

## 3. Results

# 3.1. Soil Respiration Characteristics of Farmland

The soil respiration rate increased initially and decreased afterwards during the entire growth period of maize ranging from 1.011–5.575  $\mu$ mol (m<sup>2</sup>·s)<sup>-1</sup>. The minimum soil respiration rate appeared during the maize jointing stage under the traditional tillage (T) and the maximum rate was recorded during the maize silking stage under TSD treatment (Figure 4). Soil respiration rates were significantly varied under different treatments, except for some periods where there was no significant difference. However, ridge tillage reduced the soil respiration from -29.41% to -13.79%. Straw mulching improved the soil respiration from 13.71% to 68.73%. The TSD and RSD treatments promoted the soil respiration from the beginning of the large bell stage to the end of the complete ripening stage. Ridge tillage mainly had negative effects on soil respiration, however, the TS and RS improved the soil respiration and soil respiration did not increase significantly until one month after maize transplantation under TSD and RSD treatments. The soil respiration rate varied greatly during the whole maize growth. Soil respiration was lower during the early stage of maize growth and there was no significant difference among treatments. However, the soil respiration increased with the rapid maize growth after the harvesting of wheat. It reached to maximum level at the silking stage and began to decrease at the grain filling stage until the maize was ripened. During the whole maize growth period, the daily average soil respiration rates were 2.555, 2.208, 2.959, 2.869, 3.261 and 3.277  $\mu$ mol·(m<sup>2</sup>·s)<sup>-1</sup> under the treatment of T, R, TS, RS, TSD and RSD, respectively (RSD > TSD > TS > RS > T > R). With the addition of decomposing inoculants, TSD and RSD treatments increased the soil respiration rate due to the abundance of microorganisms.



**Figure 4.** The comparison of soil respiration rate and growth stages of maize growth season under traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS), ridge tillage + straw mulching (RS), traditional tillage + straw mulching + decomposing inoculants (TSD), and ridge tillage + straw mulching + decomposing inoculants (RSD). Different lowercase letters in the figure indicate that differences between different treatments reached significant levels (p < 0.05).

## 3.2. Relationship between Soil Hydrothermal Factor and Soil Respiration

The atmospheric temperature and soil temperature were increased throughout the growing season of maize (R > T > RSD > TSD > RS > TS). The TS and RS treatments reduced the soil temperature while the TSD and RSD treatments slightly increased the soil temperature, but soil temperature in all four treatments was lower than T or R. This difference was more pronounced with high temperatures at which TS and RS reduced the soil temperature effectively (Figure 5).

The relationship between soil respiration rate and soil temperature was in line with the law of exponential function. The results showed that the  $Q_{10}$  of the six treatments namely, T, R, TS, RS, TSD and RSD were 2.34, 2.41, 2.69, 2.41, 2.53 and 2.25, respectively, which illustrated that both ridge tillage and straw mulching increased soil temperature sensitivity of soil respiration, but decomposing inoculants reduced this trend (Table 2).



**Figure 5.** Comparison of soil temperature and growth stages of maize under traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS), ridge tillage + straw mulching (RS), traditional tillage + straw mulching + decomposing inoculants (TSD) and ridge tillage + straw mulching + decomposing inoculants (RSD). Different lowercase letters in the figure indicate that differences between different treatments reached significant levels (p < 0.05).

**Table 2.** Relation equation of soil respiration rate and soil temperature under traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS), ridge tillage + straw mulching (RS), traditional tillage + straw mulching + decomposing inoculants (TSD) and ridge tillage + straw mulching + decomposing inoculants (RSD).

Treatments	а	b	Sample Numbers	$R^2$	<i>p</i> -Value	Q10
Т	0.344	0.085	20	0.512	0.000	2.34
R	0.357	0.083	20	0.429	0.002	2.41
TS	0.279	0.099	20	0.461	0.001	2.69
RS	0.407	0.083	20	0.405	0.003	2.41
TSD	0.340	0.093	20	0.537	0.000	2.53
RSD	0.451	0.081	20	0.289	0.014	2.25

 $Q_{10}$  was the temperature sensitive indicator of soil respiration. Soil moisture stably changed except for the lower value at the transplanting stage (Figure 6). Average soil moisture under different treatments varied significantly and followed the trend of TSD > TS > RS > RSD > R > T (Figure 6). In this triple cropping system, when the winter wheat was harvested in middle of May, the maize was about to enter the large bell stage. During the large bell stage, the fresh wheat straw was covered in the whole farmland. The relationship between soil moisture content and soil respiration was complicated and there was no unified conclusion. Therefore, a quadratic function simulation of soil respiration and soil moisture was performed according to the mathematical significance of the parabolic function. The results showed that the decisive coefficient of the parabolic curve between soil respiration and soil moisture for each treatment was 0.748 (p = 0.064), 0.781 (p = 0.048), 0.559 (p = 0.194), 0.811(p = 0.036), 0.603 (p = 0.158) and 0.951 (p = 0.002) for T, R, TS, RS, TSD and RSD, respectively (Table 3). Soil respiration increased along with an increase in soil moisture within a certain range. We regarded the value of soil moisture that causes the inhibition of soil respiration as the soil moisture response threshold of soil respiration. By calculating the coordinates of the parabola fitted to each treatment, the soil moisture response threshold of each treated soil respiration was R < T < RS < RSD < TS < TSD ranging from 11.98% to 13.11% (Table 3). The response threshold under R was the lowest, however, the soil respiration prematurely inhibited under R on the same soil moisture condition. In contrast, the TS and RS treatments increased the response threshold of soil moisture.



**Figure 6.** The comparison of soil moisture and growth stages of maize under traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS), ridge tillage + straw mulching (RS), traditional tillage + straw mulching + decomposing inoculants (TSD) and ridge tillage + straw mulching + decomposing inoculants (RSD). Different lowercase letters in the figure indicate that differences between different treatments reached significant levels (p < 0.05).

**Table 3.** Model summary and parameter estimates about soil respiration and soil moisture under traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS), ridge tillage + straw mulching (RS), traditional tillage + straw mulching + decomposing inoculants (TSD) and ridge tillage + straw mulching + decomposing inoculants (RSD).

Model Summary						<b>Parameter Estimates</b>			Soil Moisture
Quadratic	Quadratic R Square F df1 df2 Sig.		Constant	b1	b2	Response Threshold			
Т	0.748	5.936	2	4	0.064	-4.307	121.911	-490.616	12.42%
R	0.781	7.152	2	4	0.048	-3.958	112.509	-469.726	11.98%
TS	0.559	2.537	2	4	0.194	-7.303	174.215	-680.695	12.80%
RS	0.811	8.597	2	4	0.036	-5.475	150.530	-605.781	12.42%
TSD	0.603	3.032	2	4	0.158	-7.105	175.933	-670.880	13.11%
RSD	0.951	38.856	2	4	0.002	-8.846	213.138	-849.934	12.54%

Note: Soil moisture response threshold is vertex abscissa.

#### 3.3. Relationship between Soil Fauna and Soil Respiration

The results of the present study showed that soil fauna was lower because of human activities such as the transplanting and burying of maize (Figure 7). The number of soil fauna was significantly reduced under T and R treatments compared with TS and RS treatments. Spiders were greatly varied in size under the different treatments (Figure 8). However, the TS and RS treatments reduced the degree of disturbance of human activities to soil fauna to some extent, thus a higher number of soil fauna was recorded under the TS and RS treatments compared with the R and T treatments, but trapped soil fauna did not show the consistent phenomena (Figure 9). These findings indicate that the straw mulching increased the food source of soil fauna, however, spatial obstruction affected the activities of fauna in the surface of the soil. In contrast, soil fauna under non-straw mulching treatment were more active. Soil fauna was investigated by two different methods. The soil animals collected by the Tullgren apparatus were more abundant under straw mulching, and the number of soil animals captured by the trapping method depended on the size of the soil animals' living space. Since animals that are not under straw cover become more active in order to obtain more food, they were more likely to fall into the traps. Therefore, the number of soil animals collected by the pitfall traps method was even under different treatments (Figure 9). Considering the difference of soil animal biomass obtained by different methods, it is obvious that the TS and RS treatments were significantly higher than the T and R treatments (Table 4).

The correlation between soil respiration and soil animal numbers during the same period was analyzed; the results show that there was a positive correlation between them (r = 0.838, p < 0.01).

However, there was no obvious relationship between the number of soil fauna and soil respiration under the T and RS treatments (Table 5). The number of soil fauna was not significantly related to soil respiration which captured by the Tullgren apparatus method, except for TS (r = 0.900, p = 0.037); however, there was a close correlation between the number of soil fauna captured by pitfall traps and soil respiration, where treatment R had the highest correlation coefficient, (r = 1.000, p < 0.001), followed by TS (r = 0.900, p = 0.037). The correlation between soil fauna and soil respiration of other treatments was not obvious.



**Figure 7.** Number of soil animals by the Tullgren apparatus under traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS) and ridge tillage + straw mulching (RS).



Figure 8. Spider size under traditional tillage (T) and traditional tillage + straw mulching (TS).

Table 4. The number of soil fauna captured by different methods during the whole growth period.

Growth Period	Т	R	TS	RS
Transplanting	66	64	49	67
Small bell	136	155	177	229
Silking	160	114	202	259
Filling	135	109	172	202
Complete ripeness	22	41	135	184
Total	519	483	735	941



**Figure 9.** Number of soil animals by the pitfall traps method under traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS) and ridge tillage + straw mulching (RS).

	Total Number of Soil Fauna		Number of by Tullgren	Soil Fauna Apparatus	Number of Soil Fauna by Pitfall Traps	
	R	p	R	р	r	p
Average	0.838 **	0.000	0.827 **	0.000	0.536 *	0.015
Т	0.700	0.188	0.616	0.269	0.103	0.870
R	0.900 *	0.037	0.800	0.104	1.000 **	0.000
TS	0.900 *	0.037	0.900 *	0.037	0.900 *	0.037
RS	0.700	0.188	0.700	0.188	0.154	0.805

Table 5. The correlation between soil respiration and soil animal numbers.

*Note:* the asterisks indicate that differences between different treatments reached significant levels (\* p < 0.05 and \*\* p < 0.01).

# 3.4. Carbon Source and Sink Characteristics of Maize Farmland Ecosystem

In order to roughly estimate the carbon source and sink characteristics of maize farmland ecosystems, we need to differentiate soil respiration and quantify the ratio of autotrophic and heterotrophic respiration in total soil respiration. To simplify the calculation, this study indicated that the root respiration of the maize accounted for 50% of the total respiration, the root to shoot ratio was 0.1% and the plant carbon content was 40%. Farmland under different treatments presented as carbon sink in the maize growing season, and straw mulching and ridge tillage based on RS increased the farmland carbon sink from 2.91% to 6.55% (Table 6).

**Table 6.** Estimation of net carbon sinks in different treatment farmland ecosystems under traditional tillage (T), ridge tillage (R), traditional tillage + straw mulching (TS), ridge tillage + straw mulching (RS), traditional tillage + straw mulching + decomposing inoculants (TSD) and ridge tillage + straw mulching + decomposing inoculants (RSD).

Treatments	Carbon Sinks g(C)/m <sup>2</sup>			Carbon So	urces g(C)/m <sup>2</sup>	Net Carbon	Sinks
	Above Ground	Under Ground	Total	Total Soil Respiration	Heterotrophic Respiration	Storage g(C)/m <sup>2</sup>	Amplitude %
Т	755.966d	75.597d	831.563d	304.638	152.319	679.244	-
R	755.130cd	75.513cd	830.643cd	263.264	131.632	699.011	2.91
TS	817.656bc	81.766bc	899.422bc	352.806	176.404	723.018	6.44
RS	794.389bc	79.439bc	873.828bc	342.077	171.038	702.790	3.47
TSD	823.867b	82.387b	906.253b	388.816	194.408	711.846	4.80
RSD	835.569a	83.557a	919.126a	390.723	195.362	723.764	6.55

Note: Different lowercase letters in the table indicate that differences between the treatments reached significant levels (p < 0.05).

### 4. Discussion

Numerous factors including soil temperature, soil moisture, soil organic content, land use, fertilization, soil texture, planting crops, soil biology, etc., affect the rate of respiration in soil. These factors are not only affected by the environment but also by the soil itself with a close relevance to soil respiration as well as an interplay between each other [31]. The results of the present study show that soil respiration in maize farmland increased initially and decreased afterwards, and soil temperature rises constantly and soil moisture changes stably (Figure 4). The relationship between soil respiration and influencing factors was not simply linear so that the single factor model cannot fully explain soil respiration, however, it is needed with various factors in order to make a reasonable explanation [32].

#### 4.1. Soil Respiration Rate under Straw Mulching and Ridge Tillage

Previous studies have investigated soil respiration rates under straw mulching and ridge tillage but failed to get a unified conclusion due to differences in regional climate, soil and planting patterns [33-36]. The effect of straw mulching treatment on soil respiration in different crops is consistent, and previous studies reported enhanced soil respiration in different degrees under the influence of straw decomposition [33–36]. It is generally believed that the straw application could promote the release of carbon dioxide from the soil [33]. Consistent with previous findings, our results show that the effects of straw on soil respiration have gradually reduced with straw decomposition (Figure 4). Guan et al. observed that the soil respiration of winter wheat farmland was significantly increased under straw mulching in the dryland area of the Loess Plateau [34]. Zhang et al. showed that the soil respiration rate significantly increased with an increase in the amount of straw decomposition in field trials [35]. Furthermore, Wang et al. pointed out that the effect of soil respiration was divergent between ridge tillage and traditional tillage in different crops, and it was also divergent at different growth stages of the same crop [36]. Nonetheless, the soil respiration rate was higher under ridge tillage compared with conventional tillage before the grain filling stage of wheat, likewise, the soil respiration rate under ridge tillage was higher than traditional tillage in the growth period of corn [36]. In the present study, the rate of soil respiration was reduced by 29.41% in the growth period of maize, but straw mulching increased the soil respiration from 13.71% to 68.73% (Figure 4). The ridge tillage in the maize field reduced the soil respiration while the straw mulching improved it, compared with traditional tillage. Straw mulching increased the soil respiration by increasing the soil organic carbon (the soil organic carbon in the 0–5 cm soil layer was 10.77 (T), 10.38 (R), 16.09 (TS), 14.53 (RS)  $g \cdot kg^{-1}$ ) as well as the number of soil fauna, thus promoting the growth and development of crop roots. Moreover, root respiration and soil microbial respiration were the main forms of soil respiration. The decline of soil respiration caused by ridge tillage might be attributed to the changes in soil temperature and soil moisture (Figure 4).

#### 4.2. Effect of Soil Hydrothermal Factors on Soil Respiration

Soil temperature and soil moisture are the most decisive factors of soil respiration. The relationship between soil temperature and soil respiration is often expressed as a  $Q_{10}$  value, which is the multiple of the increase in soil respiration at a temperature increase of 10 °C and measure of the sensitivity of the respiratory rate to temperature changes usually 1.3–5.6 [37]. Previous studies stated that the soil respiration was declined when the soil moisture was lower than 40% of field capacity or higher than 80% [38].

The relationship between soil respiration and soil temperature in farmland ecosystems includes exponential function, linear function, power function, parabola, etc., of which exponential model are widely used for the  $Q_{10}$  and can reflect the relationship between soil respiration and soil temperature [39–41]. The results of the present study showed that the  $Q_{10}$  of the six treatments (T, R, TS, RS, TSD, RSD) was 2.34, 2.41, 2.69, 2.41, 2.53 and 2.25, respectively. Both TS and RS increased the soil temperature sensitivity of soil respiration while, TSD and RSD reduced the soil temperature sensitivity of soil respiration. The higher sensitivity of the soil temperature indicates that lower soil

temperature leads to a greater decline of soil respiration. Soil temperature intensity under different treatments sorted as R > T > RSD > TSD > RS > TS. Both TS and RS reduced the soil temperature (Figure 5) and contributed to the reduction of carbon dioxide emissions.

Soil moisture is considered as an important physical property of soil, which affects all reactions and processes of soil in the soil microbial activity, soil nutrient migration, etc. Previous studies used the parabolic function, linear function and exponential function to describe the relationship between soil respiration and soil moisture [42–44]. The response threshold under ridge tillage was lower, while that of straw mulching was higher (Table 3). Therefore, soil respiration under ridge tillage in the same soil moisture was prematurely inhibited.

# 4.3. Effect of Soil Fauna on Soil Respiration

Soil faunas are important decomposers in ecosystems and play an important role in the change of soil properties, material migration and energy conversion. As global warming increases, soil faunas have an important regulatory role in the carbon cycle of ecosystems. Due to the lack of relevant research and the fact that most are controlled in the laboratory, there are few studies on soil respiration, emission mechanisms and feedback effects of soil faunas in situ determination [8]. The results of this study indicate that there was a significant correlation between the number of soil fauna and soil respiration under the R and TS treatments. The lower correlation of soil fauna and soil respiration on T and RS treatments was conceivably because soil respiration was mainly affected by soil temperature and soil moisture due to less soil fauna under traditional farming. Both ridge tillage and straw mulching contributed to the close correlation between soil respiration and the number of soil fauna, while the interaction between ridge tillage and straw treatment reduced the correlation. The soil animals captured with the dry funnel method were mainly small and medium-sized below 2 mm, while the trapping method mainly collected soil animals without bounce on the surface of the soil. Soil animals mainly involve a variety of groups from protozoa to arthropods. The soil fauna obtained in this study did include all the soil fauna, which could account for the poor correlation between soil fauna and soil respiration. The correlation between soil respiration and soil fauna would be enhanced if more types of soil fauna could be collected. The interplay among large-scale, micro-soil fauna and soil microorganisms as well as all soil fauna and soil respiration are needed for further study. In the future, it is worthy to carry out research on the coupling of hydrothermal and bio composite factors in soil respiration in order to clarify the mechanism of soil respiration and provide a scientific basis for carbon sequestration in soil.

# 5. Conclusions

The soil respiration rate in farmland increased initially and decreased afterwards during the whole growth period of maize. Soil respiration rates of different tillage treatments were significantly different. Ridge tillage reduced the soil respiration in maize fields, while straw mulching increased it, compared with traditional tillage. However, ridge tillage and straw mulching were both conducive to the carbon sink of farmland ecosystems. The soil respiration of straw mulching treatment had a higher sensitivity to soil temperature, while ridge tillage reduced the sensitivity of soil temperature. The response threshold of soil moisture under ridge tillage was lower but straw mulching was found to increase it. Soil fauna promoted soil respiration and the correlation coefficient of ridge tillage was the highest. There was a certain relationship between soil respiration and the number of soil animals on the surface of the soil on the conditions of ridge tillage and straw mulching, however, there was no obvious relationship between the number of soil animals and soil respiration on the condition of traditional farming.

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