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Differential Influence of No-Tillage and Precipitation Pulses on Soil Heterotrophic and Autotrophic Respiration of Summer Maize in the North China Plain

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Received: 26 November 2020; Accepted: 15 December 2020; Published: 20 December 2020

Abstract: It is important to strengthen the studies on the response of soil respiration components to tillage practices and natural precipitation in cropland. Therefore, soil heterotrophic respiration (R_H) and autotrophic (R_A) respiration were monitored by a root exclusion method in the North China Plain (NCP). The tillage practices included no-tillage (NT) and conventional tillage (CT), and the study periods were the summer maize growth stages in 2018 and 2019. R_H , R_A , soil water content and temperature were measured continuously for 113 days by an automatic sampling and analysis system. The soil R_H values on bright days and rain-affected days were higher under NT in 2018 (14.22 and 15.06 g CO₂ m⁻² d⁻¹, respectively) than in 2019 (8.25 and 13.30 g CO₂ m⁻² d⁻¹, respectively). However, the R_A values on bright days and rain-affected days were lower under NT in 2018 (4.74 and 4.97 g CO₂ m⁻² d⁻¹, respectively) than in 2019 (5.67 and 6.93 g CO₂ m⁻² d⁻¹, respectively). Moreover, NT decreased R_H but increased R_A compared to CT in 2019. Compared to bright days, the largest increase in both R_H and R_A after rain pulses was under CT in 2019 (6.75 and 1.80 g CO₂ m⁻² d⁻¹, respectively). Soil water content and soil temperature were higher in 2018 than in 2019. Moreover, NT increased soil water content and decreased soil temperature on bright days compared to CT in 2019. Furthermore, soil temperature accounted for more variations in R_H on bright days and rain-affected days, but soil water content had a greater influence on R_A on bright days. However, after precipitation, higher soil water content decreased R_A under NT in 2018, while soil water content was positively related to R_A under CT in 2019. This study determined the differential response of R_H and R_A to tillage practices and natural precipitation pulses, and we confirmed that excessively dry soil increases soil carbon loss after rain events in the NCP.

Keywords: soil respiration components; precipitation; no-tillage; automatic chamber; maize; North China Plain

1. Introduction

Soil respiration (R_S) in cropland is a critical source of increasing atmosphere CO₂ [1]. Soil respiration includes autotrophic respiration (R_A) from the roots and rhizosphere communities, and heterotrophic

respiration (R_H) from soil microbes [2]. Moreover, R_H is positively correlated with net primary productivity and is essential for assessing terrestrial carbon emissions to the atmosphere [3]. Conservation tillage practices, such as no-tillage (NT), tend to decrease R_H and R_A when compared to conventional tillage (CT) because of having a lower soil disturbance, which affects the soil water content and temperature and has a significant impact on R_H and R_A [4,5]. However, it was reported that R_S was higher under NT because less soil disturbance and soil water content is conserved under NT conditions [6,7]. Moreover, Liu et al. [8], Pareja-Sanchez et al. [6] and Salem et al. [7] suggested that the influence of NT on soil CO_2 emissions varied with NT transformation time, soil properties, and climate. Thus, to further understand the response of soil CO_2 emissions to NT, it is critical to explore the influence of short-term NT on R_H and R_A .

Soil water content and soil temperature are key factors influencing R_H and R_A [9–11]. Precipitation is a critical environmental factor that causes significant changes in soil water content and temperature, leading to variations in R_S [12]. Higher annual precipitation can lead to greater R_A and R_H due to increased soil water content [9,11,13–15]. Moreover, a rain pulse can increase soil CO_2 emissions compared to emissions on bright and dry days [16,17], and dry soil is more sensitive to rain events [18,19]. Many previous studies have reported that the precipitation manipulation method is valuable for climate change studies [6,12,20,21]. However, it can be problematic as it is difficult to simulate real precipitation scenarios and environment factors [22]. Therefore, less direct monitoring of R_S , R_H , and R_A can be conducted under natural precipitation pulses and environment conditions [23]. As such, the response of R_H and R_A to natural precipitation pulses under different environment factors (i.e., soil water content and temperature) remains unknown.

The North China Plain (NCP) covers 1.445 million km^2 and is an intensively cultivated agricultural area within China [24]. It is important to study and decrease the cropland soil CO_2 emissions in a large area like the NCP. However, few studies have focused on the response of continuous daily R_H and R_A to short-term NT and natural precipitation pulses in the NCP. Therefore, we conducted an experiment to evaluate the performance of R_H and R_A for a summer maize field in the NCP. The objectives of this study are to (1) determine the influence of NT and precipitation pulses on R_H and R_A , and (2) quantify the critical environment factors influencing the R_H and R_A of maize in the NCP. The hypotheses of this study are as follows: (1) the higher annual soil water content and temperature conditions in 2018 increased R_H and R_A on bright days and rain-affected days compared to those in 2019; (2) R_H and R_A are higher under NT than under CT in 2019; and (3) soil water content is more important in influencing R_H and R_A when compared with soil temperature in the NCP.

2. Material and Methods

2.1. Site Description

The study site is located at the Yucheng Shandong Agro-ecosystem National Observation and Research Station belonging to the Ministry of Science and Technology in the NCP (36°50' N, 116°34' E). This area has a warm temperate continental monsoon climate. The long-term mean annual temperature is 13.3 °C, and the mean annual precipitation is 559.8 mm [25,26]. The primary local soil type is a calcareous fluvisol and the texture is silt loam (sand, 12%; silt, 66%; clay, 22%) (Tu and Li, 2017; Zhao et al., 2018). In the 0–20 cm region, the soil pH (soil: water, 1:5) is 8.3, total organic matter is 12.6 g kg^{-1} , total N is 0.89 g kg^{-1} , total P is 2.11 g kg^{-1} , and total K is 21.4 g kg^{-1} [27].

2.2. Field Management and Experimental Design

The experimental treatments were established in October 2014 and included two tillage practices (NT and CT) under a randomized complete block design. The experimental plot area was 5 m × 10 m (three replicates). The study was conducted during the summer maize growth periods in 2018 and 2019. The annual precipitation in 2018 and 2019 was 898.5 and 338.6 mm, respectively. The annual

temperature in 2018 and 2019 was 14.5 and 14.4 °C, respectively. The cumulative rainfall during the maize growth stage (from day 171 to 283) was 472.9 mm in 2018 and 220.3 mm in 2019 [27] (Figure 1).

Figure 1. Mean, minimum, and maximum air temperature (°C) and precipitation (mm) during the maize growth stage (day 171–283) (a: 2018, b: 2019) at the Yucheng experimental station in the North China Plain. BD: bright days [27].

The former rotation crops of winter wheat (*Triticum aestivum* L.) and summer bean (*Glycine max* L.) were transformed into winter wheat–summer maize (*Zea mays* L.) in June 2018. Maize seeds (Denghai 605) were manually hole-sown in rows spaced 60 cm apart in mid-June. No irrigation was applied in 2018; however, 100 mm of irrigation was applied before seeding in late July 2019 because severe drought inhibited seed establishment. The total amount of nitrogen fertilization (207 kg N ha^{−1}) was applied via top-dressing after the rainfall in late July. During all maize growth periods, no plowing, additional irrigation, or wheat residue application was performed. All maize in the experimental plots was manually harvested on the same day in mid-October.

After the maize residues were removed, 100 mm of irrigation (from underground water) was applied to each plot. Tillage (15 cm) was applied with a rotary tiller only in the CT groups. Winter wheat (Jimai 22) was sown with a planting density of 262.75 kg ha^{−1} in 20 cm rows. Base fertilization including nitrogen (as urea, 46.4% nitrogen content, 105 kg N ha^{−1}), phosphorus (750 kg P₂O₅ ha^{−1}), and potassium (160 kg K₂SO₄ ha^{−1}) was applied in the sowing stage. The urea fertilization (105 kg N ha^{−1}) was top-dressed when the first 100 mm of underground water was applied in March of the following year. A second irrigation (100 mm) was applied in mid-May. The winter wheat was harvested in the second week of June.

2.3. Soil CO₂ Sampling and Measurement

Two transparent chambers (0.5 m × 0.5 m × 0.5 m) were installed in the centers of the plots in late May 2018. No plants were sown in the chambers. The collars of the two chambers were 5 cm deep (for R_S) [27] and 20 cm deep (for R_H). Furthermore, one row of maize was not planted at every side of the chamber for R_H to achieve bare soil status in the R_H chamber according to some previous studies [28,29]. Thus, according to the root exclusion method, the difference between R_S and R_H was R_A (i.e., R_A = R_S − R_H) [28,30]. However, R_H and R_A data under CT were not available because the instruments for R_H were broken in the CT plot until the maize harvest in 2018. Therefore, this study only reported R_H and R_A in 2018-NT, 2019-NT and 2019-CT.

The automatically closed chambers and a Picarro G2508 analyzer (Picarro, Inc., Santa Clara, USA; cavity ring-down spectroscopy) were used to sample and measure the CO₂ mole fraction in all chambers [31]. The chamber brackets and plates were made of stainless steel and acrylic plastic,

respectively. Two automatic push rods were installed to achieve an open or closed chamber. To ensure sufficient gas stirring in each chamber, two fans (12 V) operated in the two up and down diagonals of the chamber when the chamber was closed (image shown in Supplementary Information S1).

Chambers were left open to decrease the potential warming effect on soil when not sampling. Each chamber was closed for 200 s in turn every hour to sample the gas, except for 00:00 and 01:00 on one day (for other gas measurement). The sampled gas was transported to the analyzer through a 50 m long intake tube (inner diameter: 4.35 mm) by an Edwards pump (10 L/min, 50 Mb, 60 Hz, Edwards Inc., Crawley, UK). The flow rates ($150 \pm 3 \text{ mL min}^{-1} \text{ CO}_2$) of the sampled gas were accurately controlled by a mass flow controller (FMA5400A, OMEGA Engineering, Inc., Norwalk, USA). CO_2 concentration data were collected and recorded using a CR3000 data logger (Campbell Scientific, Inc., Logan, UT, USA).

The air pressure and temperature in the chamber were monitored using a barometric pressure transducer (Setra 278, Setra Systems Inc., MA, USA) and a Vaisala HMP155A sensor (Vaisala Inc., Helsinki, Finland), respectively.

The following equation was used to calculate the soil CO_2 flux [32]:

$$F = \frac{dC/dt \times \rho \times h \times T_0 \times P \times 10^{-3}}{T \times P_0} \quad (1)$$

where dC/dt ($\mu\text{L L}^{-1} \text{ h}^{-1}$) is the linear variance of CO_2 concentration during the sampling period ($R^2 > 0.9$), ρ (g C m^{-3}) is the standard CO_2 density at $T_0 = 273 \text{ K}$ and $P_0 = 1013 \text{ hPa}$, h (m) is the chamber inner height, T (K) is the mean air temperature and P (hPa) is the mean pressure during chamber closure. Data from 0 to 60 s were regarded as invalid data due to the last gas flush.

Wang et al. [33] suggested that soil respiration from 09:00 to 11:00 could represent the mean CO_2 flux over 24 h in a single day. To increase the accuracy of the data and reduce the influence of instrument failure, we calculated the daily R_H and R_A using nine hours of data (averaged over 8 h intervals), including 01:00–04:00, 09:00–12:00, and 17:00–20:00. Our previous study indicated a strong positive correlation between soil respiration data measured at 9 h and 23 h ($R^2 > 0.99$) and no significant difference between the data of the two methods [27].

The daily air temperature and precipitation data are shown in Figure 1. We selected the days from June 20 (day 171) to October 10 (day 283) as the study period. Rainy days and the three days following each rain event were denoted as rain-affected days (Figure 1). If it rained on consecutive days and the length of time between two precipitation events was less than three days, we assumed a single continuous rainfall event. All other days were denoted as bright days. The number of bright days and rain-affected days was 67 and 46 days in 2018, and 68 and 45 days in 2019, respectively. The mean R_H and R_A on bright days and rain-affected days were calculated using the daily soil CO_2 flux for each weather type in every year.

2.4. Auxiliary Measurements

Vertical soil water content and temperature sensors (CS655, Campbell Scientific, Inc., Logan, UT, USA) were installed in the soil (to 30 cm depth) in each chamber. A linear calibration for the soil water content measurement was conducted using the drying method for every CS655 sensor. A datalogger CR1000 (Campbell Scientific, Inc., Logan, UT, USA) was used to collect data on soil water content, soil temperature, air pressure, and air temperature.

2.5. Data Analysis

Daily R_H , R_A , soil water content, and soil temperature data were calculated using R version 3.5.2 (R Foundation for Statistical Computing, Vienna, Austria). The effects of tillage practices were tested by one-way analysis of variance at $p = 0.05$, using SPSS Statistics Client 19.0 (SPSS China, Beijing, China). The relationships between R_H and R_A with soil water content and soil temperature were examined

using a stepwise linear regression with SPSS 19.0. Figures were drawn using OriginPro 8.0 (OriginLab Corporation, Northampton, MA, USA).

3. Results

3.1. R_H and R_A

Both R_H and R_A varied significantly with tillage practices and maize growth stages (Figure 2). On bright days, the mean R_H under NT was 72.18% higher in 2018 than in 2019; however, the mean R_A was lower in 2018 than in 2019. Compared with CT, NT decreased R_H by $1.21 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ but increased R_A by $0.93 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2019 (Table 1). Precipitation increased R_H and R_A when compared to bright days (Table 1). Comparing the two years, under NT, the increase in R_H and R_A after rainfall was higher in 2019 (by 5.05 and $1.26 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, respectively) than in 2018 (by 0.84 and $0.23 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, respectively) ($p < 0.05$) (Table 1). Similarly, the increase in R_H and R_A after precipitation was higher under CT (by 6.75 and $1.80 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, respectively) than under NT in 2019 (Table 1). Furthermore, the contribution of R_H and R_A on rain-affected days to the total R_H and R_A under two weather conditions showed the relationship as 2019-CT (53.14%, 52.87%) > 2019-NT (51.62%, 44.72%) > 2018-NT (42.10%, 41.86%).

Figure 2. Daily soil heterotrophic respiration (R_H) (A) and autotrophic respiration (R_A) (B) in response to tillage practices during maize growth stages in 2018 and 2019.

Table 1. Mean ($\pm$ SE) daily R_H and R_A ($\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) on BD and RAD in response to tillage practices during maize growth stages in 2018 and 2019.

Weathers	Respiration	2018-NT	2019-NT	2019-CT
BD	R_H	$14.22 \pm 0.19 \text{ a}$	$8.25 \pm 0.25 \text{ c}$	$9.46 \pm 0.19 \text{ b}$
	R_A	$4.74 \pm 0.10 \text{ b}$	$5.67 \pm 0.31 \text{ a}$	$2.59 \pm 0.25 \text{ c}$
RAD	R_H	$15.06 \pm 0.19 \text{ b}$	$13.30 \pm 0.13 \text{ c}$	$16.21 \pm 0.17 \text{ a}$
	R_A	$4.97 \pm 0.40 \text{ b}$	$6.93 \pm 0.32 \text{ a}$	$4.39 \pm 0.30 \text{ b}$
RAD-BD	R_H	$0.84 \pm 0.07 \text{ c}$	$5.04 \pm 0.17 \text{ b}$	$6.75 \pm 0.11 \text{ a}$
	R_A	$0.23 \pm 0.32 \text{ c}$	$1.26 \pm 0.07 \text{ b}$	$1.80 \pm 0.06 \text{ a}$
RAD/(BD+RAD)	R_H	42.10%	51.62%	53.14%
	R_A	41.86%	44.72%	52.87%

Note: The same letters in a row indicate no significant difference between values ($p > 0.05$); BD: bright days; RAD: rain-affected days.

3.2. Soil Water Content and Soil Temperature

Tillage practices and precipitation had a significant influence on soil water content ($p < 0.05$) (Figure 3, Table 2). The mean soil water content was $0.28 \text{ cm}^3 \text{ cm}^{-3}$ higher in 2018 than in 2019. Compared to CT, NT increased mean daily soil water content on bright days by $0.61 \text{ cm}^3 \text{ cm}^{-3}$ in 2019 ($p < 0.05$). Similarly, after precipitation, soil water contents were greater under NT. Moreover, under NT, the increase in soil water content derived from rain events was higher in 2018 compared to 2019 (Table 2).

Figure 3. Soil water content (A) and soil temperature (B) in response to tillage practices during maize growth stages in 2018 and 2019.

Table 2. Mean ($\pm$ SE) soil water content ($\text{cm}^3 \text{ cm}^{-3}$) and soil temperature ($^{\circ}\text{C}$) in response to tillage practices in 2018 and 2019.

Treatments	Days	2018-NT	2019-NT	2019-CT
Soil water content	BD	20.34 ± 0.09 a	20.06 ± 0.11 b	19.45 ± 0.09 c
	RAD	25.08 ± 0.19 a	21.92 ± 0.05 b	21.20 ± 0.09 c
	RAD-BD	4.74 ± 0.17 a	1.87 ± 0.12 b	1.75 ± 0.15 b
Soil temperature	BD	26.03 ± 0.08 a	25.26 ± 0.11 c	25.43 ± 0.07 b
	RAD	25.84 ± 0.14 a	24.77 ± 0.09 b	24.82 ± 0.05 b
	RAD-BD	-0.19 ± 0.21 b	-0.50 ± 0.13 a	-0.61 ± 0.03 a

Note: The same letters in a row indicate no significant difference between values ($p > 0.05$); BD: bright days; RAD: rain-affected days.

Mean soil temperature on bright days under NT was 0.77°C greater in 2018 than in 2019 ($p < 0.05$) (Table 2). NT decreased soil temperature by 0.17°C when compared with CT in 2019 ($p < 0.05$). After rain events, soil temperature decreased, and this decrease in soil temperature was greater under CT in 2019 ($p < 0.05$) (Table 2). Tillage practices had no significant influence on soil temperature after rain in 2019 ($p > 0.05$).

3.3. Relationship between R_H , R_A with Soil Water Content and Soil Temperature

The stepwise analysis results showed that soil temperature was more critical in influencing R_H on bright days and rain-affected days under NT in 2018; however, soil water content affected more

variation in R_A after precipitation under NT in 2018, and higher soil water content even decreased R_A in 2018 (Table 3). Moreover, under NT, soil temperature had a more important effect on R_H and R_A when compared with soil water content in 2019 (Table 3). By contrast, under CT, soil water content contributed more variations in R_H and R_A on bright days in 2019 (Table 3).

Table 3. Multiple linear stepwise regression analysis between R_H and R_A with soil water content (SWC) and soil temperature (ST) in 2018 and 2019.

Weathers	Treatments	R_H			R_A		
		SWC	ST	Partial R^2	SWC	ST	Partial R^2
BD	2018-NT	—	0.915	0.834 **	—	—	—
	2019-NT	0.257	0.307	0.187 *	0.354	0.454	0.794 **
	2019-CT	0.317	—	0.087 **	0.709	—	0.495 **
	All	0.152	0.786	0.394 **	0.270	0.046	0.062 **
RAD	2018-NT	—	0.792	0.618 **	−0.330	—	0.090 *
	2019-NT	—	0.544	0.280 **	—	0.386	0.129 **
	2019-CT	0.286	0.492	0.350 **	0.439	—	0.174 **
	All	0.105	0.554	0.327 **	−0.058	0.253	0.048

Note: * $p < 0.05$; ** $p < 0.01$. BD, bright days; RAD, rain-affected days; “—” means not significant in the stepwise regression analysis.

4. Discussion

4.1. Annual Variation in R_H and R_A

In accordance with the first hypothesis, under NT, R_H on bright days was higher in 2018 than in 2019 (Table 1). This could be explained by the greater soil water content and temperature in 2018 (Table 2), and an increased effect of temperature on R_H between the two years (Table 3), as Dossou-Yovo et al. and Poll et al. highlighted [11,34]. In contrast to the first hypothesis, under NT, R_A on bright days was lower in 2018 when compared with 2019 in this study (Table 1), which is in line with the findings of Song et al. and Wang et al. [23,35]. This could be explained by the fact that roots grow deeper in dry soil to access water and enable plant growth [36], leading to higher R_A .

Similarly, under NT, after precipitation R_H and R_A were greater in 2018 when compared with those in 2019 due to higher soil water content after rain in 2018 (Tables 1 and 2). This is in line with our first hypothesis. This response was derived from the greater effect of soil temperature on R_A on rain-affected days under NT in both years (Table 3). We suggest that the response of R_H and R_A to precipitation was limited by background respiration on bright days, as highlighted by the previous study [12].

Furthermore, R_H and R_A were higher on rain-affected days than on bright days (Table 1), similar to the findings of Refs. [37] and [17]. Austin et al., Gonsiorkiewicz et al., and Koncz et al. [16,17,38] indicated that precipitation pulses increased soil CO_2 emissions because the additional soil water content after rain increases the soil microbial activity, organic substrate decomposition, and primes root effects. Moreover, the increase in R_H and R_A under NT was higher in 2019 than in 2018 (Table 1). It was reported that soil respiration in dry soil was more sensitive to added soil water content from precipitation and irrigation [13,18]. Concordantly, soil water content under NT was higher in 2018 than in 2019 (Table 2), leading to higher variations in R_H and R_A in 2019 (Table 1).

4.2. Influence of No-Tillage and Precipitation on R_H and R_A

The second hypothesis was partly disproved because NT decreased R_H on bright days in 2019 (Table 1), in line with the results of Ref. [34]. Almaraz et al. and Dossou-Yovo et al. [10,39] indicated that soil respiration under NT was lower than that under CT due to lower soil disturbance and the following less effusive oxygen. Furthermore, soil temperature was higher under CT, and soil temperature was more important in influencing R_H in this study (Table 3). In line with R_H on bright days, R_H after

precipitation was lower under NT than under CT (Table 1). It was reported that the response of soil CO₂ fluxes after rain events to tillage practices was affected by that on bright days [6]. Moreover, a higher soil temperature increased R_H after precipitation in 2019 (Table 2, Table 3), as Dossou-Yovo et al. and Poll et al. [10,11] suggested.

Ali et al. [20] highlighted that NT decreased R_A due to the lesser soil disturbance, which led to lower root growth. By contrast, R_A on bright days was greater under NT than under CT in 2019 (Table 1), in accordance with our second hypothesis. It was observed that soil water content on bright days was higher under NT (Table 2), resulting from the enhanced conservation of soil water content due to less soil disturbance [40,41]. Moreover, 2019 was a dry year (Figure 1). Besharat et al. [42] reported that dry soil conditions had a negative effect on root growth. Therefore, higher soil water content led to greater R_A under NT (Table 1).

In 2019, the increase in R_H and R_A after rain pulses was higher under CT than under NT (Table 1), which could be explained by the possibility that the oxygen and CO₂ exchange between soil and atmosphere was higher under CT due to the greater soil porosity [15,43].

4.3. Soil Water Content and Temperature and the Relationship with R_H and R_A

The soil water content–temperature relationship varies across many precipitation manipulation experiments [6,20]. In our previous study, we suggested that high air temperature led to greater soil temperature in 2018 when compared with that in 2019 (Figure 1) [27]. However, the soil water content was higher in 2018 than in 2019. This result indicates that air temperature was more influential on soil temperature after precipitation than soil water content in the two study years. Furthermore, the increase in soil water content after rain events was higher in 2018 than in 2019 (Table 2), suggesting that the soil water content was still insufficient after precipitation in 2019, and this dry condition had a significant impact on soil CO₂ emissions.

In this study, soil water content and temperature were highly correlated with R_H and R_A (Table 3), as observed by Silva et al. and Poll et al. [11,44]. Soil temperature was more important in influencing R_H on bright days and rain-affected days under NT, but soil water content was more influential for R_H under CT on bright days (Table 3). These results are partly in line with the third hypothesis. It was reported that soil disturbance was more intensive under CT, and the following soil water evaporation was higher, leading to lower soil water content and greater soil temperature under CT [4,5,41]. Thus, the relationship of R_H with soil temperature was more significant than that with soil water content under NT. By contrast, soil water content was the limiting factor when the soil was dry on bright days, as Balogh et al. and Eshel et al. [18,45] suggested. However, it was suggested that soil temperature was a more important factor affecting R_H when soil water content was increased after precipitation [16,17].

In 2018, the precipitation was more than 40% higher than the mean rainfall during maize growth (Figure 1). Extra water in the soil led to less O₂ and CO₂ exchange between the soil and atmosphere, as many previous studies have reported [9,16]. Similarly, on bright days, soil temperature was more effective in limiting R_A under NT in 2019. However, under CT in 2019, the soil water content was more effective in limiting R_A on bright days and rain-affected days (Table 3). In 2019, the low soil water content was the limiting factor for root growth due to the significantly lower soil water content on bright days in 2019 (Table 2), and because the soil water content was insufficient even after rain events (Table 2).

Global climate change leads to altered soil water content and soil temperature conditions, and causes substantial variations in soil respiration due to frequent severe droughts and flooding [1]. Therefore, it is essential to analyze the effect of annual environmental factors (such as soil water content and soil temperature) and tillage practices on soil CO₂ emissions via R_H and R_A . Moreover, continuous long-term observations of daily soil CO₂ emissions are required to monitor every rain event in order to study the influence of NT on soil respiration in the NCP.

It was observed that R_H and R_A in the dry soil were more sensitive to added soil water content, and short-term NT accelerated the total soil respiration by increasing R_A compared to CT (Table 1).

The summer maize cropland accounts for an important percent of the total farmland in the NCP [46]. Furthermore, irrigation was the only way to keep the soil water content and guarantee the corn yield of summer maize in the dry year in the NCP [25]. Therefore, we suggest that to decrease soil respiration in the NCP, cropland transform from tillage to no-tillage practices should not be conducted in the dry year, and we encourage proper but not excessive irrigation during summer maize growth stages under low annual precipitation conditions.

5. Conclusions

The influence of tillage practices and precipitation pulses on the R_H and R_A of summer maize was quantified using a root exclusion method. Continuous daily R_H , R_A , soil water content, and temperature were directly monitored across the maize growth stages with an in-situ automatic sampling and measurement system. It was observed that R_H was higher on bright days and rain-affected days under NT in 2018 than in 2019 owing to the greater soil temperatures in 2018. However, under NT and both weather conditions, R_A was lower in 2018 than in 2019. Similarly, NT decreased R_H on bright days when compared with CT due to the lower soil temperature and higher soil water content under NT. Moreover, NT increased R_A on bright days due to conserved soil water content under NT in 2019. The influence of tillage practices on R_H and R_A after precipitation was in line with that on bright days. Furthermore, the R_H and R_A values in dry soil, especially under CT in 2019, were more sensitive to rain events. On bright days in 2019, soil temperature was more effective in accounting for the variations in R_H and R_A values under NT, but soil temperature was more effective under CT. After precipitation, soil temperature was more important in influencing R_H under NT and CT. However, an excessive soil water content inhibited R_A in 2018, and soil water content was positively correlated with R_A under CT in 2019. This study revealed the different responses of soil respiration components to altered rain events and tillage management. Long-term continuous observations are critical in order to understand the influence of precipitation and tillage practices on R_H and R_A in the NCP.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4395/10/12/2004/s1>.

Author Contributions: Conceptualization, F.L. and K.D.; methodology, K.D.; software, K.D. and P.L.; validation, F.L. and K.D.; formal analysis, F.L. and K.D.; investigation, K.D., P.L., Z.L. (Zhao Li) and Z.L. (Zhaoxin Li); resources, F.L. and Y.Q.; data curation, F.L., K.D., P.L., C.T. and Y.Q.; writing—original draft preparation, K.D.; writing—review and editing, F.L. and K.D.; supervision, F.L. and K.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (No. 41771292, No. U1906219, No. 31170414), National Natural Science Foundation of China, and United Nations Environment Programme (No. 41761144053).

Acknowledgments: We would like to thank colleagues at the Yucheng experimental station for experimental support and constructive advice on this manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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