atmosphere

Article

Effects of Supplementary Irrigation on Soil Respiration of Millet Farmland in a Semi-Arid Region in China

Xiaoli Gao [1,2,*], Nan Zhao [3], Yuhui Lu [1], Xuan Han [1] and Zhiping Yang [2]

[1] College of Water Resources Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China
[2] Shanxi Key Laboratory of Soil Environment and Nutrient Resources, Taiyuan 030031, China
[3] Institute of Soil and Water Conservation Science, Shanxi Agricultural University, Taiyuan 030013, China
* Correspondence: gaoxiaoli01@tyut.edu.cn

Abstract: Carbon dioxide (CO_2) is recognized as key part of evaluating the soil environment, and the soil respiration rate is an effective indicator of CO_2 emission. To explore the influence and coupling mechanism of irrigation on the soil respiration of millet farmland in the Northern Shanxi Province in China, conventional rainfed (CK) and supplementary irrigation (W1) at the late jointing stage were conducted. The soil respiration rate and carbon emission flux in millet farmland under different treatments were observed. The relationship between soil respiration rate and soil physical–chemical properties and the crop growth index was further analyzed. The result showed that the soil respiration rate and carbon emission flux of W1 were higher than those of CK treatment. The comparison of the linear regression correlation between soil respiration rate and soil physical–chemical properties revealed that the major regulating factors of the soil respiration rate were soil moisture (<10.6%) followed by soil pH, soil moisture (>10.6%), soil temperature, and finally soil organic matter content. There are uncertainties regarding the soil moisture content variation range in soil respiration. Moreover, supplementary irrigation promoted the growth indexes, yield, and irrigation water use efficiency in millet farmland. Further research with less irrigation treatment is necessary for exploring an optimization model of water use efficiency and low carbon dioxide emissions in millet fields, which would be helpful to realize agricultural water utilization and a "carbon peak" in the sense of farmland.

Keywords: carbon emission; soil physical–chemical properties; growth index; irrigation; rainfed

Citation: Gao, X.; Zhao, N.; Lu, Y.; Han, X.; Yang, Z. Effects of Supplementary Irrigation on Soil Respiration of Millet Farmland in a Semi-Arid Region in China. *Atmosphere* **2022**, *13*, 1584. https://doi.org/10.3390/atmos13101584

Academic Editor: Shihong Yang

Received: 8 August 2022
Accepted: 24 September 2022
Published: 28 September 2022

1. Introduction

Soil respiration is considered to be a critical index for the accurate assessment of carbon exchange between the ecosystem and atmosphere and for the estimation of the carbon fixation potentiality of farmland ecosystems [1]. Agricultural CO_2 exchange in whole land ecosystem plays an important role in global warming. Annual CO_2 emissions from various lands into the atmosphere through soil respiration account for about 5–25% of CO_2 emissions, which is more than 10 times that of fossil fuels [2]. The contribution rate of CO_2, the major greenhouse gas, to global warming has reached up to 60%, meaning that CO_2 is considered to be the leading greenhouse gas causing global warming [3]. The research on soil respiration in farmland is an important way to mitigating climate warming [4].

Research into carbon emissions mainly focuses on tillage measures, such as fertilization, mulching, and returning straw to the field. Straw mulching showed the lowest carbon footprint (0.38 kg CO_2-eq kg^{-1}), and plastic film mulching increased the carbon footprint compared with no mulching [5]. Ahmad [6] evaluated the carbon footprint size of alfalfa production in different fertilization and irrigation modes and found that the treatment with nitrogen fertilizer at 375 kg N ha^{-1} and irrigation of 600 mm ha^{-1} were significantly higher than other treatments. Guo et al. [7] found that no-tillage significantly reduced cumulative carbon emissions compared with conventional tillage, while Ren et al. concluded that no-tillage increased carbon emissions by 0.2 Mg C ha^{-1} a^{-1} [8]. Irrigation and appropriate crop management measures under no-tillage and adjusted N fertilizer usage can contribute to the sequestration of large amounts of atmospheric CO_2 [9].

The irrigation method affects soil carbon emissions, and determining factors analysis has been studied in various crops. Zhong et al. [10] showed that deficit irrigation reduced CO_2 emissions. Zornoza et al. [11] estimated that medium (total water applied 457 mm) and moderate (326 mm) irrigation regimes in orchard fields reduced 13.4% and 38.8% of CO_2 emissions compared to a full irrigation regime of 694 mm, respectively. Bowles et al. [12] observed that a lower irrigation regime of 187 mm in tomato fields decreased soil CO_2 emissions by 23% compared with the control irrigation regime of 327 mm. Hou et al. [13] found that surface drip irrigation released less CO_2 than the sprinkler irrigation method. Flynn et al. [14] reported that extreme deficit irrigation significantly reduced CO_2 emissions by 30% compared with irrigation treatment under drip maize in the Great Plains of Colorado. Hou et al. [15] showed that deficient irrigation treatment resulted in a significant reduction of soil CO_2 emissions compared with full irrigation in summer maize fields. Wang et al. [16] expressed that the total cumulative CO_2 emissions from alternate drip irrigation at 50%, 60%, and 70% field capacity were 42.1%, 27.7%, and 46.8% greater than that of mulched drip irrigation, respectively. Xu et al. [17] found that the soil respiration rate under a ridge-furrow mulching system with supplementary irrigation was significantly higher than that under traditional flat land during the growth period of winter wheat in years with less rainfall. Yang et al. [18] stated that controlled irrigation promoted the soil respiration rate in paddy fields. Reasonable irrigation is an important way to reduce agricultural greenhouse gas emissions. CO_2 emission from soil are affected by soil and air temperature, soil moisture, soil pH, soil organic matter content, and vegetation [19–21]. Zhao et al. [22] reported that soil temperature displayed a positive effect on CO_2 emission. Buragiene et al. [23] showed that CO_2 emission from soil showed a positive linear correlation with soil moisture content. Das et al. [24] illustrated that soil pH had a significant relationship with soil CO_2 emissions. Jabro et al. [25] indicated that CO_2 emissions increased with organic matter. Hou et al. [15] analyzed the relationship between soil CO_2 emissions and maize yield under different irrigation treatments. Less irrigation changed the soil physical-chemical properties and crop growth index, which can resulted in lower soil CO_2 emissions in farmland.

The above study mainly focused on the research into carbon emissions under different irrigation methods involved in rice, wheat, maize, tomato, and orchard farming. Millet has the characteristic of strong drought resistance, making it suitable for planting in semi-arid regions. Shanxi Province is a classical semi-arid region; in addition, it is the “grain capital in China” due to the growth of millet, resulting from the unique conditions of terrain, climate, and soil. Due to the high protein, vitamin, selenium, and iron in millet, millet has medicinal and health care effects and high nutritional value. Millet, the first of the miscellaneous grains, has played a significant role in dryland farming in Shanxi Province. The total cultivated area and yield of millet in Shanxi Province ranks first in China, at close to 216,000 hm^2 and 550 thousand tons, respectively. Millet, a C_4 plant, belongs to the high-yielding crop type with a strong ability to fix CO_2 and high net photosynthetic rate [26]. Nevertheless, the yield of millet was about 300.0 kg/hm^2 using the usual rain-fed method, which was severely reduced in dry years. The production of millet was seriously affected by soil water deficit [27]. Gao [28] proposed that appropriate supplementary irrigation should be carried out during the jointing stage of millet in normal or dry years to ensure high water use efficiency in the northern Shanxi province of China. However, the effect of irrigation on soil carbon emission in millet farmland has been rarely reported. Study into carbon emissions from millet farmland ecosystems affected by supplementary irrigation is necessary.

Irrigation changes the physical–chemical environment, such as soil and air temperature, soil moisture, soil pH, soil organic matter content, soil microorganisms, and soil enzyme activity, which are important factors for soil respiration [19–21]. In order to reveal the soil respiration characteristics of millet farmland under different water use patterns, a millet field experiment of supplemental irrigation during the critical growth period (jointing stage) and rain-fed conditions was conducted. Soil properties, the crop growth index, and the soil respiration rate during the millet growth period were observed. The characteristics and the influencing mechanism of soil CO_2 from millet farmland were further analyzed. The research results can provide guidance for millet cultivation and countermeasures to climate change in northern Shanxi Province.

2. Materials and Methods

2.1. Site Description

The experiment was carried out in Gaojie Village, Daixian County, Xinzhou City, Shanxi Province on 6 May 2021. The test site was located at 113°1′58″ E and 38°58′42″ N. The area belongs to a semi-arid continental monsoon climate zone with four distinct seasons. The annual average precipitation, evaporation, temperature, extreme maximum temperature, lowest temperature, and frost-free period are 424.3 mm, 1 759.8 mm, 8.5 °C, 38.9 °C, −24.5 °C, and 160 days, respectively. The soil is classified as loam with an average soil bulk density of 1.3 g/cm^3, field water holding capacity of 26.5%, organic matter content of 13.9 g/kg, pH of 6.5, nitrogen content of 6.6 g/kg, alkali-hydrolyzable nitrogen of 98.8 mg/kg, available phosphorus of 15.8 mg/kg, and available potassium of 146.9 mg/kg.

2.2. Experiment Design

The field experiment was carried out in a field plot with an area of 6 m^2 (2 × 3 m^2). The millet was planted with an average row spacing of 30 cm and plant spacing of 10 cm. Plastic impermeable membranes of 60 cm depth were used to separate different treatments to prevent water infiltration between plots.

The sensitivity of soil respiration largely has a close relationship with global climate change and the carbon cycle [29]. There are uncertainties regarding the influencing factors of soil moisture content, soil temperature, soil pH, and soil organic matter on soil respiration due to the soil enzyme activity induced by the complexity of underground ecological processes, which are manifested in the soil depth, time scale, root respiration, and microbial ratio [30,31]. In order to eliminate and reduce the uncertainty of soil moisture content regarding soil respiration, we designed different treatments with rainfed and supplementary irrigation under farm management methods similar to local practices, such as fertilizer and pesticide application and weed control. The experiment included two irrigation treatments, supplemental irrigation (70 mm) (W1) and conventional rainfed (CK), with three replicate measurements during each stage. Water at the seeding stage can ensure normal germination of millet. The irrigation water requirements are most influenced by insufficient precipitation at the late jointing stage. Therefore, the supplemental irrigation was set at 20 mm and 50 mm before sowing and in the late jointing stage, respectively. Water deficit in these stages will lead to an extremely low yield of millet. The uncertainty of the other influencing factors of soil depth, time scale, root respiration, and microbial ratio were slight due to the same experimental condition.

The millet variety of Jingu No. 53 was sown on 6 May and harvested on 8 September in 2021. The whole growth period of millet can be divided into five stages: the seedling stage (from 6 May to 14 June), jointing stage (from 15 June to 18 July), heading stage (from 19 July to 4 August), filling stage (from 5 August to 21 August), and maturity stage (from 22 August to 8 September). Basal fertilizer ($N:P_2O_5:K_2O$ = 18:18:18) at 600 kg/hm^2 was applied in the experiment field before sowing. The total nutrient content accounted for 54% of total fertilizer. The planning–wetting layer depth was 60 cm.

2.3. Measurements and Calculation Methods

2.3.1. Soil Respiration Rate and CO_2 Emission Flux

CO_2 emissions were measured by applying a self-made Polyvinyl Chloride (PVC) transparent static chamber connected with a portable infrared CO_2 analyzer (FS-3080D). The static chamber was composed of a base (10 cm × 20 cm) and a cylindrical transparent chamber. The base was directly inserted into the soil at a depth of 10 cm to prevent the leakage of the soil CO_2 junction with the soil surface. The upper parts of the base and cylindrical transparent chamber were designed with a water tank, which was connected with the chamber and the CO_2 analyzer, respectively. To realize the encapsulated effect, water was added to the water tank at the connection point during each measurement. During the growth period, CO_2 emissions were measured every 15–20 days at 10:00 am and repeated three times each time. The heights of the CO_2 measuring cylindrical transparent chamber at the seedling stage, jointing stage, and heading stage were 40 cm, 80 cm, and 120 cm, respectively. The observed height of the CO_2 measuring cylindrical transparent chamber both at the filling stage and maturity stage was 160 cm. A tripod was used in CO_2 measurement to ensure stable operation. The upper part of the cylindrical transparent chamber of the PVC static box needed to be connected with the portable infrared CO_2 analyzer before measuring. The preheating needed to be started 10–15 min in advance to ensure that the gas in the static box was evenly mixed. The soil respiration rate was automatically measured every 2 min a total of 3 times. Accumulated soil CO_2 emissions during the growth stage can be calculated as follows:

$$F = \frac{86,400}{10^6} \times \sum_{i=1}^{n} \frac{(S_{i+1} + S_i)}{2} \times (t_{i+1} - t_i) \times 44 \tag{1}$$

where F is accumulated CO_2 emissions (g/m^2), S is the ith measurement of the soil CO_2 emission rate, $(t_{i+1} - t_i)$ is the interval time of two consecutive measurements, and n is the total number of measurements.

2.3.2. Soil Physical and Chemical Properties

Soil samples in the depth of 0–20 cm from each plot were collected once every 7 to 10 days during the whole growth stage of millet, which were divided into two parts for the measurement of soil moisture content in the field and the analysis of soil pH and soil organic matter in the laboratory. The soil moisture, surface soil temperature, soil pH, and soil organic matter at three measuring points evenly arranged in the field were measured applying the drying method, portable soil temperature tester (Zhejiang Top Instruments Limited Company), extraction solution with KCl, and external heating method of potassium dichromate and sulfuric acid oxidation [23], respectively.

2.3.3. Growth Index

(1) The millet height, stem diameter, and leaf area index

The millet height, stem diameter, and length and width of millet leaves were measured by a tape, slide gauge, and measuring scale from 17:30 to 18:30 during each growth period, respectively. The leaf area index was then calculated. The height, stem diameter, and leaf area index of millet were calculated as the average of the corresponding measured value of three randomly selected plants. The leaf area index can be calculated by Formula (2).

$$\mathrm{LAI} = \mathrm{S_1 N / S_2} \tag{2}$$

where S_1 represents the total area of a single plant (the product of the number of leaves of a single plant and the area of a single leaf; the area of a leaf is the product of the length and width multiplied by 0.76), in m^2; S_2 represents the unit land area; and N is the number of plants per unit area.

(2) Dry matter weight of plant

Three representative millet plants were collected for each treatment at each growth stage. The roots of the plants, including the broken roots, were washed in nylon mesh bags. The above-ground plants (stem, leaf, leaf sheath, ear) and root organs were separated into envelopes and placed in a drying oven, heated to 105 °C for 30 min, and then dried to a constant mass at 80 °C. The dry matter weight of plants was measured by an electronic balance with a precision of 0.001 g. The sum value was the total dry matter weight of the plant.

(3) Yield

Grains in each plot were harvested at the mature period. All plants of millet in each plot were collected for yield weight measurement after drying and threshing.

2.3.4. Water Use Efficiency

The water consumption (evapotranspiration, ET) of millet in the whole growth stage was calculated by using the field water balance equation. The water use efficiency (WUE) was the yield (Y) per unit of crop water consumption. The calculation formula of the WUE was as follows:

$$WUE_y = Y/ET \tag{3}$$

2.4. Statistical Analysis

SPSS (version 22.0, IBM, Chicago, IL, USA) was used for a one-way analysis of variance (one-way ANOVA) followed by a T test. The Shapiro–Wilk test was used to test data normality before analysis. The relationships between soil respiration rate and soil physical–chemical properties were further examined using linear regression analysis, quadratic regression analysis, and exponential regression analysis. The one-way ANOVA was applied to analyze differences between individual treatments in terms of cumulative soil CO_2 emissions, millet height, stem diameter, leaf area index, dry matter weight of millet, water consumption, yield, and water use efficiency. A linear regression analysis was applied to analyze and compare the coupling relationship between soil respiration rate and soil physical-chemical properties. In this study, $p < 0.01$ and $p < 0.05$ represent extremely significant and significant values, respectively. Origin (version 9.1, OriginLab, Northampton, MA, USA) was used for drafting.

3. Results

3.1. Variation of Soil Respiration Rate during Growing Season

The variation of the soil respiration rate of millet farmland under supplemental irrigation and rainfed conditions during the whole period is shown in Figure 1. Compared with rainfed treatment, the soil respiration rate of millet field from the late jointing stage to the filling stage under supplemental irrigation increased significantly. With the advancement of the growth period, the soil respiration rate of the millet field under rainfed treatment changed slightly in a range of 6.26–7.09 μmol m^{-2} s^{-1} from the late seeding stage to the filling stage. The soil respiration rate of millet farmland from the late stage of supplementary irrigation to the filling stage increased by 2.33–6.29 μmol m^{-2} s^{-1} compared with the rainfed treatment. The soil respiration rate of millet farmland under supplemental irrigation reached the peak of 13.38 μmol m^{-2} s^{-1} at the heading stage, which was 88.74% higher than the rainfed millet. The soil respiration rate of millet farmland under supplemental irrigation was slightly lower in other stages than the conventional rainfed millet. After 47.6 mm of rainfall on August 4 in 2021 at the heading stage, supplemental irrigation significantly promoted the soil respiration rate of millet farmland. The soil respiration rate was almost constant throughout the study period except for the supplementary irrigation during the filling stage. The result showed that soil water content has a primary effect on soil respiration, especially with the lower soil water content in millet fields.

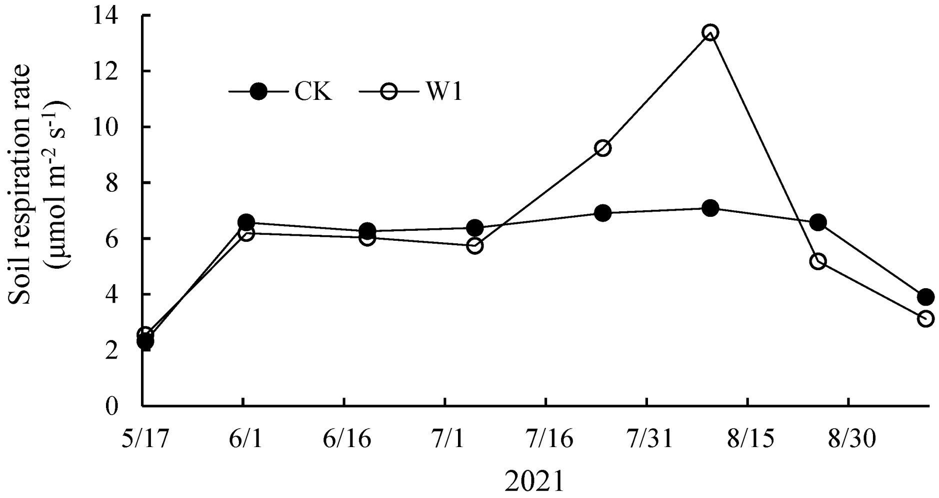

Figure 1. Variation of soil respiration rate of millet farmland under supplemental irrigation and rainfed conditions during the whole period.

3.2. Accumulated Soil CO_2 Emissions under Different Treatments

Compared with rainfed treatment, the accumulated soil CO_2 emissions of millet farmland under supplementary irrigation treatment were higher. As shown in Figure 2, the accumulated soil CO_2 emissions of millet farmland under supplementary irrigation were as high as 3165.501 g m^{-2} (CO_2), which was significantly higher by 11.56% ($p < 0.05$) than the rainfed treatment. The result showed that supplementary irrigation promotes the carbon dioxide emission of millet farmland.

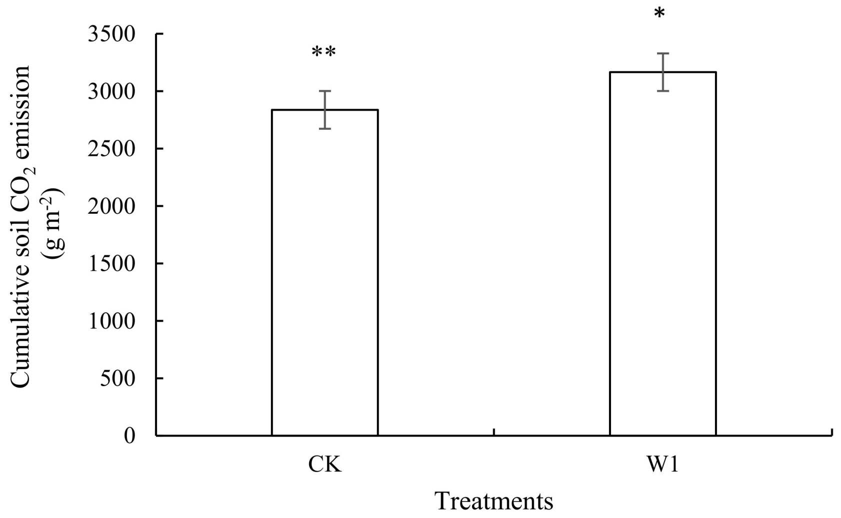

Figure 2. Effect of supplemental irrigation on accumulated soil CO_2 emissions of millet farmland (Note: ** represents an extremely significant effect ($p < 0.01$) for different soil water treatments during each growth stages and the whole growth period, while * represents a significant effect ($p < 0.05$) for different soil water treatments during each growth stage and the whole growth period).

3.3. Analysis on Influencing Factors of Soil Respiration Rate

3.3.1. Soil Moisture Content

In all treatments, the variation of soil moisture content in the soil surface layer of millet farmland basically decreased gradually from the seedling stage to jointing stage, while it increased first and then decreased from heading stage to maturity stage. The Figure 3 shows the variation of soil moisture content at the depth of 0–20 cm in millet farmland under different irrigation modes. The soil moisture content of S1 treatment increased sharply after supplementary irrigation at the late jointing stage. The soil moisture content in the late growth stage in the two treatments was generally higher than the early growth stage. The difference in the soil moisture content between the two treatments in the late growth stage was small, which was mainly due to rainfall mostly occurring in the later growth stage. Affected by supplementary irrigation at seeding stage, the soil moisture content of supplementary irrigation at the early growth stage was 21.62–231.28% higher than that of conventional rainfed irrigation. The supplementary irrigation at the filling stage led to a lower soil moisture content by 14.22% than that of conventional rainfed irrigation.

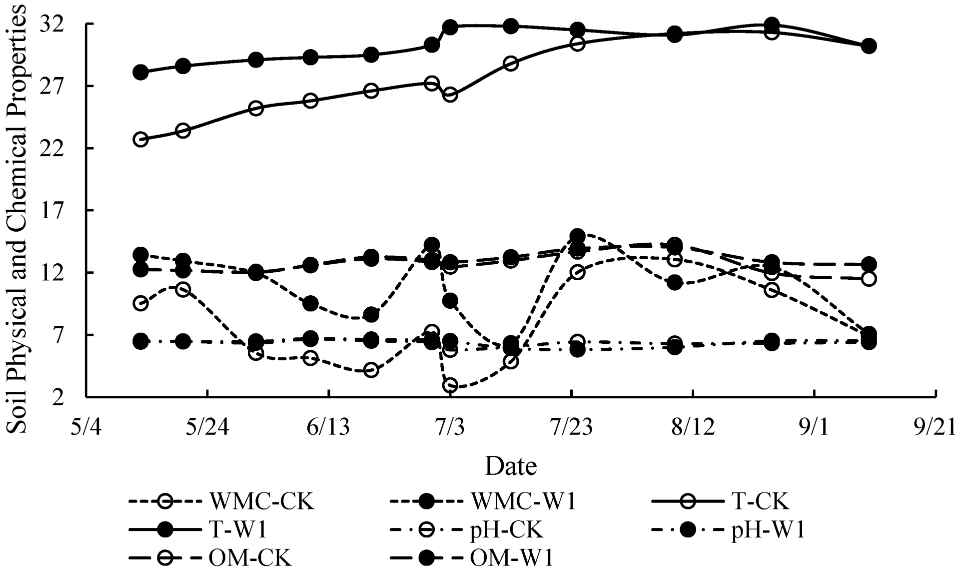

Figure 3. Variation of soil physical and chemical properties at the depth of 0–20 cm in millet farmland under different irrigation modes (WMC-CK, WMC-W1, T-CK, T-W1, pH-CK, pH-W1, OM-CK OM-W1 means the soil water moisture content of CK, the soil water moisture content of W1, the soil temperature of CK, the soil temperature of W1, the soil pH of CK, the soil pH of W1, the soil organic matter of CK, and the soil organic matter of W1, respectively).

The soil respiration rate exhibited different responses in different ranges of soil moisture content. The soil respiration rate showed a significant positive correlation with the soil moisture content ($R^2 = 0.5184$) when the soil moisture content was greater than 10.6%, while it showed a significant negative correlation with the soil moisture content ($R^2 = 0.4512$) when the soil moisture content was less than 10.6%. The variation of soil respiration rate with soil moisture content showed the trend of first declining and then increasing and reached the minimum at a soil moisture content of 10.6%, which resulted from the uncertainties of the influencing factors of the range of soil moisture content change on soil respiration [31]. The results showed that the moisture content condition can create an unsuitable environment for the respiration of millet plant roots and soil microorganisms when the soil moisture content is about 10.57%, leading to the minimum soil respiration rate (Figure 4).

3.3.2. Soil Temperature

The increase of soil temperature can enhance and accelerate plant root respiration, soil microbial activities, and soil organic decomposition. The soil respiration rate increased with the increasing soil temperature in the early growth stage. As shown in Figure 3, the soil surface temperature gradually increased with the advance of the growth period, which was similar to climate change during the growth period of millet. The soil surface temperature of millet farmland tended to be stable after the heading stage. The ranges of soil temperature of millet farmland under conventional rainfed and supplemental irrigation conditions were 30.2–31.3 °C and 30.2–31.9 °C, respectively.

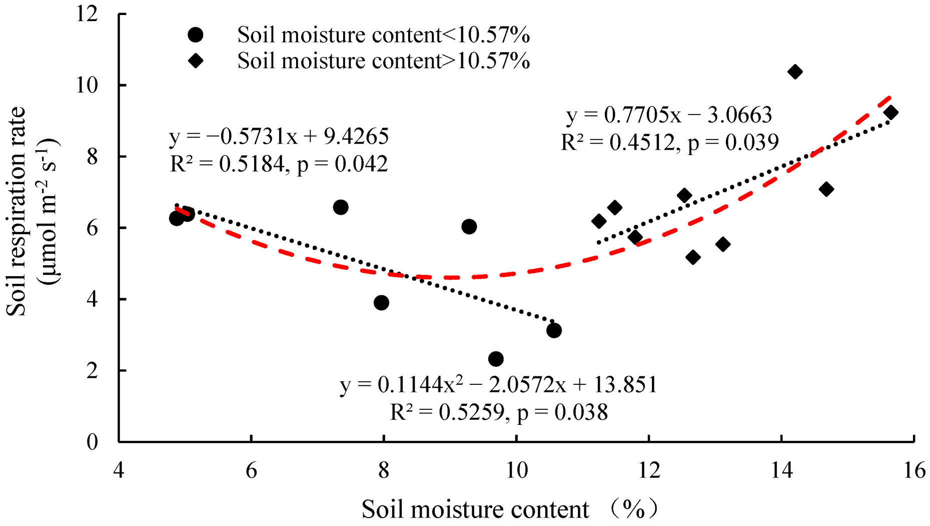

Figure 4. The relationship between soil moisture content and soil respiration rate.

Soil temperature showed a strong relationship with the soil CO_2 respiration rate of millet from the seedling stage to heading stage. During the early growth stage, soil temperature promoted crop growth and further accelerated the soil respiration rate of millet farmland. The soil respiration rate increased with the increase of soil surface temperature (Figure 5). There was a significant linear regression relationship between soil respiration rate and soil surface temperature (R^2 = 0.4290). Soil temperature tended to be stable, and the soil respiration rate gradually decreased after the heading stage. Soil temperature had little effect on the soil respiration rate of millet in the later growth period.

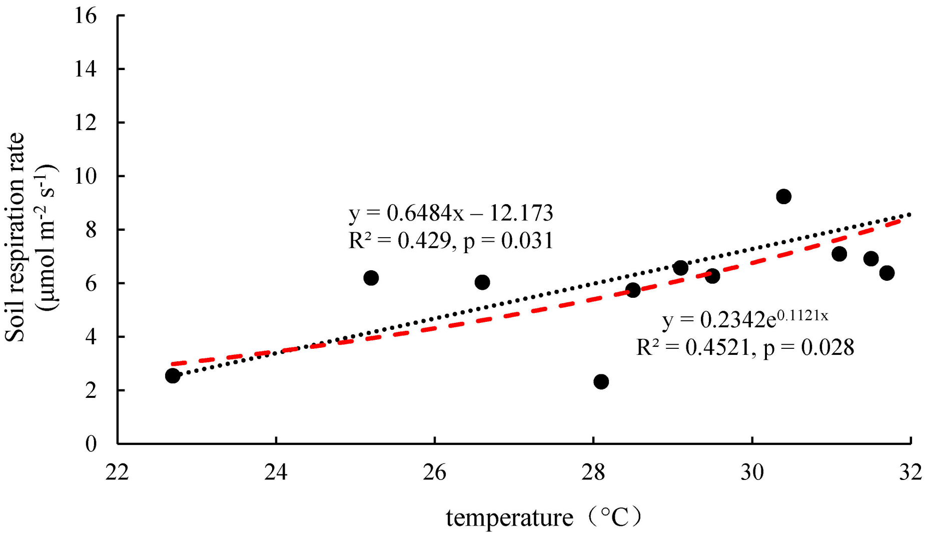

Figure 5. The relationship between soil temperature and soil respiration rate.

3.3.3. Soil pH

The soil pH of millet was shown to be relatively stable in the early growth stage, gradually decreased in the late jointing stage, and increased after maturity. Variations of soil pH at the depth of 0–20 cm in millet farmland under different irrigation modes are shown in Figure 3. The soil pH of the rainfed millet field was 0.1–0.6 higher than the supplementary irrigation treatment, with an increase of 1.63–10.48% during the heading stage. The soil respiration rate decreased with the increase of soil pH after the jointing stage. As shown in Figure 6, there was a significant negative correlation between soil pH and soil respiration rate in millet farmland (R^2 = 0.4739).

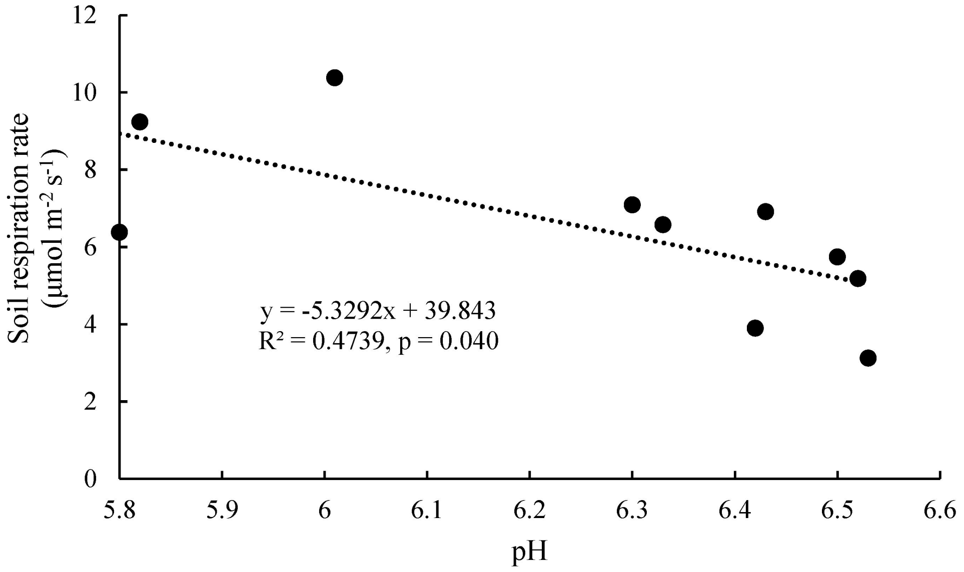

Figure 6. The relationship between soil pH and soil respiration rate.

3.3.4. Soil Organic Matter

During the millet growing season, the soil organic matter content at 0~20 cm soil depth under various treatments increased first and then decreased with the advancement of the growth period, reaching the maximum at the heading stage. With the rainfall and gradual decomposition of soil microorganisms, the soil organic matter in the upper soil layer of each treatment increased gradually with the growth period. The soil organic matter of millet farmland under rainfed and supplemental irrigation conditions at the mature stage reached the maximum of 14.2 g/kg and 14.0 g/kg, respectively, which were 16.07% and 14.17% higher than seedling stage. Figure 3 shows that the soil organic matter of supplementary irrigation was higher than rainfed millet. Figure 7 further shows that the soil respiration rate increased with the increasing soil surface organic matter content. There was a significant positive correlation between soil organic matter and soil respiration rate ($R^2 = 0.4122$). Compared with the rainfed millet, the soil organic matter of supplemental irrigation was larger. Supplementary irrigation promoted the formation of organic matter content in millet farmland soil.

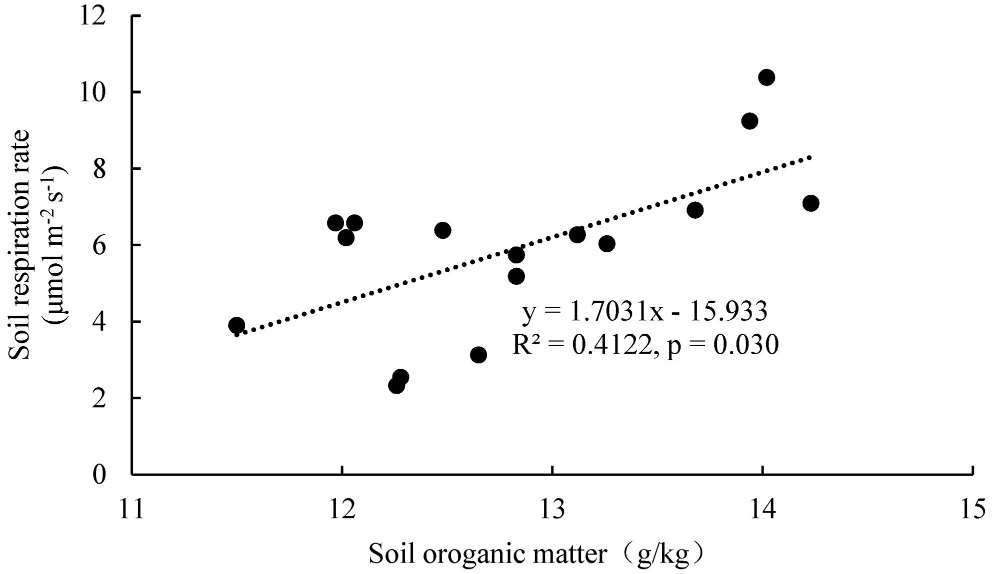

Figure 7. The relationship between soil organic matter and soil respiration rate.

The comparison of linear regression revealed that the most important factor influencing soil respiration rate was soil moisture (<10.6%), followed by soil pH, soil moisture (>10.6%), soil temperature, and finally soil organic matter content. Soil temperature and soil organic matter content showed a positive significant correlation with the soil respiration rate, while soil pH exhibited a negative significant correlation with the soil respiration rate. The effect of soil moisture content on the soil respiration rate was influenced by the value of the soil moisture content.

3.4. Analysis of Supplemental Irrigation on Millet Growth

3.4.1. Crop Growth

Table 1 shows that the variation trends of the plant height, stem diameter, leaf area index, and dry matter mass of millet under different treatments were relatively consistent. As shown in Table 1, the leaf area index and dry matter mass increased with the advancement of the growth period, while the plant height and stem diameter displayed an increase first and then a decrease. Increasing weight led to the bending of millet ears in the horizontal direction, which decreased the plant height slightly at the maturity period. The plant heights of millet during the filling period under rainfed and supplementary irrigation conditions reached peaks of 179 cm and 208 cm, respectively. Compared with rainfed millet, the stem diameter of supplemental irrigation increased by 10.17–60.62%, which was not conducive to resisting windy weather. The stem diameter of millet at the heading stage under CK and W1 reached 1.20 cm and 1.32 cm, respectively. The leaf area of millet increased rapidly from the seedling stage to jointing stage; however, the growth rate gradually slowed down in the later stage. The growth of millet and dry matter mass was relatively slow before the jointing stage and accelerated rapidly after the jointing stage. Due to water stress at the jointing stage, the growth of millet in the later growth stage of rainfed millet was inhibited to some extent, which resulted in the lower dry matter mass of CK than W1. There was little difference between the individual growth indicators at the seedling stage. However, supplementary irrigation promoted the development of the plant height, stem diameter, leaf area index, and dry matter quality of millet from the jointing stage to maturity stage, which further affected the soil respiration rate. The soil respiration rate increased with the increase of the growth indicators of millet.

Table 1. Growth indicators of millet at individual growth stages under different treatments.

Period	**Height/cm**		**Stem Diameter/cm**		**Leaf Area Index**		**Dry Matter Mass/g**	
	CK	**W1**	**CK**	**W1**	**CK**	**W1**	**CK**	**W1**
Seeding stage	35 ± 1	35 ± 1	0.42 ± 0.03	0.44 ± 0.03	0.20 ± 0.01	0.21 ± 0.01	0.20 ± 0.01	0.19 ± 0.01
Jointing stage	62 ± 1 *	85 ± 1 *	0.65 ± 0.03 *	1.04 ± 0.04 **	2.03 ± 0.05 *	2.37 ± 0.05 **	3.90 ± 0.05 *	5.30 ± 0.07 **
Heading stage	137 ± 2 *	146 ± 2 *	1.20 ± 0.04 *	1.32 ± 0.05 *	3.26 ± 0.06 *	3.97 ± 0.07 *	17.05 ± 0.22	18.10 ± 0.24 *
Filling stage	179 ± 3	208 ± 3 *	0.81 ± 0.03 *	0.97 ± 0.03 **	3.95 ± 0.07 *	4.18 ± 0.08 **	44.60 ± 0.35 *	48.60 ± 0.36 *
Mature stage	167 ± 3	199 ± 3 **	0.80 ± 0.03	0.80 ± 0.03 *	4.37 ± 0.08 *	5.29 ± 0.10 **	73.75 ± 0.86 *	99.33 ± 0.92 **

Note: ** represents an extremely significant effect ($p < 0.01$) for different soil water treatments during each growth stages and the whole growth period, while * represents a significant effect ($p < 0.05$) for different soil water treatments during each growth stage and the whole growth period.

3.4.2. Water Use Efficiency

The yield and WUE of millet increased with the increase of crop water consumption. It can be seen from Table 2 that the water stress of rainfed treatment at the jointing stage directly affected the growth of millet, which reduced the grain formation at the grain filling stage and further resulted in the lowest WUE of only 1.67 $kg \cdot m^{-3}$ in the rainfed treatment. Due to slight water stress, the WUE of millet under supplementary irrigation reached up to 2.15 $kg \cdot m^{-3}$, which increased by 28.74% compared with rainfed millet. Supplementary irrigation promoted the yield and WUE of millet.

Table 2. Yield and water use efficiency of millet under different irrigation modes.

Treatment	Crop Water Consumption/mm	Yield/kg·hm^{-2}	WUE/kg·m^{-3}
W1	254.49	5478.26	2.15
CK	201.92	3363.12	1.67

4. Discussion

4.1. Influencing Factors of Soil Respiration Rate

Soil moisture is one of the key factors influencing agro-ecosystems [32]. There is a close relationship between the soil respiration rate and soil environmental factors [33]. Irrigation alters soil water conditions, which participate in a variety of biological and chemical reactions in the soil environment. Soil CO_2 emission is further regulated by the effects of soil nutrients, soil permeability, microbial activity, soil structure, and root growth [34]. Supplemental irrigation changes the soil physical and chemical environment of millet farmland after the jointing stage, such as soil temperature, soil moisture content, pH, and soil organic matter content, which could create a more suitable growth environment for soil microorganisms and plant roots. Furthermore, it both strengthens the activities of aerobic microorganisms and microbial biomass in the soil and enhances the soil respiration rate.

Soil moisture content is the major factor affecting soil respiration. Appropriate soil moisture can increase the amount of soil microbial populations, improve soil biological activities, enhance their decomposition ability, and promote root respiration [35]. In this study, the soil moisture content of millet farmland with supplemental irrigation was higher, which increased the oxygen content and enzyme activity in soil as well as improving the soil temperature. This can promote the mineralization of soil nutrient elements and improve the content of soil nutrients and the absorption intensity of nutrients by plant roots. Due to the uncertainties of the influencing factors of the range of soil moisture content variation on soil respiration [36], the soil respiration rate showed different responses in different soil moisture content ranges in this study, which was similar to the existing results. Linn and Doran (1984) believed that when the soil moisture content was 50–80% of the saturated moisture content, this represented a more suitable moisture content for soil biological activities [37]. The research of Yang et al. (2018) on soil moisture content and soil CO_2 emission flux in rice fields showed that the soil respiration rate increased gradually with the increase of soil volume moisture content by less than 43%, while it decreased when the increase of soil volume moisture content exceeded 43% [38]. The different relationship between soil respiration and soil moisture content in different ranges results from uncertainties regarding the soil moisture content variation range for soil respiration [29].

Soil temperature is closely related to the soil respiration rate. Increasing soil temperature improves microbial activities and soil mineralization, leading to a higher soil respiration rate [39]. The soil respiration rate was found to increase with the increase of soil surface temperature at the early stage of millet growth, which was consistent with the previous conclusion. Liu et al. (2002) thought that temperature change was an important reason for the diurnal and seasonal changes of soil respiration [40].

Soil respiration mainly includes root respiration (autotrophic respiration) and soil microbial respiration (heterotrophic respiration), and soil organic matter controls heterotrophic respiration [41]. The soil organic matter in millet farmland reached the maximum at the heading stage, which led to the peak of soil respiration rate in the filling stage affected by the hysteresis effect. However, the soil respiration rate of supplemental irrigation in the filling stage is much higher than rainfed treatment. The increase of soil respiration can promote the decomposition of soil organic matter, and the soil organic matter under supplemental irrigation was slightly lower than rainfed treatment. As the change of soil organic matter is slow and long term [42], the influence of the soil organic matter content on soil respiration rate was relatively small compared with other influencing factors. Microbial biomass and root biomass are key regulators of auto and heterotrophic respiration [43].

Nevertheless, this study did not track the root growth characteristics and the effect of root exudates on soil respiration. Therefore, related research on the effect of root exudates on soil respiration needs to be further carried out.

Owing to the activities of soil microorganisms and the synthesis and decomposition of organic matter, soil CO_2 emission was affected by soil pH [44]. The results of this study showed that there was a negative correlation between soil CO_2 emissions and a soil pH of 6–8, which was consistent with the research results of Han et al. [45].

4.2. Charateristics of Millet Growth

There were interactions between soil properties and plant growth [46]. Especially in terms of root growth, roots may play a significant role in regulating soil respiration depending on rhizospheric activities [47]. Soil autotrophic respiration mainly refers to root respiration controlled by the photosynthetic products of crops [48]. The growth and development of millet roots were relatively vigorous after entering the jointing stage. Root respiration accounts for more than 50% of the total soil respiration in some ecosystems [49]. Soil respiration is affected by root exudates, influencing soil organic matter content and soil physical and chemical properties, indirectly enhancing the intensity of soil respiration [50,51]. The photosynthetic products of millet began to form at the heading stage. The root growth rate reached the maximum at the heading stage, which resulted in a peak of soil autotrophic respiration. The millet growth index presented a positive effect on the soil respiration rate (Table 1), which was consistent with the previous research conclusion [52,53].

Water stress at the jointing stage can increase the stem diameter of millet. Due to the lag effect of water stress, the stem diameter of millet at the heading stage and filling stage under rainfed treatment was smaller than that under supplemental irrigation treatment. The large amount of local precipitation was mostly concentrated in the heading stage of millet. Hence, appropriate supplemental irrigation would be of benefit to enhance the lodging resistance of millet in northern Shanxi. Besides, irrigation can promote the growth of millet leaves and the increase of leaf area, which can further promote the photosynthesis of millet. The increase of leaf area and photosynthesis activities under supplemental irrigation promoted soil respiration, which maybe indirectly resulted from higher root respiration by heterotrophic respiration [47].

Supplemental irrigation can effectively improve soil moisture in millet farmland and further improve the yield and water use efficiency of millet. The yield and water use efficiency of millet are the critical factors for the development of millet industry in arid and semi-arid areas. In order to improve the yield and water use efficiency of millet, water storage and water conservation measures, such as film mulching irrigation and ridge irrigation, can be adopted. Furthermore, soil water replenishment measures, such as gully rainwater collection and supplemental irrigation in key growth periods, can also be adopted. The development and research of the above measures is important to achieve a high and stable yield of millet.

The supplementary irrigation improved the soil moisture after the irrigation, which varied the soil physical–chemical properties with soil pH, soil temperature soil organic matter, and microbial biomass after the late jointing stage in the millet field. The changed soil environment was also beneficial for individual millet growth indexes. The altered soil environment and vigorous roots under supplementary irrigation led to even higher soil respiration.

5. Conclusions

This study showed that supplementary irrigation changed the soil environment after the irrigation, which promoted the crop indexes at each growth stage, as well as yield and irrigation water use efficiency. The altered soil environment and more vigorous roots enhanced the soil respiration rate and carbon emission flux compared with rainfed millet. Moreover, the comparison of the linear regression correlation between soil respiration rate and soil physical–chemical properties revealed that the major affecting factors of the soil respiration rate were soil moisture (<10.6%) followed by soil pH, soil moisture (>10.6%), soil temperature, and finally soil organic matter content. In general, supplementary irrigation could lead to climate warming due to more harmful CO_2 emissions to the atmospheric environment. There are existed uncertainties regarding the influencing factors of the range of soil moisture content variation on soil respiration. The soil respiration rate increased significantly with the increasing soil moisture content (R^2 = 0.5184) when the soil moisture content was over 10.6%, while it decreased notably with the rise of soil moisture content (R^2 = 0.4512) when the soil moisture content was lower than 10.6%. Soil temperature and soil organic matter content showed a positive correlation with soil respiration rate, with correlation coefficients of 0.4521 and 0.4122, respectively. Soil pH exhibited a negative correlation with soil respiration rate, with a correlation coefficient of 0.4739. To realize the optimal combination of high water use efficiency and reduced soil CO_2 emissions to the atmosphere, more supplemental treatments with less irrigation need to be designed and conducted for further study.

Author Contributions: Experimental design: X.G. and N.Z. Data collection: X.G. and N.Z. Laboratory analysis: Y.L. and X.H. Statistical analysis: X.G. and N.Z. Supervision of experiments: X.G. and Z.Y. Interpretation of results: X.G. Writing of first draft of the manuscript: X.G. Preparation of final draft: All authors. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Basic Research Program of Shanxi Province (Nos. 20210302124370) and the Open Fund for Key Laboratory of Organic Dry Farming in Shanxi Province (Nos. 201805D111015-3).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors greatly acknowledge Shanxi Academy of Agricultural Sciences for providing the field for the experiment.

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

References

1. Mosongo, P.S.; Pelster, D.E.; Li, X.; Gaudel, G.; Wang, Y.; Chen, S.; Li, W.; Mburu, D.; Hu, C. Greenhouse Gas Emissions Response to Fertilizer Application and Soil Moisture in Dry Agricultural Uplands of Central Kenya. *Atmosphere* **2022**, *13*, 463. [CrossRef]
2. Kim, G.S.; Kim, A.R.; Lim, B.S.; Seol, J.; An, J.H.; Lim, C.H.; Joo, S.J.; Lee, C.S. Assessment of the Carbon Budget of Local Governments in South Korea. *Atmosphere* **2022**, *13*, 342. [CrossRef]
3. Rodhe, H. A Comparison of the Contribution of Various Gases to the Greenhouse Effect. *Science* **1990**, *248*, 1217–1219. [CrossRef] [PubMed]
4. Ishikura, K.; Darung, U.; Inoue, T.; Hatano, R. Variation in Soil Properties Regulate Greenhouse Gas Fluxes and Global Warming Potential in Three Land Use Types on Tropical Peat. *Atmosphere* **2018**, *9*, 465. [CrossRef]
5. Luo, X.; Guo, Y.; Wang, R.; Wang, N.; Li, C.; Chu, X.; Feng, H.; Chen, H. Carbon footprint of a winter wheat-summer maize cropping system under straw and plastic film mulching in the Loess Plateau of China. *Sci. Total Environ.* **2021**, *794*, 148590. [CrossRef] [PubMed]
6. Ahmad, I.; Yan, Z.; Kamran, M.; Ikram, K.; Ghani, M.U.; Hou, F. Nitrogen management and supplemental irrigation affected greenhouse gas emissions, yield and nutritional quality of fodder maize in an arid region. *Agric. Water Manag.* **2022**, *269*, 107650. [CrossRef]
7. Guo, L.; Wang, X.; Wang, S.; Tan, D.; Han, H.; Ning, T.; Li, Q. Tillage and irrigation effects on carbon emissions and water use of summer maize in North China Plains. *Agric. Water Manag.* **2019**, *223*, 105729. [CrossRef]
8. Huang, Y.; Ren, W.; Grove, J.; Poffenbarger, H.; Jacobsen, K.; Tao, B.; Zhu, X.C.; McNear, D. Assessing synergistic effects of no-tillage and cover crops on soil carbon dynamics in a long-term maize cropping system under climate change. *Agric. For. Meteorol.* **2020**, *291*, 108090. [CrossRef]
9. Pareja-Sánchez, E.; Cantero-Martínez, C.; Álvaro-Fuentes, J.; Plaza-Bonilla, D. Soil organic carbon sequestration when converting a rainfed cropping system to irrigated corn under different tillage systems and N fertilizer rates. *Soil Sci. Soc. Am. J.* **2020**, *84*, 1219–1232. [CrossRef]

10. Zhong, Y.; Li, J.; Xiong, H. Effect of deficit irrigation on soil CO_2 and N_2O emissions and winter wheat yield. *J. Clean. Prod.* **2020**, *279*, 123718. [CrossRef]
11. Zornoza, R.; Rosales, R.; Acosta, J.A.; De la Rosa, J.M.; Arcenegui, V.; Faz, Á.; Pérez-Pastor, A. Efficient irrigation management can contribute to reduce soil CO_2 emissions in agriculture. *Geoderma* **2016**, *263*, 70–77. [CrossRef]
12. Bowles, T.M.; Barrios-Masias, F.H.; Carlisle, E.A.; Cavagnaro, T.R.; Jackson, L.E. Effects of arbuscular mycorrhizae on tomato yield, nutrient uptake, water relations, and soil carbon dynamics under deficit irrigation in field conditions. *Sci. Total Environ.* **2016**, *566*, 1223–1234. [CrossRef] [PubMed]
13. Hou, H.; Yang, Y.; Han, Z.; Cai, H.; Li, Z. Deficit irrigation effectively reduces soil carbon dioxide emissions from wheat fields in Northwest China. *J. Sci. Food Agric.* **2019**, *99*, 5401–5408. [CrossRef] [PubMed]
14. Flynn, N.E.; Stewart, C.E.; Comas, L.H.; Del Grosso, S.J.; Schnarr, C.; Schipanski, M.; Fischer, J.C.; Stuchiner, E.R.; Fonte, S.J. Deficit irrigation impacts on greenhouse gas emissions under drip-fertigated maize in the Great Plains of Colorado. *J. Environ. Qual.* **2022**, *51*, 877–889. [CrossRef] [PubMed]
15. Hou, H.; Han, Z.; Yang, Y.; Abudu, S.; Cai, H.; Li, Z. Soil CO_2 emissions from summer maize fields under deficit irrigation. *Environ. Sci. Pollut. Res.* **2019**, *27*, 4442–4449. [CrossRef]
16. Wang, J.; Li, Y.; Niu, W. Effect of alternating drip irrigation on soil gas emissions, microbial community composition, and root–soil interactions. *Agric. Water Manag.* **2021**, *256*, 107123. [CrossRef]
17. Xu, Y.; Ma, X.; Wang, Y.; Ali, S.; Cai, T.; Jia, Z. Effects of ridge-furrow mulching system with supplementary irrigation on soil respiration in winter wheat fields under different rainfall conditions. *Agric. Water Manag.* **2020**, *239*, 106237. [CrossRef]
18. Yang, S.; Sun, X.; Ding, J.; Jiang, Z.; Liu, X.; Xu, J. Effect of biochar addition on CO_2 exchange in paddy fields under water-saving irrigation in Southeast China. *J. Environ. Manag.* **2020**, *271*, 111029. [CrossRef]
19. Sun, X.; Mu, C.; Song, C. Seasonal and spatial variations of methane emissions from montane wetlands in Northeast China. *Atmos. Environ.* **2011**, *45*, 1809–1816. [CrossRef]
20. Mancinelli, R.; Marinari, S.; Brunetti, P.; Radicetti, E.; Campiglia, E. Organic mulching, irrigation and fertilization affect soil CO_2 emission and C storage in tomato crop in the Mediterranean environment. *Soil Tillage Res.* **2015**, *152*, 39–51. [CrossRef]
21. Haddaway, N.R.; Hedlund, K.; Jackson, L.E.; Kätterer, T.; Lugato, E.; Thomsen, I.K.; Jørgensen, H.B.; Isberg, P.-E. How does tillage intensity affect soil organic carbon? A systematic review. *Environ. Évid.* **2017**, *6*, 30. [CrossRef]
22. Zhao, P.; Pumpanen, J.; Kang, S. Spatio-temporal variability and controls of soil respiration in a furrow-irrigated vineyard. *Soil Tillage Res.* **2020**, *196*, 104424. [CrossRef]
23. Buragienė, S.; Šarauskis, E.; Romaneckas, K.; Adamavičienė, A.; Kriaučiūnienė, Z.; Avižienytė, D.; Marozas, V.; Naujokienė, V. Relationship between CO_2 emissions and soil properties of differently tilled soils. *Sci. Total Environ.* **2019**, *662*, 786–795. [CrossRef]
24. Das, S.; Chatterjee, S.; Rajbanshi, J. Responses of soil organic carbon to conservation practices including climate-smart agriculture in tropical and subtropical regions: A meta-analysis. *Sci. Total Environ.* **2021**, *805*, 150428. [CrossRef] [PubMed]
25. Jabro, J.D.; Sainju, U.; Stevens, W.B.; Evans, R.G. Carbon dioxide flux as affected by tillage and irrigation in soil converted from perennial forages to annual crops. *J. Environ. Manag.* **2008**, *88*, 1478–1484. [CrossRef]
26. Nematpour, A.; Eshghizadeh, H.R.; Zahedi, M.; Gheysari, M. Interactive effects of sowing date and nitrogen fertilizer on water and nitrogen use efficiency in millet cultivars under drought stress. *J. Plant Nutr.* **2019**, *43*, 122–137. [CrossRef]
27. Liu, Q.; Xu, H.; Mu, X.; Zhao, G.; Gao, P.; Sun, W. Effects of Different Fertilization Regimes on Crop Yield and Soil Water Use Efficiency of Millet and Soybean. *Sustainability* **2020**, *12*, 4125. [CrossRef]
28. Gao, X.L.; Ma, J.J.; Jia, Y.R.; Liu, E.K.; Song, L.L. Study on Water Consumption Law and Water High-Use Efficiency Utilization of Millet in the North Region of Shanxi Province. *J. Irrig. Drain.* **2021**, *40*, 40–47. (In Chinese) [CrossRef]
29. Han, G.; Zhou, G. Review of spatial and temporal variations of soil respiration and driving mechanisms. *Chin. J. Plant Ecol.* **2009**, *33*, 197–205.
30. Binkley, D.; Giardina, C. Why do Tree Species Affect Soils? The Warp and Woof of Tree-soil Interactions. *Biogeochemistry* **1998**, *42*, 89–106. [CrossRef]
31. Liu, H.; Liu, H.; Wang, Z.; Xu, M.; Han, X.; Li, L. The temperature sensitivity of soil respiration. *Prog. Geogr.* **2008**, *27*, 51–60.
32. Singh, R.; Srivastava, P.; Singh, P.; Sharma, A.K.; Singh, H.; Raghubanshi, A.S. Impact of rice-husk ash on the soil biophysical and agronomic parameters of wheat crop under a dry tropical ecosystem. *Ecol. Indic.* **2019**, *105*, 505–515. [CrossRef]
33. Soong, J.L.; Jiménez, S.M.; Cotrufo, M.F.; Boeckx, P.; Bodé, S.; Guenet, B.; Peñuelas, J.; Richter, A.; Stahl, C.; Verbruggen, E.; et al. Soil microbial CNP and respiration responses to organic matter and nutrient additions: Evidence from a tropical soil incubation. *Soil Biol. Biochem.* **2018**, *122*, 141–149. [CrossRef]
34. Truong, T.H.H.; Marschner, P. Respiration, available N and microbial biomass N in soil amended with mixes of organic materials differing in C/N ratio and decomposition stage. *Geoderma* **2018**, *319*, 167–174. [CrossRef]
35. Srivastava, P.; Singh, R.; Tripathi, S.; Singh, H.; Raghubanshi, A.S.; Mishra, P.K. A new insight into the warming potential of organically amended agro-ecosystems. *Org. Agric.* **2018**, *8*, 275–284. [CrossRef]
36. Nikolova, P.S.; Raspe, S.; Andersen, C.P.; Mainiero, R.; Blaschke, H.; Matyssek, R.; Häberle, K.-H. Effects of the extreme drought in 2003 on soil respiration in a mixed forest. *Forstwiss. Centralblatt* **2008**, *128*, 87–98. [CrossRef]
37. Linn, D.M.; Doran, J.W. Effect of Water-Filled Pore Space on Carbon Dioxide and Nitrous Oxide Production in Tilled and Nontilled Soils. *Soil Sci. Soc. Am. J.* **1984**, *48*, 1267–1272. [CrossRef]

38. Yang, S.; Liu, X.; Liu, X.; Xu, J. Effect of water management on soil respiration and NEE of paddy fields in Southeast China. *Paddy Water Environ.* **2017**, *15*, 787–796. [CrossRef]
39. Tong, X.; Li, J.; Nolan, R.H.; Yu, Q. Biophysical controls of soil respiration in a wheat-maize rotation system in the North China Plain. *Agric. For. Meteorol.* **2017**, *246*, 231–240. [CrossRef]
40. Liu, X.; Wan, S.; Su, B.; Hui, D.; Luo, Y. Response of soil CO_2 efflux to water manipulation in a tallgrass prairie ecosystem. *Plant Soil* **2002**, *240*, 213–223. [CrossRef]
41. Wei, L.; Su, J.; Jing, G.; Zhao, J.; Liu, J.; Cheng, J.; Jin, J. Nitrogen addition decreased soil respiration and its components in a long-term fenced grassland on the Loess Plateau. *J. Arid Environ.* **2018**, *152*, 37–44. [CrossRef]
42. Liu, J.; Schulz, H.; Brandl, S.; Miehtke, H.; Huwe, B.; Glaser, B. Short-term effect of biochar and compost on soil fertility and water status of a Dystric Cambisol in NE Germany under field conditions. *J. Plant Nutr. Soil Sci.* **2012**, *175*, 698–707. [CrossRef]
43. Kumari, T.; Singh, R.; Verma, P.; Raghubanshi, A.S. Monsoon-phase regulates the decoupling of auto- and heterotrophic respiration by mediating soil nutrient availability and root biomass in tropical grassland. *CATENA* **2021**, *209*, 105808. [CrossRef]
44. Li, H.; Fu, S.; Zhao, H.; Xia, H. Forest soil CO_2 fluxes as a function of understory removal and N-fixing species addition. *J. Environ. Sci.* **2011**, *23*, 949–957. [CrossRef]
45. Han, C.D.; Ye, X.H.; Ma, L.; Ma, J.H.; Zou, H.T.; Zhang, Y.L. The characteristics of soil CO_2 emission and its impact factors of greenhouse potato soil undLer different controlled irrigation low limits. *J. Irrig. Drain.* **2020**, *39*, 46–55. (in Chinese) [CrossRef]
46. Epron, D.; Nouvellon, Y.; Roupsard, O.; Mouvondy, W.; Mabiala, A.; Saint-André, L.; Joffre, R.; Jourdan, C.; Bonnefond, J.-M.; Berbigier, P.; et al. Spatial and temporal variations of soil respiration in a Eucalyptus plantation in Congo. *For. Ecol. Manag.* **2004**, *202*, 149–160. [CrossRef]
47. Shi, P.L.; Zhang, X.Z.; Zhong, Z.M.; Ouyang, H. Diurna land seasonal variability of soil CO_2 efflux in a cropland ecosystem on the Tibetan Plateau. *Agric. For. Meteor.* **2006**, *137*, 220–233. [CrossRef]
48. Hou, M.; Jin, Q.; Lu, X.; Li, J.; Zhong, H.; Gao, Y. Growth, Water Use, and Nitrate-15N Uptake of Greenhouse Tomato as Influenced by Different Irrigation Patterns, 15N Labeled Depths, and Transplant Times. *Front. Plant Sci.* **2017**, *8*, 666. [CrossRef]
49. Wang, W.; Guo, J. The contribution of root respiration to soil CO_2 efflux in Puccinellia tenuiflora dominated community in a semi-arid meadow steppe. *Chin. Sci. Bull.* **2006**, *51*, 697–703. [CrossRef]
50. Wang, W.; Feng, J.; Oikawa, T. Contribution of Root and Microbial Respiration to Soil CO_2 Efflux and Their Environmental Controls in a Humid Temperate Grassland of Japan. *Pedosphere* **2009**, *19*, 31–39. [CrossRef]
51. Liu, Y.; Han, S.-J.; Zhou, Y.-M.; Li, X.-F. Soil and Root Respiration Under Elevated CO_2 Concentrations During Seedling Growth of P inus sylvestris var. sylvestriformis. *Pedosphere* **2007**, *17*, 660–665. [CrossRef]
52. Du, W.; Xu, M.; Yin, Y.; Sun, Y.; Wu, J.; Zhu, J.; Guo, H. Elevated CO_2 levels alleviated toxicity of ZnO nanoparticles to rice and soil bacteria. *Sci. Total Environ.* **2021**, *804*, 149822. [CrossRef] [PubMed]
53. Zhang, J.; Tang, X.; He, X.; Liu, J. Glomalin-related soil protein responses to elevated CO_2 and nitrogen addition in a subtropical forest: Potential consequences for soil carbon accumulation. *Soil Biol. Biochem.* **2015**, *83*, 142–149. [CrossRef]