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ORIGINAL ARTICLE

Soil respiration of hot pepper (*Capsicum annuum L.*) under different mulching practices in a greenhouse, including controlling factors in China

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Soil respiration is an important component of the carbon cycle and is also recognized as one of the primary pathways that release CO_2 from the soil into the atmosphere in terrestrial ecosystems. Soil CO_2 flux resulting from soil microbial activity and root respiration is one of the major components of the total carbon flux in agro-ecosystems. However, the impact of agronomic practices such as mulching on soil respiration in greenhouses has been less thoroughly studied. Consequently, field experiments were conducted during the growing seasons of 2011 and 2012 in greenhouse to evaluate soil respiration and the biotic and abiotic factors that influence it in hot pepper cultivation under four types of mulch practices (without mulch, wheat straw mulch, plastic film mulch, and combined mulch with plastic film and wheat straw). Soil water content had an overriding influence on soil respiration in hot pepper culture during the growing season under mulching treatments in a greenhouse, whereas the influence of soil temperature was relatively less. Additionally, the study showed that root biomass and root vigor should also be incorporated as predictor variables for soil respiration under mulching in greenhouses.

Keywords: soil respiration; variation; hot pepper; mulching practices; greenhouse

Introduction

Mulching is an important soil management practice in many parts of the word (Saroa & Lal 2003; Mupangwa et al. 2007; Jordán et al. 2010; Balwinder et al. 2011; Xia et al. 2013). This practice is defined as the application of various types of cover materials to the soil surface (Jordán et al. 2011). Mulching protects the soil from water-caused erosion by reducing the impact of rainfall. The use of mulch can strongly affect run-off dynamics and reduce the amount of run-off (Mulumba & Lal 2008). Mulching has also been linked to changes in soil nutrient availability and to decreases in soil temperature (T_s) through shading and increases in infiltration (Buerkert et al. 2000). Studies in China have indicated that the use of plastic mulch on wheat can increase yield, reduce water use, and improve water-use efficiency (Zhang & Yang 2001). Recent studies have shown that straw mulching is a promising management option for farmers to control soil salinity, as it decreases soil water evaporation and regulates soil water and salt movement (Qiao et al. 2006; Pang et al. 2010). In addition, the application of crop residue mulches increases soil organic carbon (SOC) content (Saroa & Lal 2003). Duiker and Lal (1999) reported a positive linear effect of mulch application rate on SOC concentration.

Soil respiration (R_s) is an important component of the global carbon balance and is also recognized as one of the primary pathways that release CO_2 from the soil into the atmosphere in terrestrial ecosystems (Buchmann 2000; Schindlbacher et al. 2009; Kruse et al. 2013). The global CO_2 emission from R_s has been estimated at approximately 75×10^{15} g C yr^{-1}. It is probable that this large natural flux will increase due to changes in the earth's characteristics (Schlesinger & Andrews 2000). R_s is derived from the respiration

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of both soil organisms and plant roots (Luo & Zhou 2006) and from the decomposition of organic matter, followed by the subsequent release of CO_2 at the soil surface. In addition to T_s and soil moisture, root biomass, net primary productivity, litter inputs, microbial populations, root nitrogen concentrations, soil texture, and substrate quantity and quality have all been shown to have effects on R_s (Buchmann 2000; Fang & Moncrieff 2001; Dilustro et al. 2005). Generally, T_s and soil moisture are considered the most influential factors controlling R_s base on different carbon models such as Roth-C, CENTURY, and quadratic models (Han et al. 2007; Peng et al. 2009; Zhang et al. 2010). Moreover, Guan et al. (2011) also found that mulching had a strong influence on the diurnal and seasonal variation in R_s in a winter wheat field. Therefore, knowledge of R_s dynamics and its controlling factors in various terrestrial ecosystems is essential to find proper management policies and relevant technologies to decrease soil CO_2 emissions and enhance carbon sequestration.

Hot pepper (*Capsicum annuum L.*), originating in tropical Central and South America, is one of the most economically important vegetables in China. Hot pepper cultivation covers 1.3 million ha, and the total production is approximately 28 million t yr^{-1} (Li et al. 2009). Mulching is always recommended as a component within a proper management policy for vegetable productions in greenhouse in the world (Korir et al. 2006; Shtienberg et al. 2010; Qiu et al. 2013). However, mulching effects have been studied primarily under open-field conditions, and little information is reported on the response of hot pepper to mulching in greenhouse culture in China. It is well known that the micro-climates (Wang et al. 2013) of the plants grown in greenhouses and open-field conditions differ significantly, and such differences are also found for R_s. Zhai et al. (2008) found that the R_s in all mulching treatments was significantly higher than that of control (CK, un-mulched) and there was a significant positive correlation between R_s and T_s for cucumber in greenhouse. Zeng et al. (2011) also demonstrated that R_s for tomato was highest in the growth season when the soil relative water content was in the range of 90%–100% and T_s and soil moisture had a significant positive correlation with R_s in greenhouse condition. Nevertheless, the quantification of R_s and the factors that influence it in hot pepper under mulching in greenhouses has not been performed. Therefore, an understanding of the variation in R_s in greenhouses under mulching practices, as presented by our study (pepper with the area of 96 m^2 and the production is approximately 1034.4 kg yr^{-1}), will be useful for calculating carbon emissions in greenhouses more accurately.

Accordingly, the objectives of the current research are as follows: (1) to investigate the seasonal and diurnal variation in R_s in hot pepper under mulching in greenhouse culture during the growing season and (2) to analyze the effects of the controlling factors on R_s and its variability in hot pepper culture under greenhouse conditions.

Materials and methods

Experiment site description

The experiments were carried out in the experimental greenhouse of Institute of the Soil and Water Conservation, the Chinese Academy of Science and Ministry of Water Resources in Yangling (3412–3420N; 108–1087E, elevation 560 m), Shaanxi, China, from May to September in 2011 and 2012, respectively. Monthly average air temperature and air relative humidity (Figure 1) were recorded automatically by HOBO (CO-UX100-011) in 2012, which was located in the middle of the plot area at a height of 1.5 m. The soil texture was dark loessial soil (46.4% sand, 37.0% silt, and 16.6% clay, on average) with a pH value of 7.9. Soil water holding capacity was 24% (mass basis) and the soil bulk density was 1.26 g cm^{-3}; soil electrical conductivity (SEC) was 0.7 ms cm^{-1}; organic matter content was 14.66 g kg^{-1}; total N content was 0.82 g kg^{-1}; total P_2O_5 content was 0.99 g kg^{-1}; available N (1 mol L^{-1} NaOH hydrolysis) was 28.75 mg kg^{-1}; available P (0.5 mol/L $NaHCO_3$) was 30.46 mg kg^{-1}; and available K (1 mol/l neutral NH_4OAc) was 153.68 mg kg^{-1}.

Experimental design

There were four treatments including CK (conventional practice un-mulch), plastic film mulch (FM, a common method; the first step was to cover 0.01 mm transparent polythene film, and then to dibble on film and transplant pepper plants in each holes), combined mulch with plastic film and wheat straw (CM, plastic film covered in planting row and then wheat straw covered in operation row, and the 5 cm length of wheat straw with 2500 kg ha^{-1}), and wheat straw mulch (SM, 3 cm length of wheat straw with 5000 kg ha^{-1}). Hot pepper plants (cultivar featured horn pepper, a common variety) were transplanted at the depth of 30 cm on 20 May 2011 and on 27 May 2012 with a density of 40,000 plants ha^{-1} at the same place. Plot size was 2.5 m long and 2.4 m wide, using a randomized block design with four replications, and four rows of pepper plants with interrow spacing of 50 cm and interplant spacing of 50 cm were transplanted in each plot in two years. The

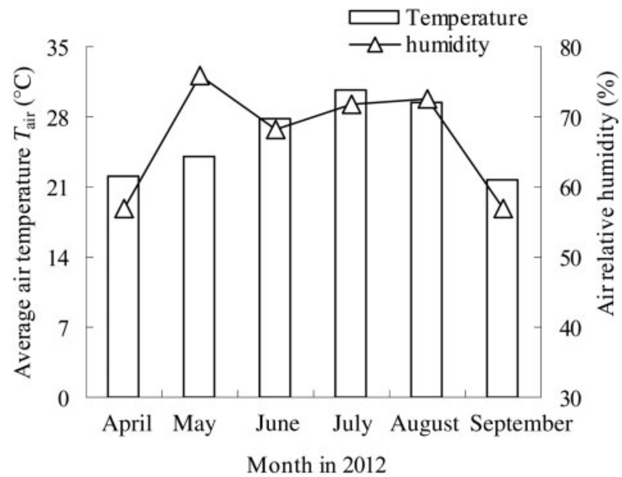

Figure 1. Average monthly air temperature (T_{air}°C) and air relative humidity in 2012 at the study site.

plastic membrane was set underground about 100 cm depth to prevent interpenetration of water. After the harvesting, the plastic film was removed and the wheat straw was incorporated into the soil. Fertilizers were applied with 75 kg ha^{-1} N (urea) and 75 kg ha^{-1} P_2O_5 (diammonium phosphate) and K_2O at 75 kg ha^{-1} for each plot on 19 May and 20 July 2011 and on 26 May and 27 July 2012, respectively. Treatments were established on 18 June 2011 and 26 June 2012, and we harvested the pepper on 21 September 2011 and 28 September 2012. On average, soil moisture was maintained around 80% of field moisture capacity with drip irrigation system using Time Domain Reflectometry (TDR) measurement, which was embedded to the depth of 40 cm in the soil. Three probes were used as replicates in each plot.

R_s measurements

R_s was measured during the growing season (July–September) in 2011 and 2012 using a LICOR-6400 portable photosynthesis system equipped with a LICOR 6400-9 R_s chamber (LICOR, Inc., Lincoln, NE, USA; Li et al. 2010). Polyvinyl chloride soil collars 10.4 cm in diameter and 5 cm in height were used for the measurements. To minimize the soil surface disturbance-induced CO_2 efflux, the collars were installed at least 24 h prior to each measurement. Collars were inserted in the soil to a depth of 4 cm, and three replicate measurements were made on each collar on the observation days. The collar on each experimental plot was placed near the plants (5 cm from the plant), interplants (25 cm from the plants) and interrows (in the middle of four plants, approximately 35 cm from the plants). The litter in the collars was removed before the measurements began. All the measurements were performed between 9:00 and 11:00 h. In addition, diurnal variations were measured every 2 h from 8:00 to 20:00 h on 7 August and 26 August 2011 and 26 July, 27 August and 13 September 2012.

Assessment of biotic and abiotic factors

Five soil samples per plot were collected at depths of 0–30 cm in an area with a diameter of 5 cm within a 10-m radius surrounding each site in May (before transplanting pepper), July (pepper vigorous growth) and September (after harvesting pepper). The samples were mixed by hand, and a 2-kg composite sample was obtained from each plot. All of the soil samples were air-dried to analyze soil pH, SEC, soil organic matter (SOM), and other soil properties.

T_s in each plot was measured simultaneously with R_s using a copper/constantan thermocouple penetration probe (LI-6400-09 TC, LiCor) inserted 5 cm deep in soil, in the vicinity of the soil collars.

Soil water content (SWC; 0–40 cm) was recorded with TDR and three TDR probes were used in each plot with three replicated measurements made for each probe. SWC was measured for each experimental plot on the observation days (the day we measured R_s) and also on the day before we irrigated. Each measurement was calibrated by gravimetry.

The responses of soil pH, SEC, and SOM to mulching were recorded in 2011 and 2012. The soil pH was measured in aqueous soil extract in deionized water and soil (1:2.5 soil:water). SEC was measured in aqueous soil extract in deionized water (1:5 soil:water) with a Nissan B-173 conductivity meter. SOM was determined with the oil bath-K_2CrO_4 titration method after digestion.

To determine root biomass, five sample pepper plants in each treatment were clipped to ground level, and soil cores within a 50-cm diameter were

Table 1. The seasonal dynamic variation of R_s of hot pepper (*C. annuum L.*) in response to mulch in 2011 and 2012 during the growing seasons.

		R_s (μmolm $^{-2}$s^{-1}) (Mean ± SE)			
Year	Date	CK	FM	CM	SM
2011	8 July	2.30 ± 0.06d	3.0 ± 0.06c	5.4 ± 0.12a	3.7 ± 0.17b
	3 August	1.7 ± 0.17c	2.6 ± 0.15b	3.4 ± 0.06a	2.9 ± 0.23ab
	7 August	2.8 ± 0.12c	2.3 ± 0.23c	4.2 ± 0.12a	3.4 ± 0.23b
	26 August	2.2 ± 0.23b	2.8 ± 0.17 b	4.3 ± 0.12a	3.9 ± 0.23a
2012	13 July	2.8 ± 0.23d	5.2 ± 0.17c	7.7 ± 0.09a	6.9 ± 0.12b
	23 July	1.9 ± 0.12c	4.8 ± 0.17a	4.2 ± 0.06b	5.1 ± 0.23a
	26 July	2.5 ± 0.17c	3.7 ± 0.29b	4.9 ± 0.29a	3.4 ± 0.17b
	27 August	3.4 ± 0.15b	2.6 ± 0.12c	4.6 ± 0.17a	3.4 ± 0.17b
	13 September	2.3 ± 0.08a	1.9 ± 0.08b	2.4 ± 0.16a	2.5 ± 0.16a

Note: CK, un-mulched control; FM, plastic film mulch; CM, combined mulch with plastic film and wheat straw; SM, wheat straw mulch. Values followed by the same letter in each row show no significant differences ($p < 0.05$).

taken to a depth of 50 cm in the rows and between the rows. All the samples were oven-dried at 105°C until a constant weight was obtained. Any material not derived from the roots was removed before weighing the final product. Root vigor was measured with triphenyl tetrazolium chloride.

Statistical analysis

The data were analyzed with SPSS 13.0 for Windows (USA). A one-way analysis of variance was performed to evaluate the influence of biotic and abiotic factors on R_s. Subsequently, a Duncan multiple range test was used to identify statistically significant differences ($p < 0.05$) between the mean values of R_s within each mulching practice.

Results

R_s variation in response to mulching

The seasonal variation of R_s in response to mulching

The highest R_s value was obtained under CM (combined mulch with plastic film and wheat straw) and the lowest under CK (control, no mulch) conditions in both 2011 and 2012. In all cases, the R_s measured in the control soil was always lower than that for any mulch material treatment over the entire growing season. The differences between CK and FM (plastic film mulch) and CM and SM (wheat straw mulch) were significant at $p < 0.05$ (Table 1). Compared with the CK value, the average mean R_s for the entire growing season increased by 18.89%, 92.2%, and 54.4% under FM, CM, and SM, respectively, in 2011, and by 41.09%, 84.50%, and 65.11%, respectively, in 2012. R_s increased from July onwards, reached a maximum in August and then began to decrease in 2011, reaching its lowest value in September 2012. Under different mulching practices, R_s also varied among the different positions (Table 2). Both in 2011 and 2012, the average R_s during the growing season had the following sequence: near the plant > interplants > interrows under all the mulching practices. Furthermore, the average R_s during the growing season at the three positions differed significantly ($p < 0.05$) in the pepper culture under the four mulching conditions in both 2011 and 2012 (Table 2).

Diurnal variation of R_s in response to mulch

Diurnal patterns of change in R_s were observed on 7 August and 26 August 2011 and 26 July, 27 August, and 13 September 2012. The observations were made every 2 h from 8:00 to 20:00 (Figure 2). R_s exhibited a similar diurnal pattern of variation under the studied mulching conditions in both 2011 and 2012, with a minimum value at 20:00 and a maximum value between 12:00 and 14:00 (Figure 2). The range of variation from 8:00 to 20:00 was the greatest in CM (3.6 μmol m^{-2} s^{-1}), whereas the other treatments (CK, FM, and SM) showed almost the same range of variation (2.8, 3.0, and 2.6 μmol m^{-2} s^{-1}, respectively) on 7 August 2011. The range of variation on 26 August 2011 under different mulching conditions was similar to that observed on 7 August 2011. The range of diurnal variation on 26 July 2012 was greater than that on the other two representative days. On 26 July 2012, the range of variation was the greatest for CM (2.5 μmol m^{-2} s^{-1}), intermediate for CK (1.7 μmol m^{-2} s^{-1}), and lowest for FM (1.1 μmol m^{-2} s^{-1}) and SM (1.1 μmol m^{-2} s^{-1}). The diurnal average daily R_s followed the order CM > SM > FM > CK on all five observation days (Figure 2). The influence of combined mulch with plastic film and wheat straw (CM) was significant at all levels in 2011 and 2012, with a trend similar to that found for seasonal variation (Table 1).

Table 2. R_s of hot pepper (*C. annuum L.*) at near plant, interplants and interrows during the growing seasons in 2011 and 2012.

Year	Date	Treatments	Position			Year	Date	Treatments	Position		
			Interplants	Interrows	Near plant				Interplants	Interrows	Near plant
2011	8 July	CK	2.58a	1.98c	2.33b	2012	13 July	CK	3.69b	1.71c	4.05a
		T1	2.69c	2.97b	3.32a			T1	7.20b	4.90c	10.86a
		T2	3.10b	3.15b	4.80a			T2	4.69b	2.17c	8.79a
		T3	3.15b	4.03c	6.92a			T3	6.98b	5.45c	8.36a
	3 August	CK	1.59a	1.78a	1.76a		23 July	CK	1.86a	1.83a	2.03a
		T1	3.04a	2.13c	2.64b			T1	4.16a	3.84a	4.71b
		T2	2.97b	2.06c	3.72a			T2	3.46c	3.76b	4.82a
		T3	3.12b	2.73c	3.98a			T3	5.93a	6.24a	3.17b
	7 August	CK	1.97a	3.55a	2.40b		26 July	CK	2.82a	1.85b	2.83a
		T1	3.51a	1.85b	1.53b			T1	4.76a	4.83a	4.96b
		T2	3.25b	2.74c	4.20a			T2	2.42c	3.74b	4.81a
		T3	4.51b	2.83c	5.28a			T3	3.84a	4.02a	3.18b
	26 August	CK	2.31b	1.79c	2.39a		27 August	CK	3.59b	2.50c	4.22a
		T1	2.04c	3.55a	2.63b			T1	4.18b	3.90b	5.58a
		T2	3.89b	3.11c	4.55a			T2	2.05b	3.81a	1.97b
		T3	2.86c	3.95b	6.04a			T3	2.61b	2.90b	4.66a
							13 September	CK	2.38b	1.93c	2.85a
								T1	2.36b	2.37b	2.55a
								T2	1.51b	1.69b	2.38a
								T3	2.02b	2.11b	3.21a

Note: CK, un-mulched control; FM, plastic film mulch; CM, combined mulch with plastic film and wheat straw; SM, wheat straw mulch.
Values followed by the same letter in each row show no significant differences ($p < 0.05$)

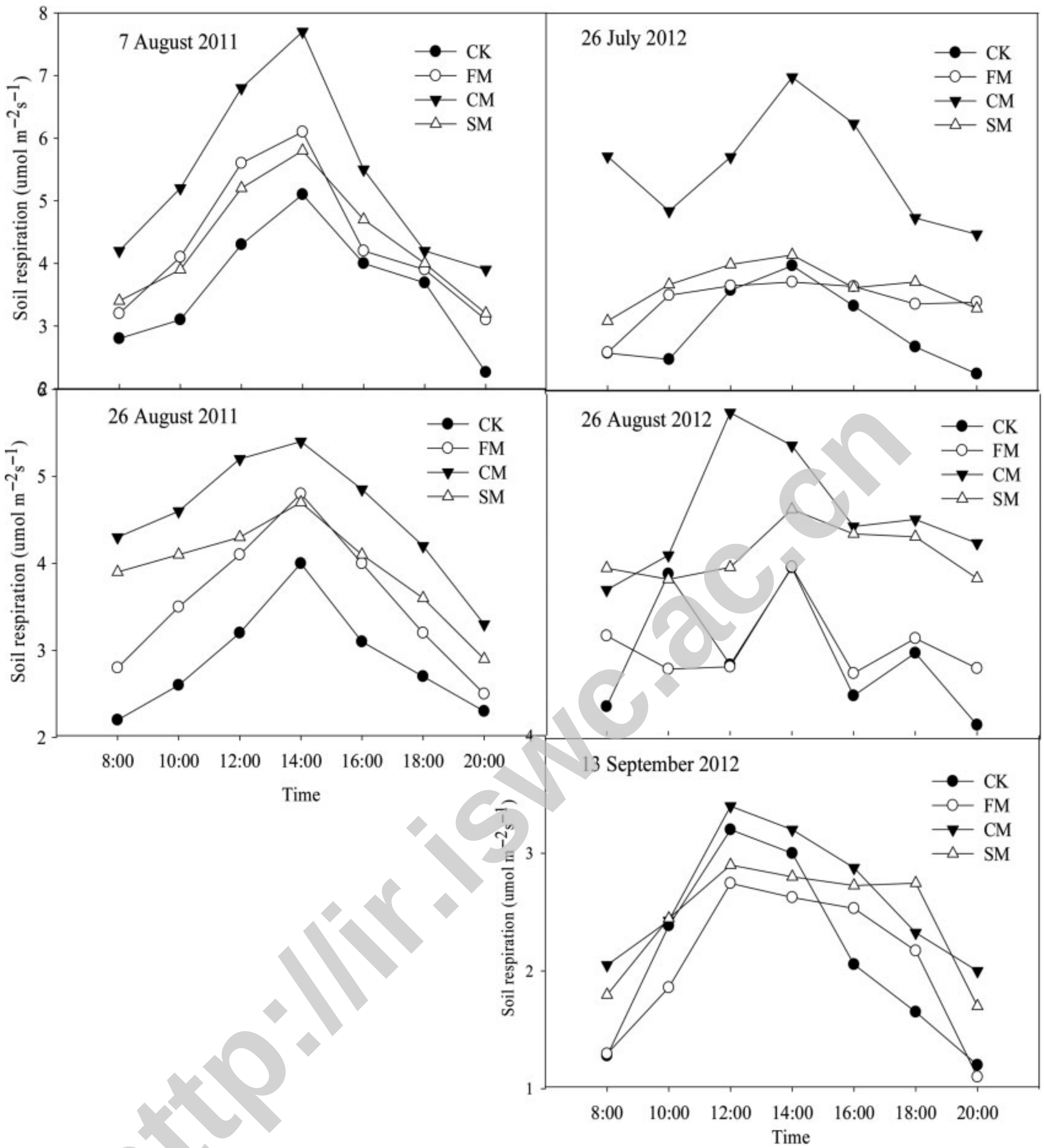

Figure 2. The diurnal variation (from 8:00 to 20:00) of R_s in response to mulch (CK, un-mulched control; FM, plastic film mulch; CM, combined mulch with plastic film and wheat straw; SM, wheat straw mulch) on 7 August, 26 August 2011 and 26 July, 26 August and 13 September 2012.

Effect of controlling factors on R_s in relationship to mulching

Effects of SWC and temperature on R_s

The seasonal patterns of soil moisture and T_s, as well as relative humidity and air temperature, were observed in 2012. The seasonal R_s–SWC relationship is expected to follow an optimum curve (Byrne et al. 2005) and can be described together with the R_s response to T_s by a response plane, as shown in Figure 3. The results shown in Figure 3 indicate that the R_s of hot pepper was influenced more strongly by seasonal T_s (the dots in response plane are more near to T_s plane) than by SWC under the CK and SM treatments, whereas R_s depended more on SWC (the dots in response plane are more near to SWC plane) than on seasonal T_s under the FM and CM treatments. A correlation analysis (Table 3) showed that both T_s and air temperature had significant positive correlations with the seasonal variation of R_s under the CK, CM, and SM treatments, whereas there was no significant correlation under FM. There were significant negative correlations between SWC and R_s and between relative humidity and R_s in response to all the mulching practices.

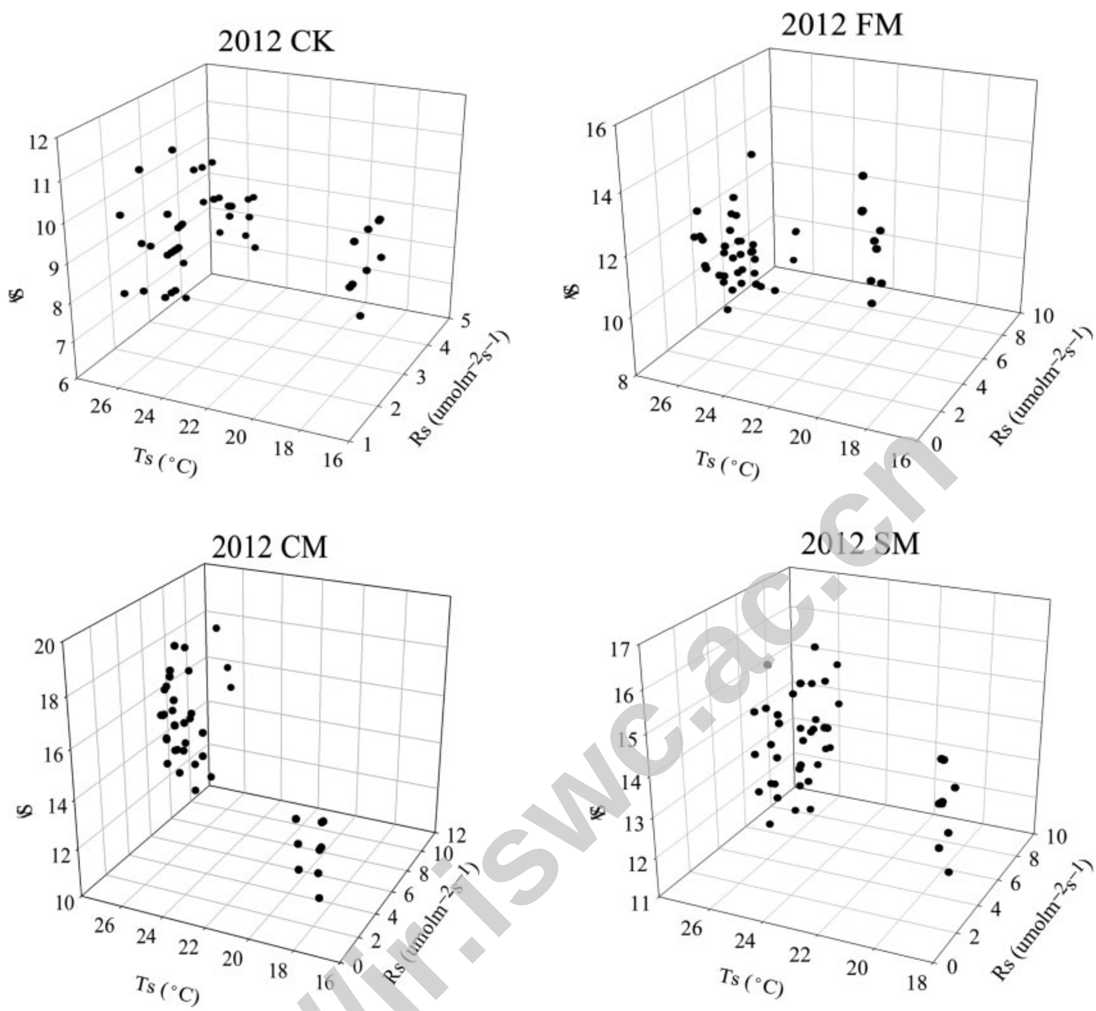

Figure 3. Dependence of R_s on T_s (at 5 cm soil depth) and SWC (0–10 cm) under different mulching practice (CK, un-mulched control; T1, plastic film mulch; T2, combined mulch with plastic film and wheat straw; T3, wheat straw mulch) in 2012.

Effects of pH, SEC, and SOM on R_s

In 2011, significant differences were found in SOM and SEC under different mulching treatments (Table 4; $p < 0.05$), whereas no significant differences were found in soil pH. The trends in the variation of soil pH, SEC, and SOM in response to the mulching treatments in 2012 were similar to those found in 2011. These three factors influenced R_s in both study years. However, the exact influence varied. SOM was significantly related to R_s in both 2011 and 2012 (Figure 4; $p < 0.01$) except for the treatment with FM in 2012 ($R^2 = 0.4337$, $p = 0.06$); no relationships were found between R_s and soil pH and SEC in 2011 and 2012.

Table 3. Correlation coefficients of R_s to abiotic factors in 2012 under different mulching treatments.

	CK		FM		CM		SM	
Factors	Pearson correlation	Sig. (2-tailed)	Pearson correlation	Sig. (2-tailed)	Pearson correlation	Sig. (2-tailed)	Pearson correlation	Sig. (2-tailed)
T_s	0.847**	0.004	0.751**	0.02	0.349	0.358	0.678*	0.045
Air temperature	0.776*	0.014	0.293	0.445	0.407	0.276	0.799**	0.01
SWC	−0.818**	0.007	−0.762*	0.017	−0.761*	0.017	−0.734*	0.024
Air relative humidity	−0.774*	0.004	−0.792*	0.011	−0.726*	0.027	−0.695*	0.038

Note: CK, un-mulched control; FM, plastic film mulch; CM, combined mulch with plastic film and wheat straw; SM, wheat straw mulch treatments.
*Correlation is significant at the 0.05 level; **Correlation is significant at the 0.01 level.

Table 4. Influences of mulching on soil pH, SEC and SOM of hot pepper in 2011 and 2012 experiments.

		Treatments				
		CK	FM	CM	SM	SE
2011	Soil pH	8.13a	8.13a	8.10a	8.13a	0.02
	SEC ($s\ m^{-1}$)	0.06a	0.07b	0.09c	0.06a	0.11
	SOM (%)	1.43a	1.54b	1.79b	1.83b	0.19
2012	Soil pH	8.12a	8.14a	8.15a	8.13a	0.01
	SEC ($s\ m^{-1}$)	0.07a	0.07a	0.08b	0.08b	0.06
	SOM (%)	1.39a	1.79b	1.65c	1.72d	0.17

Note: CK, un-mulched control; FM, plastic film mulch; CM, combined mulch with plastic film and wheat straw; and SM, wheat straw mulch.
Values are not different at the 5% level of significance if followed by the same letter.

The control of R_s by root biomass and root vigor

Figure 4 shows the effects of root biomass and root vigor on R_s under the studied mulching and control treatments in 2011 and 2012. The mulching treatments increased root biomass significantly compared with the control. These trends were the same as those shown by R_s. Variation in R_s may be influenced by biotic factors (root biomass) but not abiotic factors because R_s and root biomass were strongly correlated under the CK (R^2 = 0.8469 in 2011 and R^2 = 0.7242 in 2012), FM (R^2 = 0.9250 in 2011 and R^2 = 0.9210 in 2012), CM (R^2 = 0.9306 in 2011 and R^2 = 0.6130 in 2012), and SM (R^2 = 0.8805 in 2011 and R^2 = 0.6820 in 2012) treatments. Similarly, R_s increased with increases in root vigor, and the relationship between R_s and root vigor was significant under all four treatments (Figure 4; $p < 0.01$).

Discussion

Variation in R_s in response to mulching

Mulch improves soil quality and productivity and has favorable effects on soil properties (Jordán et al. 2010). García-Orenes et al. (2009) found that mulch was able to improve soil properties significantly as well as influence R_s, as also shown by the results of the current study. Our results from the two years of study (2011 and 2012) demonstrated that the seasonal average R_s of hot pepper culture in the greenhouse was greater with mulching than in the absence of mulching. The order of effectiveness of the mulching treatments was CM > SM > FM > CK (Table 1), and the differences among the treatments were significant. These results show that differences in soil conditions and microbial biomass and activity in hot pepper culture under different mulching treatments may have implications for R_s (Tu et al. 2006). The mulch layer above the soil can prevent water exchange between the soil and air, causing reduced evaporation and excessive water consumption (Yang et al. 2006). Variations in T_s are the initial response observed in mulching applications and depend on the type of mulch (Yang et al. 2006). The higher R_s found with the CM treatment shows that this type of mulch was more effective either in preserving soil moisture or in improving T_s, as previously shown by Li et al. (2004) and Liang et al. (2011).

Over most of the observation days, R_s in hot pepper culture under different mulching treatments showed strong temporal and spatial variation. R_s increased beginning in July, reached a maximum in August and then began to decrease, reaching its lowest value in September in both 2011 and 2012. Respiration by the soil originates primarily from root respiration (autotrophic) and microbial (heterotrophic) activities. Seasonal changes in root respiration depend primarily on the phenological stages of the plant (Jia et al. 2006), as carbon is the principal source of energy for root respiration at growing stage (Shi et al. 2006). The rapid rate of growth and high root biomass of hot pepper often resulted in high nutrient availability to the pepper crop in August. As a result, R_s was greater. During the stage of rapid growth, the respiration of the rhizosphere was enhanced by photosynthetic activity due to the transfer of assimilates into the roots and soil (Kuzyakov & Cheng 2001). In our study, we found the same R_s pattern (near the plant > interplant > interrows) under all the mulching treatments (Table 2). These findings are consistent with the results of an analysis of R_s in a maize ecosystem by Han et al. (2007). The reason for this result may be that the dicotyledonous pepper has taproot systems with a main root and lateral root development; these roots grow almost vertically throughout the soil. In addition, the microbial communities in pepper culture are affected by three different root exudates (Bais et al., 2006; Nannipieri et al. 2008). It is possible that these differences resulted in the differences in the spatial variation of R_s found in hot pepper culture in the greenhouse. The result of this study cannot be generalized to all R_s in greenhouse in the world; however, the result did show that the quantification of R_s in hot pepper under mulching in greenhouses at regional scale. Therefore, an understanding of the variation in R_s in greenhouses will be useful for calculating carbon emissions in greenhouses more accurately in China.

Factors controlling R_s under mulching conditions in the greenhouse environment

R_s is controlled by a range of biotic and abiotic factors, e.g., SWC, temperature, root biomass, aboveground

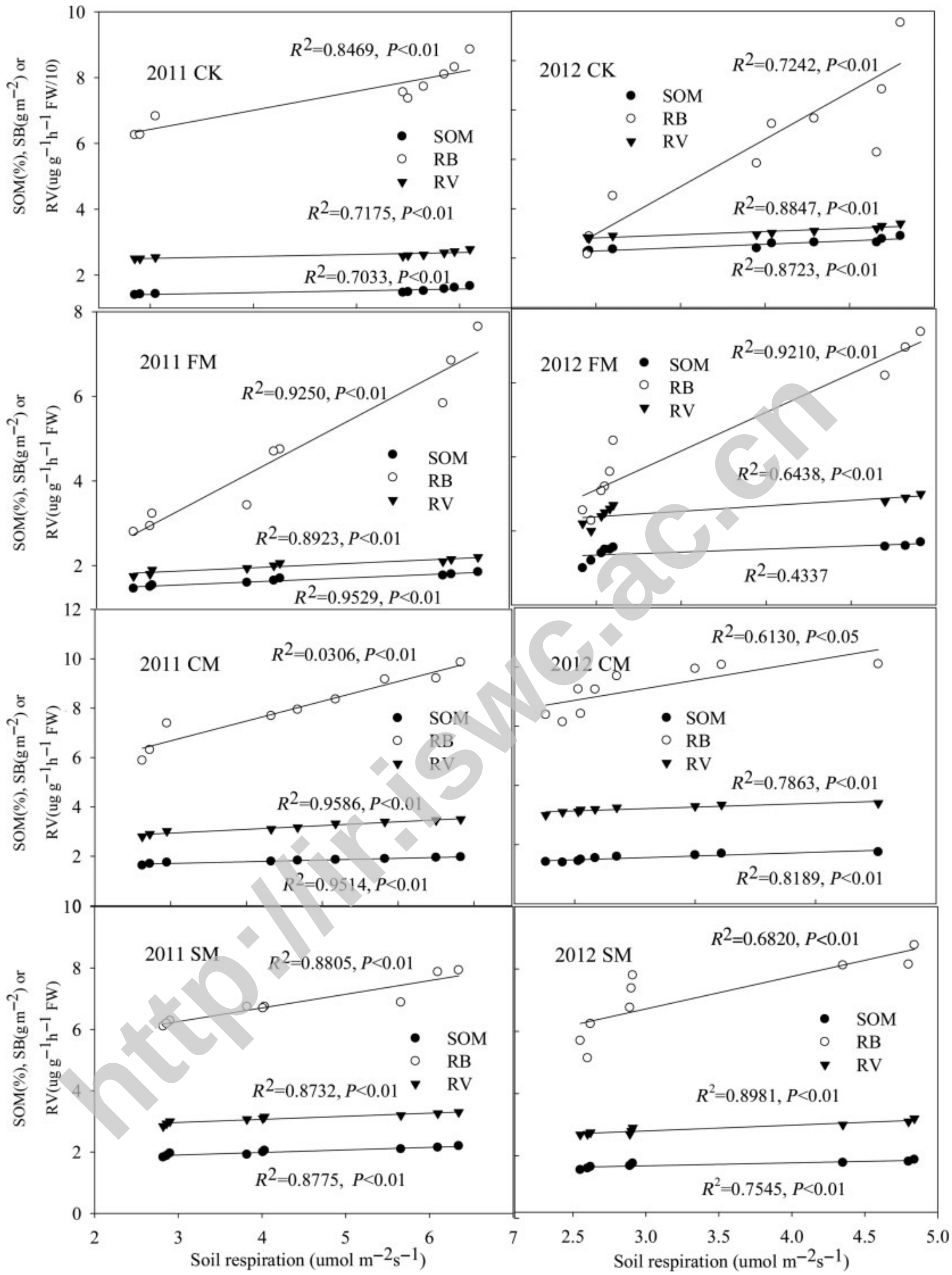

Figure 4. Relationships between R_s and SOM, root biomass, and root vigor under mulching practices (CK, un-mulched control; FM, plastic film mulch; CM, combined mulch with plastic film and wheat straw; SM, wheat straw mulch) in greenhouse in both 2011 and 2012.

vegetation structure, and photosynthetic activity (Subke et al. 2006). Various components of R_s respond differently to these factors. In the present study, the seasonal pattern of R_s generally indicated that R_s was correlated with T_s under all the mulch treatments; however, no relationship was observed for the CM measurements in 2011 or 2012. In contrast, R_s was significantly associated with SWC and relative humidity under all the mulching practices. These results are in contrast to the findings of previous studies (Bowden et al. 1998; Conant et al. 2004) that showed that T_s was the principal factor influencing R_s, whereas SWC was secondary. Temperature can be a strongly controlling factor for R_s rates under certain conditions, but the limiting factors in many, if not most, cases are those determining substrate availability, e.g., water status and the supply of assimilate. In our greenhouse, T_s was much higher under the T2 treatment, whereas SWC was lower. Therefore, the effect of SWC was more important for R_s relative to the higher and sufficient seasonal T_s under the CM treatment in greenhouse conditions. A number of other studies have also shown that SWC has a stronger impact than temperature on R_s under soil saturation or water deficit (Hanson et al. 1993; Jia et al. 2006). Throughout the study period, SWC fluctuated between 8% and 16%. Low SWC can limit belowground biological activity, and R_s was positively correlated with SWC and air relative humidity throughout this study.

Soil pH and SEC were not correlated with R_s during the growing season under the four mulching practices. The reason for these findings is that soil properties may be more homogeneous in the microclimate of the greenhouse. The soil properties did not fluctuate markedly and did not differ significantly among the mulching treatments (Table 4) during the growing season. In this study, we also verified the direct effect of SOM on R_s and showed a highly correlated relationship under all mulching practices (Figure 4). Such effects of mulching may result from improvements in soil carbon and water availability in the rhizosphere of the hot pepper culture and from the activity of microorganisms, which directly affected the mineralization and accumulation of SOM as well as R_s.

Root biomass and root vigor, the biotic factors, also affected R_s (Figure 4). Our results showed that higher soil root biomass and activity were associated with high R_s under the mulching treatments. First, the respiration of roots directly below the measurement chamber exerted a significant influence on R_s because root respiration is an integral part of R_s (Hanson et al. 2000). Second, root exudates associated with assimilation and root litter entering the soil during the growing season enhanced R_s by stimulating microbial growth and activity (Lohila et al. 2003). Third, high soil root biomass and activity often facilitate high nutrient availability to hot pepper through the enhancement of both root biomass turnover and degradation of nonmicrobial organic materials. Moreover, Bulluck et al. (2002) have found that the numbers of free-living nematodes were significantly higher in mulched soils than in conventionally managed soils. Thus, the seasonal change in R_s was most likely controlled by the combination of microbial physiological activity and root respiration and root exudates under mulching in the greenhouse. Consequently, understanding the factors that control belowground terrestrial carbon cycling in greenhouse is critical for estimating global carbon stock and finding proper management policies to decrease soil CO_2 emissions and enhance carbon sequestration in China.

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