

# Tree-scale spatial variation of soil respiration and its influence factors in apple orchard in Loess Plateau

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**Abstract** Although small-scale spatial variation of soil respiration has been studied in a wide variety of ecosystems, there are few studies investigating the spatial variation of soil respiration at tree-scale. An inaccurate estimation of soil respiration would be obtained if the spatial variation of soil respiration was ignored. Soil respiration, soil temperature, soil moisture and fine roots biomass were measured in different directions (0, 120, and 240°) at different distances (0.5 and 2 m radial distance) from the trunk of three representative trees for the period 2011–2013 in a mature apple orchard established on the Loess Plateau in 2000. The mean soil respiration rate at 0.5 m-distance was 21, 35 and 42 % higher, respectively. The cumulative soil respiration at 0.5 m-distance was 20, 31, and 38 % higher; and the temperature

sensitivity of soil respiration ( $Q_{10}$ ) at 0.5 m-distance was 15, 30 and 12 % higher than that at 2 m-distance in 2011, 2012, and 2013, respectively. There was no significant difference in soil temperature and moisture between 0.5 m- and 2 m-distance, whereas fine root biomass at 0.5 m-distance was 64, 108, and 114 % higher than that at 2 m-distance in 2011–2013, respectively. Fine root biomass had a positive linear relationship with accumulative soil respiration and  $Q_{10}$ . Mean annual cumulative soil respiration was 0.46, 0.45, and 0.57 kg C m<sup>-2</sup> year<sup>-1</sup> in 2011–2013, respectively. Fine root biomass contributed to the spatial variation of soil respiration in apple orchard, and soil respiration at 2 m-distance could represent the C respired in orchard level.

**Keywords** Soil respiration · Apple orchard · Temperature sensitivity of soil respiration · Fine root biomass

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## Introduction

Soil respiration is a key component of the carbon cycle of the terrestrial ecosystems, and thus an accurate estimation of soil respiration is essential to evaluating the ecosystem carbon budget. However, this can be extremely difficult due to the high spatial heterogeneity of soil respiration, especially across small spatial scales (Buchmann 2000; Casals et al. 2000; Xu and Qi

2001; Han et al. 2007). A large number of sampling points are required to attain reliable estimates of ecosystem respiration, whereas the number of feasible sampling points is usually limited by labor and time (Adachi et al. 2005). Stratified sampling has been used to reduce the number of sampling points and to attain the required accuracy in the estimation of soil respiration (Adachi et al. 2005; Degens and Vojvodi 1999; Rodeghiero and Cescatti 2008).

Spatial variability of soil respiration has been linked to several biotic and abiotic factors, such as soil temperature, soil moisture, and fine root biomass (Ngao et al. 2012). Soil temperature and moisture could be significantly influenced by vegetation species composition, age, and distribution in a given ecosystem (Gray et al. 2002). Soil temperature was higher in the gap than under the closed canopy, because the canopy intercepted solar radiation (Binkley and Giardina 1998; Boone et al. 1998; Hanson et al. 2000; Smith and Johnson 2004; Ritter et al. 2005). Canopy gap resulted in increased light levels, and subsequently increased soil and air temperatures (Ritter et al. 2005). Soil moisture varied with the fraction of precipitation reaching the ground as stemflow or throughfall (Bryant et al. 2005). Root biomass also varied significantly, with the highest root biomass generally occurring near the trunk (Bauhus and Bartsch 1995; Gan et al. 2010; Ceccon et al. 2011; Wang et al. 2013). In addition, fine root biomass was generally lower in gaps than under canopies (Xu and Qi 2001).

Small-scale spatial heterogeneity of soil respiration has been extensively investigated in the forest ecosystem (Xu and Qi 2001; Franklin and Mills 2003; Maestre and Cortina 2003), but little attention has been devoted to the orchard ecosystem. Unlike the forest ecosystem, trees in the orchard ecosystem are generally of the same species and age, spaced apart at a fixed distance, and frequently disturbed by field practices, such as fertilization, tillage and harvesting, thus resulting in a high spatial heterogeneity of soil respiration. Understanding the small-scale spatial heterogeneity of soil respiration is the premise to estimate soil respiration at an orchard scale. However, small-scale spatial variation in soil respiration and the relationship with influencing factors remain poorly understood in apple orchard ecosystem.

In this study, we measured soil respiration, fine root biomass and soil microclimates at different distances from the trunk at a tree scale in an apple orchard in the

semi-arid Loess Plateau from 2011 to 2013, and the main purposes of this study were to investigate: (1) the dynamics of soil respiration at different distances from the trunk of representative trees; and (2) biotic and abiotic factors that influenced the dynamics of soil respiration.

## Materials and methods

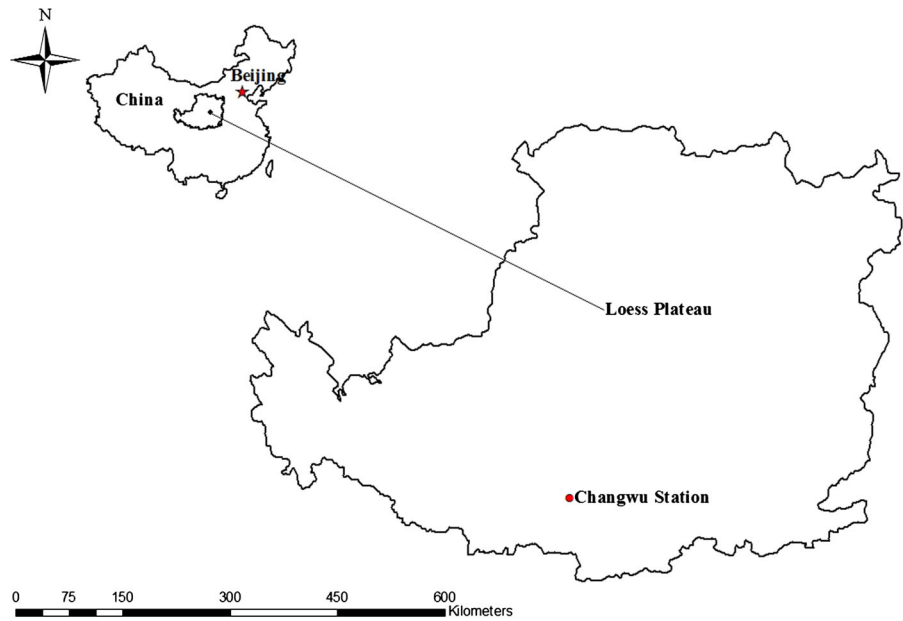
### Site description

The Loess Plateau is located in the northwest China covering a total area of 430,000 km<sup>2</sup> (Wu et al. 2008; Pang et al. 2009). It is an arid region with highly erodible soils, and this is further aggravated by intensive agriculture, such as hill slope cultivation. To address this problem, an integrated management of small watershed has been practiced since 1980s in an attempt to convert cropland to woodland or grassland, leading to a significant improvement in the ecological environment, soil productivity, and household income level (Chang et al. 2011). Apples are the most widely cultivated cash crop in this region due to its great economic (>200 billion RMB per year) and ecological value, and the planting area has increased by 20 times during the past 30 years. Now this region has developed into one of the most important apple producing areas in China, accounting for 60 % (1.3 million ha) and 55 % (15 million ton year<sup>-1</sup>) of the total planting area and fresh weight yield in China. Therefore, sustainable development of the apple orchard contributes directly to regional economic development and ecological environment construction.

The study site is located in a typical tableland-gully region of southern Loess Plateau in the middle reaches of Yellow River (35°13'N, 107°40'E; 1220 m a.s.l) in Wangdonggou, Changwu Country, Shaanxi Province of China (Fig. 1). It has a continental monsoon climate characterized by a seasonal good monsoon rhythm, hot summers and cold winters. The annual mean precipitation is 560 mm, 60 % of which occurs between July and September. The annual mean air temperature is 9.4 °C, and  $\geq 10$  °C accumulated temperature is 3029 °C. The annual sunshine hours are 2230 hours, annual total radiation is 484 kJ cm<sup>-2</sup>, and frostfree period is 171 days (Zhang et al. 2015).

The soil at the study site is a uniform loam of loess deposits that belongs to Cumulic Haplustolls according

**Fig. 1** A sketch map of the Loess Plateau



to the American system of soil classification, and originates from the parent material of calcareous loess. Soils collected at the study site in 2011 at a depth of 0–20 cm were characterized by: pH 8.3, clay content (<0.002 mm) 24 %, field capacity 22.4 %, and permanent wilting point 9.0 % (Zhang et al. 2015).

#### Experimental design

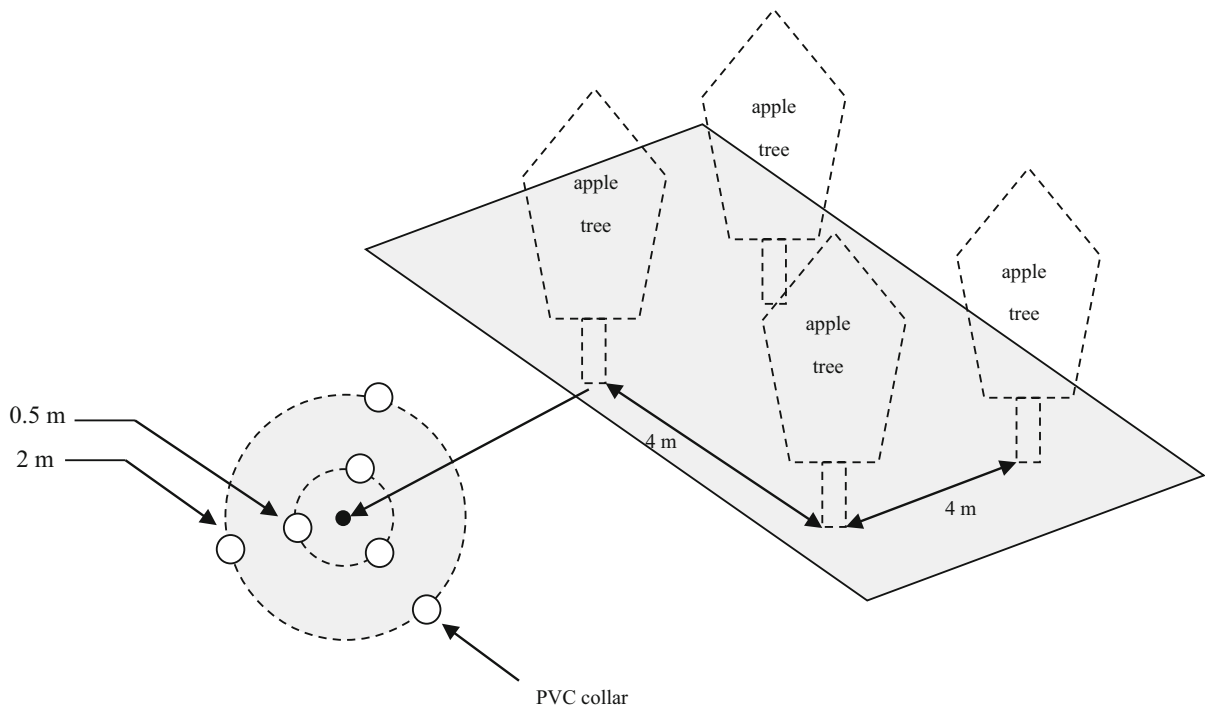
The apple orchard was converted from millet cropland in 2000. Fuji apple trees (*Malus pumila* Mill) dominated the orchard with a density of 625 plants ha<sup>-1</sup>, and the distance was 4 m along the row and 4 m between rows. The apple orchards in this area were not irrigated, and rainfall was the only source of water. The soil underneath the trees was kept weed-free using tillage. The trees were fertilized twice a year at a soil depth of 0–50 cm by digging a hole at 1 m from tree row in November (100 kg N ha<sup>-1</sup>, 385 kg P ha<sup>-1</sup>) and by top-dressing in late June (100 kg N ha<sup>-1</sup>). Apple trees were pruned in early March every year and thinned in April and May. Fruits were harvested at the middle of October, with an annual average yield (fresh weight) of about 60,000 kg ha<sup>-1</sup> year<sup>-1</sup>. All the litter biomass was removed in autumn.

The diagonal of the orchard was divided into trisection, and one apple tree which grew well and had

no diseases or insect pests was selected at random in each unit, giving a total of three trees. One week before each measurement, plastic collars (20 cm in diameter × 12 cm in height) were inserted 2 cm into the soil in three different directions (0, 120, and 240°) at different distances (0.5 and 2 m radial distance) from the main tree trunk (Fig. 2).

#### Measurements of soil respiration, soil temperature and moisture

Soil respiration was measured using an automated and closed soil CO<sub>2</sub> flux system equipped with a portable chamber of 20 cm in diameter (Li-8100, Lincoln, NE, USA). Before the measurement, all visible living organisms were artificially removed. Each plot was measured twice, with a 90 s enclosure period and a 30 s delay between measurements. If the variation between the two measurements was larger than 15 %, one or more measurements were taken to reduce variation to less than 15 %. The final instantaneous soil respiration for a given collar was the average of the two consecutive measurements. The field measurements were performed from 09:00 am to 11:00 am which could represent the whole day (Iqbal et al. 2010) during March 2011 to November 2013, but not in December, January and February due to cold weather



**Fig. 2** Diagrammatic representation of the location of the PVC collars where soil respiration was measured

which could inhabit root and microbial activity. Measurement was taken about every 15 days. A total of 17 soil respiration measurements were taken in 2011, 20 in 2012, and 16 in 2013, respectively. Soil bulk density at 0–20 cm depth was measured using a cutting ring (5 cm in depth and diameter) (Li et al. 2006).

Soil temperature (three measurements per collar) and moisture (four measurements per collar) were measured at 10 cm away from the chamber collar at the same time with the soil respiration. Soil temperature and soil moisture at 5 cm depth were measured using a Li-Cor thermocouple probe and a Theta Probe ML2X with an HH2 moisture meter (Delta-TDevices, Cambridge, England), respectively. Soil water-filled pore space (WFPS) was transformed using the following equation:  $WFPS (\%) = [\text{volumetric water content}/100 \times (2.65 - \text{soil bulk density})/2.65]$  (Ding et al. 2007).

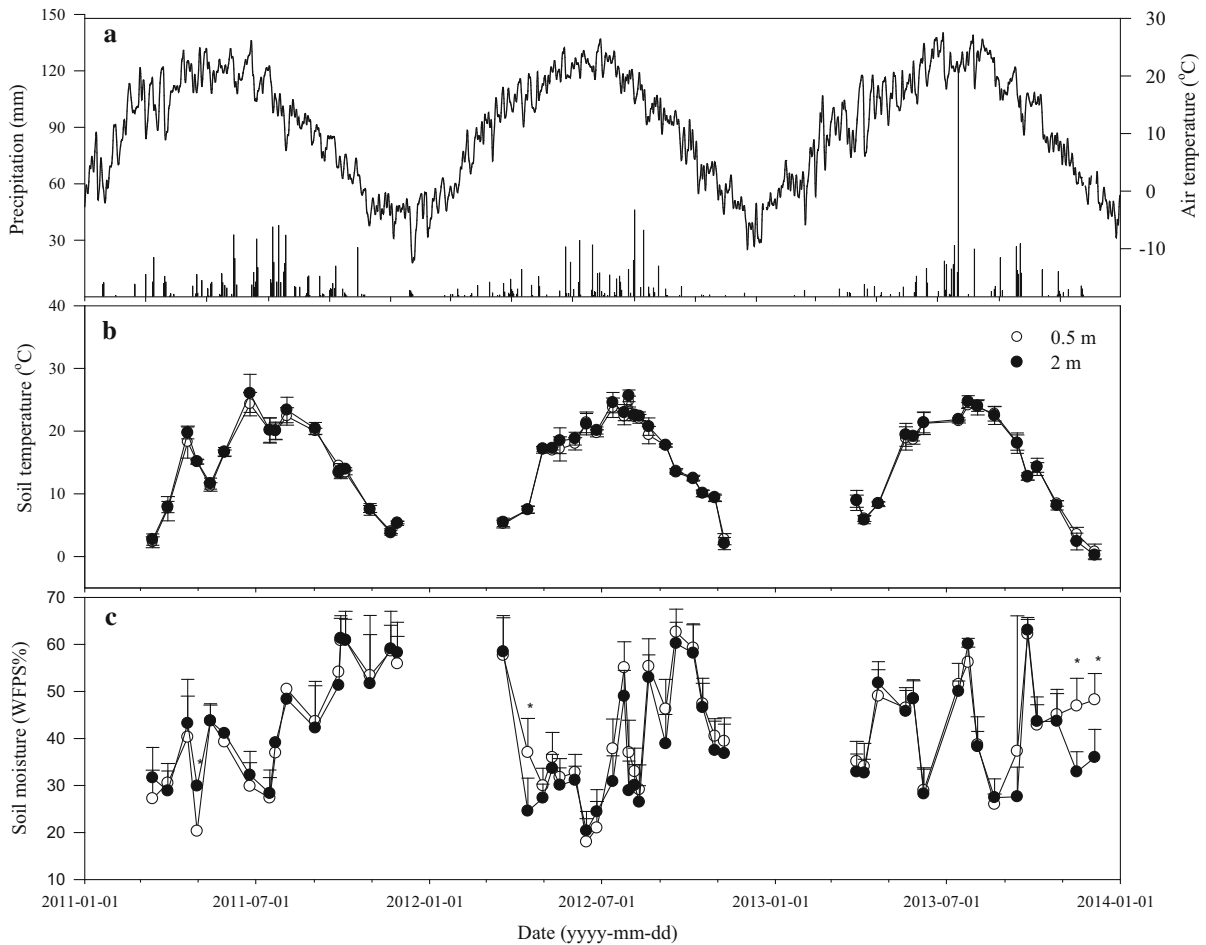
#### Root biomass

Fine root (<2 mm in diameter) biomass was collected and measured at the same six plots at the end of

autumn from 2011 to 2013 to indicate the cumulative root biomass over the season. Six soil cores (9 cm in diameter by 20 cm in depth) were collected from each plot at 0–20 cm depths. Cores collected at 0.5 m were combined to form a composite sample, as were those at 2 m. Roots were washed and oven-dried to constant weights at 60 °C for 48 h (Zhang et al. 2015).

#### Data analysis

Soil respiration, temperature and moisture data were analyzed using the GLM procedure of SAS to detect the difference between distances. An exponential function or  $Q_{10}$  function was used to simulate the relationship between soil respiration and soil temperature (Xu and Qi 2001), and a quadratic polynomial function was used to simulate the relationship between soil respiration and soil moisture (Tang et al. 2005). To examine the temperature sensitivity of soil respiration, we conducted regression analyses using  $R_s = \alpha e^{\beta T}$ , where  $R_s$  is the soil respiration,  $T$  is the soil temperature,  $\alpha$  is the intercept of soil respiration when soil temperature is zero, and  $\beta$  is the temperature sensitivity of soil respiration (Luo et al. 2001). To



**Fig. 3** Variation of **a** precipitation (mm) and air temperature (°C), **b** soil temperature (°C), and **c** soil moisture (% WFPS) over a 3-year period from 2011 to 2013. Asterisks indicate significant differences at  $P < 0.05$

estimate annual cumulative soil respiration, we first interpolated between measurement dates to estimate the mean daily soil respiration for each plot, and then calculated the sum of the mean daily soil respiration for a given year (Gilbert 1987).

## Results

### Effect of distance on abiotic and biotic factors

Soil temperatures at 5-cm depth exhibited very similar seasonal and annual variations at 0.5 m- and 2 m-distance from the trunk ( $P > 0.05$ ) (Fig. 3b). The variation of soil temperature was in good agreement with that of air temperature, with the lowest soil

temperature recorded in spring and autumn, whereas the highest soil temperature recorded in summer (Fig. 3a, b). The mean soil temperature at 0.5 m- and 2 m-distance was 13.9 and 14.2 °C in 2011, 16.2 and 16.5 °C in 2012, and 14.4 and 14.5 °C in 2013, respectively (Table 1), and the mean annual soil temperature was slightly higher at 2 m-distance than at 0.5 m-distance (15.1 vs. 14.8 °C).

Soil moisture at 0–5 cm depths also exhibited very similar seasonal and annual variations at 0.5 m- and 2 m-distance from the trunk (Fig. 3c). The annual mean soil moisture at 0.5 m- and 2 m-distance was 43.1 and 44.2 % WFPS in 2011, 40.3 and 37.3 % WFPS in 2012, and 43.5 and 41.4 % WFPS in 2013, respectively (Table 1), and it was higher at 0.5 m-distance than at 2 m-distance (42.3 vs. 40.9 % WFPS).

**Table 1** Mean soil moisture, mean soil temperature, fine root biomass and soil respiration from 2011 to 2013

Year	Distance (m)	Soil moisture (%)	Soil temperature (°C)	Fine root biomass (g m <sup>-2</sup> )	Soil respiration (μmol m <sup>-2</sup> s <sup>-1</sup> )	Cumulative respiration (kg m <sup>-2</sup> year <sup>-1</sup> )
2011	0.5	43.12 ± 12.68a	13.87 ± 6.67a	208 ± 35a	1.88 ± 0.18a	0.55 ± 0.09a
	2	44.15 ± 10.97a	14.19 ± 6.99a	127 ± 12b	1.56 ± 0.17b	0.45 ± 0.02b
2012	0.5	40.32 ± 12.61a	16.16 ± 6.39a	291 ± 21a	2.26 ± 0.77a	0.58 ± 0.05a
	2	37.29 ± 12.52a	16.48 ± 6.71a	140 ± 19b	1.67 ± 0.45b	0.44 ± 0.05b
2013	0.5	43.54 ± 9.72a	14.45 ± 7.67a	343 ± 29a	2.68 ± 1.27a	0.77 ± 0.13a
	2	41.38 ± 11.25a	14.49 ± 7.98a	160 ± 22b	1.89 ± 0.85b	0.56 ± 0.08b

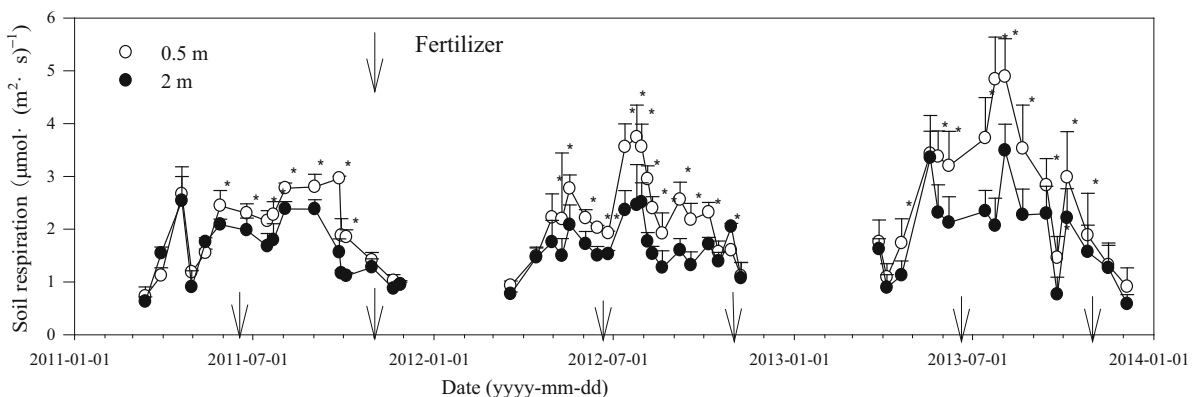
Different letters indicate significant differences at  $P < 0.05$

A significant between-distance difference was observed with regard to fine root biomass. It increased from 127 g m<sup>-2</sup> at 2 m-distance to 208 g m<sup>-2</sup> at 0.5 m-distance in 2011, from 140 to 291 g m<sup>-2</sup> in 2012, and from 160 to 343 g m<sup>-2</sup> in 2013, respectively ( $P < 0.05$ ) (Table 1).

#### Variation in soil respiration

Soil respiration showed similar seasonal and annual variations at 0.5 m- and 2 m-distance (Fig. 4). It increased gradually with increasing temperature from March to June, and decreased quickly with decreasing temperature after October. The highest soil respiration at 0.5 m-distance was 2.77 μmol m<sup>-2</sup> s<sup>-1</sup> in summer and 0.73 μmol m<sup>-2</sup> s<sup>-1</sup> in spring; whereas at 2 m-distance it was 2.38 μmol m<sup>-2</sup> s<sup>-1</sup> in summer and 0.63 μmol m<sup>-2</sup> s<sup>-1</sup> in spring in 2011, respectively. A similar trend was observed in the other years.

The mean soil respiration at 0.5 m-distance was 21, 35 and 42 % higher than that at 2 m-distance in 2011, 2012 and 2013, respectively; and the annual mean soil respiration was higher at 0.5 m-distance than at 2 m-distance (2.27 vs. 1.71 μmol m<sup>-2</sup> s<sup>-1</sup>, Table 1). However, it was noted that there was a seasonal difference in soil respiration between 0.5 m- and 2 m-distance. The between-distance difference in soil respiration was decreasing in autumn but increasing in summer. Thus, the largest difference, as indicated by the amount of increase (%), was observed in September in 2011 (90 %), August in 2012 (64 %) and June in 2013 (134 %); whereas the smallest was observed in November in 2011 (4 %), April in 2012 (1 %), and November in 2013 (5 %), respectively (Fig. 3). The annual cumulative soil respiration at 0.5 m-distance ranged from 0.55 to 0.77 kg C m<sup>-2</sup> year<sup>-1</sup> with a CV of 19 %, and from 0.44 to 0.56 kg C m<sup>-2</sup> year<sup>-1</sup> with a CV of 14 % at 2 m-distance (Table 1). The



**Fig. 4** Dynamics of soil respiration (μmol m<sup>-2</sup> s<sup>-1</sup>) from 2011 to 2013 in apple orchard in semi-arid Loess region. Asterisks indicate significant differences at  $P < 0.05$

mean annual cumulative soil respiration was also greater at 0.5 m-distance than at 2 m-distance (0.63 vs. 0.49 kg C m<sup>-2</sup> year<sup>-1</sup>), with an increase of about 23 %. The mean annual cumulative soil respiration of the whole orchard was 0.46 kg C m<sup>-2</sup> year<sup>-1</sup> in 2011, 0.45 kg C m<sup>-2</sup> year<sup>-1</sup> in 2012, and 0.57 kg C m<sup>-2</sup> year<sup>-1</sup> in 2013, respectively.

Effect of abiotic and biotic factors on soil respiration

The seasonal soil respiration increased exponentially with soil temperature (Table 2; Fig. 5), whereas showed a negative quadratic correlation with soil moisture (Table 3; Fig. 6). Soil temperature alone could explain 42–90 %, and soil moisture alone could explain 34–51 % of the variability of soil respiration.

However, soil temperature and soil moisture together could explain 62–83 % of the variation (Fig. 7).

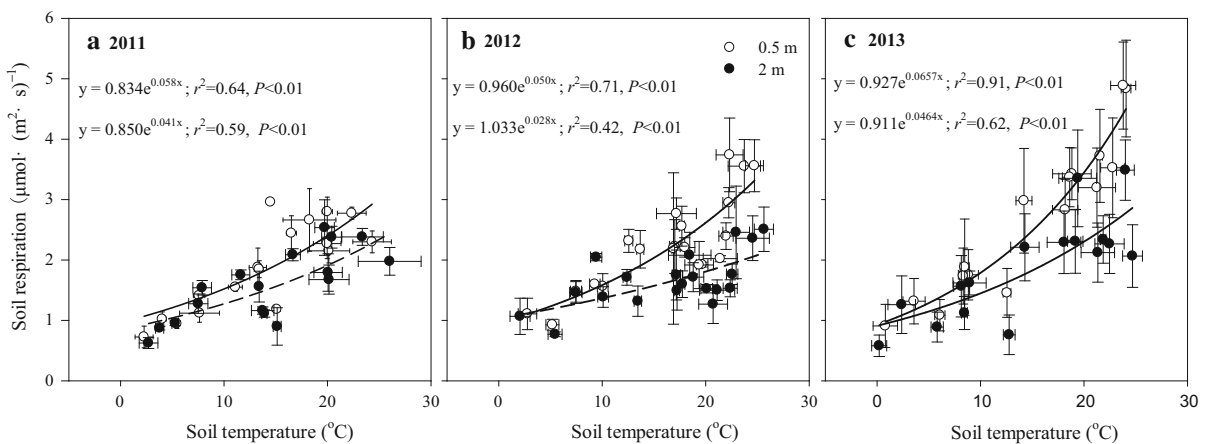
The regression analyses indicated that distance did not significantly affect  $\alpha$ , but altered the temperature sensitivity  $\beta$  (Table 2). Then, the  $\beta$  values were used to calculate  $Q_{10}$ , which decreased from 1.79 at 0.5 m-distance to 1.56 at 2 m-distance in 2011, from 1.79 to 1.38 in 2012, and from 1.93 to 1.72 in 2013, respectively (Table 2). Thus, there were no significant relationships between soil respiration variation and spatial and abiotic factors (soil temperature and soil moisture) over the experimental period. Table 1 showed that fine root biomass at 0.5 m-distance was 64 % (2011), 108 % (2012), and 114 % (2013) higher than that at 2 m-distance, respectively. More importantly, soil respiration increased linearly with fine root biomass ( $P < 0.05$ ) (Fig. 8a).

**Table 2** The relationship between temperature and soil respiration

Year	Distance (m)	$\alpha$	$\beta$	$r^2$	$t_\alpha$	$t_\beta$	$Q_{10}$
2011	0.5	0.781 ± 0.053	0.058 ± 0.004	0.64	0.024	4.115*	1.79
	2	0.795 ± 0.077	0.045 ± 0.004	0.87			1.56
2012	0.5	0.840 ± 0.116	0.058 ± 0.008	0.71	-0.022	3.649*	1.79
	2	0.843 ± 0.211	0.032 ± 0.006	0.42			1.38
2013	0.5	0.927 ± 0.204	0.066 ± 0.004	0.90	0.026	2.45*	1.93
	2	0.911 ± 0.122	0.054 ± 0.005	0.59			1.72

$\alpha$  and  $\beta$  are two coefficients in the regression line  $R_s = \alpha e^{\beta T}$ , where  $R_s$  is soil respiration and  $T$  is the temperature,  $r^2$  is the determinant coefficient,  $t_\alpha$  and  $t_\beta$  are the Student t values for testing statistical significance in coefficient a and b values, respectively, between 0.5 m- and 2 m-distances treatments

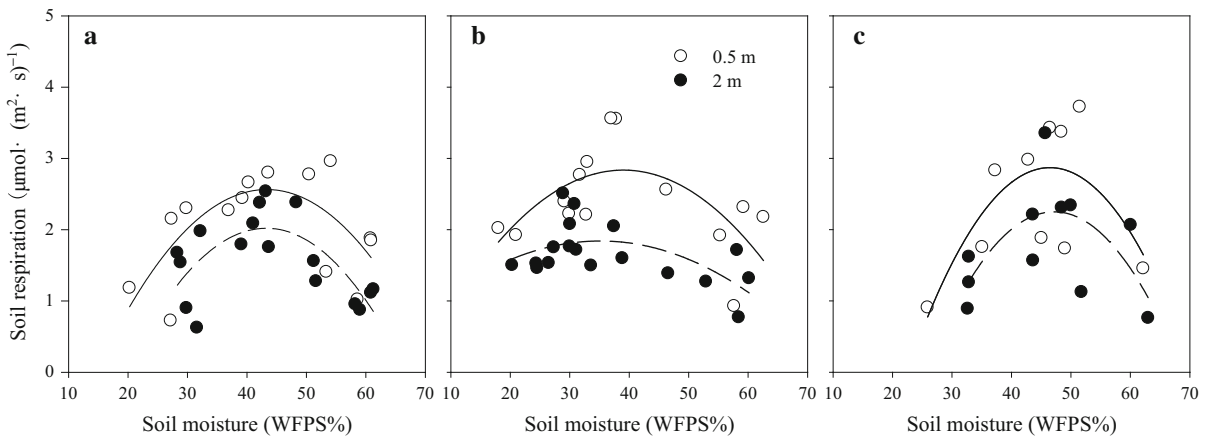
\* Indicate significant differences



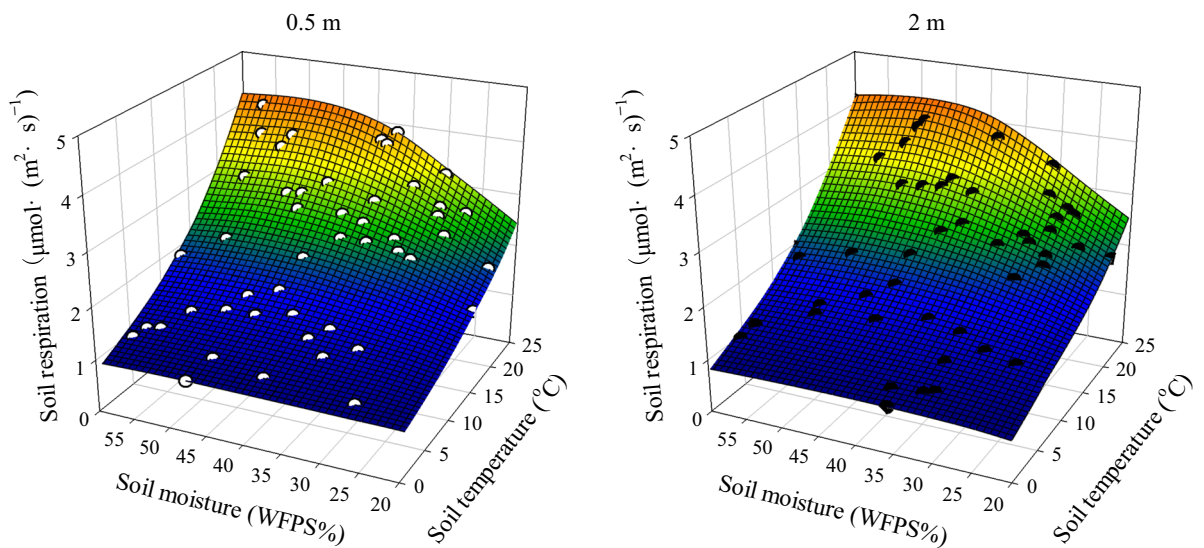
**Fig. 5** Relationship between soil respiration ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and soil temperature ( $^{\circ}\text{C}$ ) at 5 cm depth

**Table 3** The relationship between soil respiration and soil moisture ( $y - \theta$ ) for each year from 2011 to 2013

Year	Distance (m)	Functions	$r^2$	$P$
2011	0.5	$y = -0.0031\theta^2 + 0.268\theta - 3.247$	0.44	<0.01
	2	$y = -0.0036\theta^2 + 0.309\theta - 4.664$	0.49	<0.01
2012	0.5	$y = -0.0023\theta^2 + 0.178\theta - 0.646$	0.44	<0.05
	2	$y = -0.0012\theta^2 + 0.081\theta - 0.492$	0.34	<0.05
2013	0.5	$y = -0.0050\theta^2 + 0.461\theta - 7.829$	0.51	=0.08
	2	$y = -0.0048\theta^2 + 0.452\theta - 8.398$	0.43	=0.01



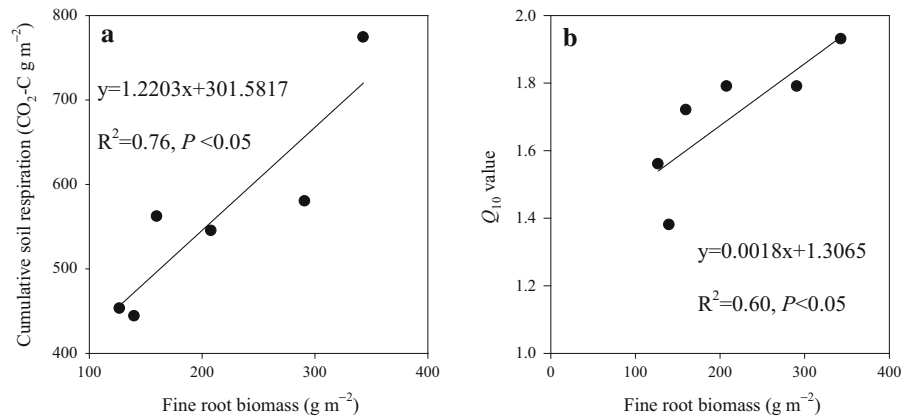
**Fig. 6** Relationship between soil respiration ( $\mu\text{mol m}^{-2} \text{s}^{-1}$ ) and soil moisture (% WFPS) at 0–5 cm depth



**Fig. 7** Response surface of soil respiration as a function of soil moisture and soil temperature at different distances from 2011 to 2013



**Fig. 8** Relationships of cumulative respiration ( $\text{g m}^{-2}$ ) with fine root biomass ( $\text{g m}^{-2}$ ), and mean  $Q_{10}$  with fine root biomass ( $\text{g m}^{-2}$ )



## Discussion

### Soil respiration in apple orchard

In this study, mean cumulative soil respiration was weighted by area. The cumulative soil respiration under tree crown ranged from 0.45 to 0.55  $\text{kg C m}^{-2} \text{ year}^{-1}$  in 2011 with a mean of 0.46; 0.44–0.58  $\text{kg C m}^{-2} \text{ year}^{-1}$  in 2012 with a mean of 0.45; and 0.56–0.77  $\text{kg C m}^{-2} \text{ year}^{-1}$  in 2013 with a mean of 0.57  $\text{kg C m}^{-2} \text{ year}^{-1}$ , respectively. The cumulative soil respiration in the apple orchard was lower than that in the black locust woodland (0.78  $\text{kg C m}^{-2} \text{ year}^{-1}$ ) in this region (Zhang et al. 2015). This could be attributed to vegetation species and distribution which could directly affect soil microclimate (Raich and Tufekcioglu 2000), soil physicochemical and microbiological properties, and aboveground litter and root biomass. Compared to other orchard systems in South China, the cumulative soil respiration in our study was lower than that of longan orchard in subtropical area (Liu et al. 2008) and peach orchard in mid-subtropical area (Iqbal et al. 2008) (Table 4), probably due to the high temperature (21.7 °C in longan orchard and 16.8 °C in peach orchard) and rainfall (1700 and 1577 mm). The higher soil respiration in longan orchard may also be related to the high SOC content (13.4 vs. 6.5  $\text{g kg}^{-1}$ ). Compared to other countries, it was also slightly lower. It was 0.68  $\text{kg C m}^{-2} \text{ year}^{-1}$  in an apple orchard in Northern Italy (Ceccon et al. 2011), and 0.59  $\text{kg C m}^{-2} \text{ year}^{-1}$  in a citrus orchard in Italy (Liguori et al. 2009) (Table 4). This is mainly due to

poor soil properties, such as SOC content and low underground productivity (mean value was 141  $\text{g m}^{-2}$ ).

### Factors influencing seasonal and interannual variability of soil respiration

The large interannual variation in soil respiration is generally attributed to the changes in precipitation (Irvine and Law 2002; Martin and Bolstad 2005). In our study, there was no significant relationship between annual cumulative soil respiration and annual precipitation during the experimental period (March 1 to November 30) (Fig. 3a), which was similar to previous studies (Mo et al. 2005; Savage and Davidson 2001; Wang et al. 2011). Annual cumulative soil respiration was low in 2011 in which the highest annual precipitation was observed. This may be related to the changes in precipitation: 115 mm of precipitation falls in October, accounting for about 18 % of the total precipitation during the experiment period. However, the soil respiration during this time period is low because of the cold temperature. Therefore, precipitation occurred in October and November, 2011 contributed little to annual cumulative soil respiration.

In the Loess Plateau with a continental monsoon climate, over 60 % of precipitation occurs during the rainy season from July to September. Compared with the dry season from March to June, the mean soil respiration in the rainy season was increased by 29 % (1.67 and 2.15  $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) in 2011, 34 % (1.75 and 2.35  $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) in 2012, and 32 % (2.17 and

**Table 4** The relevant researches on soil respiration of orchards

Site	Orchard	Cumulative respiration ( $\text{kg m}^{-2} \text{ year}^{-1}$ )	References
Subtropical area	Longan	1.47	Liu et al. (2008)
Mid-subtropical area	Peach	0.73	Iqbal et al. (2008)
Northern Italy	Apple	0.68	Ceccon et al. (2011)
Italy	Citrus	0.59	Liguori et al. (2009)

$2.87 \mu\text{mol m}^{-2} \text{ s}^{-1}$ ) in 2013, respectively. In addition, variation in soil respiration also depends on temperature (Fig. 7).

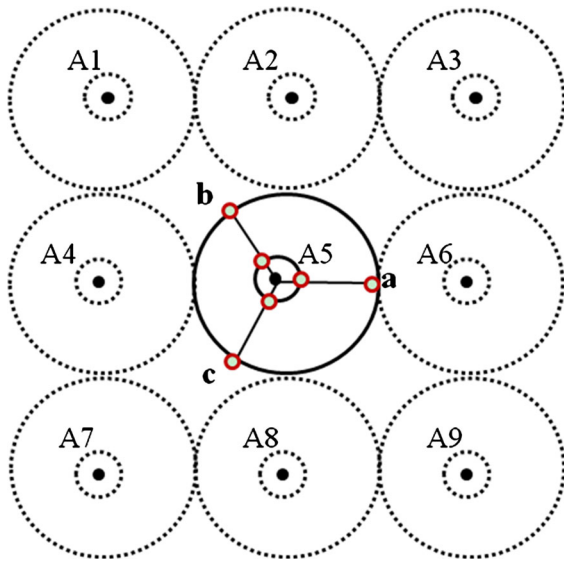
#### Abiotic and biotic factors influencing tree-scale spatial variability on soil respiration

Soil temperature and moisture varied spatially in the forest ecosystem (Binkley and Giardina 1998; Boone et al. 1998; Bryant et al. 2005; Hanson et al. 2000; Smith and Johnson 2004). However, no significant difference was observed between 0.5 m- and 2 m-distance in this study, probably due to that trees in the orchard were generally of the same species and age and spaced apart at a fixed distance, and that effective use of land did not establish gaps, especially in the mature apple orchard. In our study, soil moisture was slightly greater at the 0.5 m-distance than that at the 2 m-distance in 2012 and 2013, maybe because of soil moisture at the 0.5 m-distance come from both throughfall and stemflow, in addition, evaporation at the 0.5 m-distance maybe lower than that at 2 m-distance due to the slightly higher temperature. The cumulative soil respiration at 0.5 m-distance was 20, 31, and 38 % higher than that at 2 m-distance in 2011, 2012, and 2013, respectively (Table 1). The spatial difference in soil respiration in the apple orchard should not come as a surprise, as the small-scale spatial heterogeneity in soil respiration has also been reported in previous studies. In addition, root respiration is a major component of soil respiration. Wiseman and Seiler (2004) observed that soil respiration was consistently higher near the base of trees than midway between planting rows in loblolly pine (*Pinustaeda* L.) forest; Pangle and Seiler (2002) observed significantly greater soil respiration near the base of 2-year-old loblolly pine seedlings in comparison to rates measured away from the seedlings; Epron et al. (2004) showed higher soil

respiration in the vicinity of trunks than in the middle of the inter-rows in *Eucalyptus* plantation.

It is of great importance to understand the main factors contributing to this variability. Soil temperature and moisture have been reported as the main factor controlling soil respiration at a regional scale (Davidson and Janssens 2006). At tree-scale in our study, the low variability in soil temperature and moisture might be responsible for the lack of effect on the spatial variability in soil respiration. Variation in soil temperature due to distance could not explain the differences in soil respiration and cumulative soil respiration between 0.5 m- and 2 m-distance, thus contributing little to the difference in soil respiration. For example, the mean annual soil temperature at 2 m-distance was  $0.32 \text{ }^\circ\text{C}$  higher than that at 0.5 m-distance, whereas the cumulative soil respiration at 2 m-distance was  $0.14 \text{ kg C m}^{-2} \text{ year}^{-1}$  lower than that at 0.5 m-distance from 2011 to 2013. Differences in soil moisture also contributed little to the difference in soil respiration between 0.5 m- and 2 m-distance, because changes in soil moisture could not explain the difference in soil respiration. For instance, the mean annual soil moisture at 2 m-distance was 3 % WFPS greater than that at 0.5 m-distance, whereas the cumulative soil respiration at 2 m-distance was  $0.14 \text{ kg C m}^{-2} \text{ year}^{-1}$  lower than that at 0.5 m-distance. Thus, abiotic factors (soil temperature and soil moisture) may not be the major factors contributing to the spatial variation of soil respiration. Similar results have also been observed in a temperate beech forest in Germany (Buchmann 2000), a Mediterranean oak forest in central Italy (Tedeschi et al. 2006), and a mixed Mediterranean forest (Barba et al. 2013).

Soil respiration increased with N fertilization (Craine et al. 2001; Song and Zhang 2009; Deng et al. 2010), because it could enhance root exudation, fine root biomass production, and soil microbial activity (Pregitzer et al. 2000; Blagodatskaya et al. 2010). Soil



**Fig. 9** Mutual influence between adjacent trees. *Filled black circle* the trunk of apple tree, *red circle* the location of PVC collars, Ax: the number of the apple

respiration among PVC could vary due to localized N fertilization around apple trees. In the Loess Plateau, apple orchard is fertilized twice each year. Basal application is applied in late fall at a soil depth of 0–50 cm ( $100 \text{ kg N ha}^{-1}$ ,  $385 \text{ kg P ha}^{-1}$ ). However, low temperature during late fall or early winter could inhibit root and microbial activity, and fertilization in the subsoil 50 cm depth could decrease crop response to fertilization (Mohanty et al. 2013). The second fertilization is applied in late June ( $100 \text{ kg N ha}^{-1}$ ). Soil respiration at 0.5 m- and 2 m-distance increased in a similar manner. However, fertilization contributed little to spatial difference in soil respiration because of evenly fertilization under tree crown.

Fine root biomass was the most important biotic factor contributing to the difference in respiration observed in this orchard. In our study, fine root biomass at 0.5 m-distance was 64, 108, and 114 % higher than that at 2 m-distance in 2011, 2012 and 2013, respectively (Table 1). Verlinden et al. (2013) showed that the cumulative soil respiration was larger in the narrow inter-row spacing coinciding with a higher fine root biomass. The correlation analysis showed that cumulative soil respiration increased linearly with fine root biomass (<2 mm) (Fig. 8a), which was in line with previous studies (Hertel et al. 2009; Sheng et al. 2010). All these results suggested

that a large share of spatial variation in soil respiration was explained by fine root biomass in our study. It may also be influenced by the adjacent trees. Take tree A5 as an example (Fig. 9), PVC at position “a” was influenced by adjacent tree A6. The variation of root biomass was analyzed to determine the extent of interference from adjacent trees. In 2011, the root biomass among position “a”, “b” and “c” was 139, 127, and  $115 \text{ g m}^{-2}$ , and the soil respiration rate was  $2.06$ ,  $1.88$ , and  $1.70 \mu\text{mol m}^{-2} \text{ s}^{-1}$ , respectively.

#### Variation in temperature sensitivity of soil respiration

In this study,  $Q_{10}$  ranged from 1.79 to 1.93 and 1.38 to 1.72 at 0.5 and 2 m-distance, respectively, and decreased with the increase of distance from the trunk for the period 2011–2013, which fell right into the range of mean  $Q_{10}$  for different ecosystems (mean 2.4; range 1.3–3.3) at a global scale (Raich and Schlesinger 1992). It was also shown that fine root biomass at 0.5 m-distance was significant higher than that at 2 m-distance. Despite the influence of distance from the trunk on  $Q_{10}$ , the apparent  $Q_{10}$  did show a consistent increase with root biomass. Further analysis showed a linear relationship between fine root biomass and  $Q_{10}$  ( $P < 0.05$ ) (Fig. 8b). Thus, the results clearly implied that fine root biomass was a major factor influencing  $Q_{10}$ .

#### Sampling analyses methods

To complete the measurement in 2 h (from 09:00 am to 11:00 am), three trees were selected in the study. More accurate results would be obtained if more trees were selected, whereas the number of feasible sampling points was usually limited by labor and time in the field measurement. In this study, field measurements were performed from 09:00 am to 11:00 am, and each measurement took about 5 min, giving a total of 90 min for the 18 PVC collars. In addition, these trees were distributed at different locations.

An accurate estimation of soil respiration is essential to evaluating the ecosystem carbon budget in apple orchard. In this study, the mean cumulative soil respiration for apple orchard was calculated with the weighting method. The cumulative soil respiration at 0.5 m-distance was 20, 29, and 35 % higher than the mean value in 2011–2013, respectively. However, the

cumulative soil respiration at 2 m-distance was close to the mean value. Therefore, soil respiration at 2 m-distance could represent the C respired from apple orchard in our study.

## Conclusions

In conclusion, our study showed that soil respiration, cumulative soil respiration and  $Q_{10}$  decreased as the distance from the trunk of representative trees increased. Abiotic factor (soil temperature, soil moisture and fertilizer) could not explain the spatial variation in soil respiration and  $Q_{10}$ , whereas biotic factor (fine root biomass) was the main factor contributing to the spatial variation in soil respiration and  $Q_{10}$ . An accurate estimation of soil respiration is essential to evaluating the ecosystem carbon budget in apple orchard. In our study, soil respiration at 2 m-distance was close to the mean value obtained by weighting method, and it could represent the C respired from apple orchard.

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