



Soil respiration in an irrigated oasis agroecosystem: linking environmental controls with plant activities on hourly, daily and monthly timescales

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Abstract

Aim To investigate the responses of different components of soil respiration to environmental factors at different timescales in a vineyard ecosystem.

Methods The trenching method was used to separate total soil respiration (*TSR*) into autotrophic respiration (*AR*) and heterotrophic respiration (*HR*). Soil respiration rates were measured by an LI-8100 automated flux system.

Results On the hourly scale, there were contrasting responses in *TSR*, *HR* and *AR* to soil temperature at 5 cm (ST_5), with clockwise hysteresis loop responses of *TSR* and *HR* to ST_5 but a counterclockwise hysteresis loop between *AR* and ST_5 . The daily *TSR* didn't exponentially response to ST_5 during the growing season. On the monthly scale, the relationship between *TSR* and ST_5 showed a counterclockwise hysteresis loop. Meanwhile, the diel respiration peak lagged the peak of gross primary productivity (*GPP*), but the monthly peak of *TSR* preceded the monthly peak of

GPP. The daily *TSR* and the daily soil water content at 5 cm (SWC_5) in different months showed a quadratic relationship, but there was an exponential correlation between the monthly *TSR* and the monthly SWC_5 .

Conclusions The relationship between soil respiration and environmental factors derived for a specific timescale cannot be directly applied to other timescales.

Keywords Vineyard · Soil respiration · Soil temperature · Soil moisture · Gross primary productivity · Timescales

Introduction

Soil respiration, as the second largest global carbon flux component of terrestrial ecosystems (ranging from 68 to 98 Pg C yr⁻¹), contributes significantly to the greenhouse effect (Raich and Schlesinger 1992; Raich et al. 2002; Bond-Lamberty and Thomson 2010). Currently, agriculture directly contributes over 20% to global greenhouse gas emissions (IPCC 2013), and the potential of agricultural ecosystems to mitigate greenhouse emissions against a background of global climate change has received extensive attention (Tubiello et al. 2013; Skinner et al. 2014; Beyer et al. 2015; Gelfand et al. 2015; Knox et al. 2015; Lai et al. 2017). A small change in soil respiration processes between crops and the atmosphere may be a major component of atmospheric CO₂ concentration fluctuations and can potentially affect climate change (Reichstein et al. 2003). Thus, it is important to quantify soil respiration from

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agricultural soils and understand the processes of production and fluctuation in soil respiration in agricultural ecosystems.

Principally, total soil respiration (*TSR*) is derived from two major flux components: (1) autotrophic respiration (*AR*), the respiration of roots and their associated mycorrhizal fungi, and (2) heterotrophic respiration (*HR*), the respiration of microorganisms (Metcalf et al. 2007; Moyano et al. 2007). Soil respiration and its components are known to be highly sensitive to soil temperature, soil water content and canopy photosynthesis (Hanson et al. 2000; Davidson and Janssens 2006; Sowerby et al. 2008; Vargas and Allen 2008; Makita et al. 2018). Meanwhile, some studies have reported that the two components of soil respiration respond differently to biotic and abiotic variables (Savage et al. 2013; Song et al. 2015;). Soil temperature is the most important variable in determining soil respiration in most ecosystems, and several exponential models have been developed to describe the response of soil respiration to temperature (Arrhenius 1889; van't Hoff 1898; Lloyd and Taylor 1994). However, phase lag (hysteresis) between the signals of soil temperature and soil respiration has been documented at hourly and seasonal timescales (Tang and Baldocchi 2005; Liu et al. 2006; Riveros-Iregui et al. 2007; Gaumont-Guay et al. 2008; Vargas and Allen 2008; Bahn et al. 2009). There are few studies on the hysteresis of the two different respiration components in response to temperature, and interpretations of the hysteresis mechanism in different ecosystems are still controversial (Högberg et al. 2001; Kuzyakov and Gavrichkova 2010; Phillips et al. 2011; Martin et al. 2012). In addition, *AR* and parts of *HR* appear to be sensitive to carbon substrate supply (e.g., gross primary productivity (*GPP*)) (Vargas et al. 2010; Graham et al. 2012; Han et al. 2014; Makita et al. 2018). Seasonal variations in *AR* and *HR* have been shown to vary with plant species, plant phenology and soil fertility (Tierney et al. 2003; Phillips and Fahey 2009; Steinaker et al. 2010). Furthermore, soil water content is another important variable in controlling soil respiration, as it alters the soil effective porosity and substrate availability (Moyano et al. 2013). Low and high soil water content will reduce soil respiration by limiting substrate availability and blocking CO₂ transport, respectively (Phillips et al. 2010; Zeng et al. 2017). In particular, soil wetting events (irrigation or rain) may stimulate variations in soil respiration, depending on the pulse size and the status of plants and soil microbes during the wetting period (Lee et al. 2004; Moyes and Bowling 2013; Wang et al. 2014a, b). At

present, although studies have focused on the effects of biotic (e.g., *GPP*) and abiotic (e.g., temperature, soil moisture) factors on soil respiration (Buchmann 2000; Han et al. 2007), studies distinguishing the responses of *AR* and *HR* to environmental factors are still rare (Wang et al. 2014a, b).

Soil respiration shows large temporal variability (over hours, days or even seasons) in the field under the influence of different driving factors (Phillips et al. 2010; Hanpattanakit et al. 2015). Previous studies have mainly explored soil respiration patterns at a certain time scale (such as the daily or seasonal scale) or during a specific growth period in forest ecosystems (Tang et al. 2005b; Phillips et al. 2010; Savage et al. 2013; Zhang et al. 2013;), but few studies are based on long-term observations over several years in agricultural ecosystems. Meanwhile, whether the relationships between soil respiration and environmental factors are consistent at different timescales and whether the relationships derived from a specific time scale can be used at other timescales are still unclear. These issues all suggest that long-term, continuous, high-frequency soil respiration observations along with other concurrent data (temperature, soil moisture, precipitation, *GPP*, etc.) are necessary to reveal the underlying causes of the temporal variability in soil respiration (Savage et al. 2009; Vargas et al. 2011; Savage et al. 2014). This is crucial for elucidating the soil carbon dynamics in the context of global warming in agricultural ecosystems.

In this study, we performed long-term continuous observations of total soil respiration (*TSR*), autotrophic respiration (*AR*) and heterotrophic respiration (*HR*) from July 2013 to October 2017 in a vineyard in an oasis in arid Northwest China. The main goals of this study were to (1) characterize the response of *TSR* and its components (*AR* and *HR*) to soil temperature at 5 cm (*ST*₅) soil depth, gross primary productivity (*GPP*) and soil water content at 5 cm soil depth (*SWC*₅) on hourly, daily and monthly timescales and (2) estimate the annual soil respiration and the proportion of *AR* to *TSR* in the vineyard.

Materials and methods

Study site

The experiment was performed in an 11-year-old vineyard in the Dunhuang Nanhu Oasis in Northwest China's Gansu Province (39°52'34"N, 94°06'19"E; Fig. 1a, b). The local climate is temperate continental

climate, with mean annual rainfall and temperatures of 42.2 mm and 12.5 °C, respectively, from 1971 to 2000. Nearly 80% of the precipitation falls between May and September, with the maximum falling in July. The annual total radiation between 5903.4 and 6309.5 MWh m^{-2} , and the annual potential evapotranspiration is approximately 2400 mm. The mean elevation is approximately 1300 m asl in the site, and the topography is flat. At the study site, the soil type is an Arenosol according to the FAO classification (Bai et al. 2015). Grapevine is the most widely cultivated crop in this region because of its great economic and ecological value, and the planting area is increasing year by year.

The experiment observations were carried out in a 450 m × 160 m vineyard. Grapevines (*Vitis vinifera* cv. ‘Thompson Seedless’) were planted in the study plot in rows at spacing of 1 m between the vines and 3 m between the rows. The branches of the grapevines were supported by a 2.5-m-high T trellis. This cultivar grows from April to October, and reaches the maximum in late July or August, becoming senescent in early October. The vineyard was furrow-irrigated every month during the growing seasons, and each irrigation event totaled approximately 225 mm. Fertilization occurred twice a year in May and July with 447.8 kg of nitrogen fertilizer per hectare.

Experimental design and field measurements

We obtained continuous hourly measurements of soil respiration at 9 locations in the study plot using an LI-8100 automated soil CO_2 flux system and an LI-8150 multiplexer using model 8100–104 long-term soil respiration chambers (Li-Cor Inc., Lincoln, NE, USA) between July 2013 and October 2017. For each chamber, a polyvinyl chloride (PVC) soil collar with a height of 11.4 cm and a diameter of 21.3 cm was inserted into the soil, and the upper edge of the collars protruded 3 to 5 cm above the average soil surface. Previous studies have found a significant difference in the soil respiration observed in rows and in interrows (1.25 m away from rows) (Lardo et al. 2015). Therefore, we placed 6 measuring chambers at distances of 50 cm and 3 chambers at 150 cm from the trunks of the grapevines for *TSR* and *HR* observations, respectively. To ensure that there was no root system in the *HR* observation area, the three plots at 150 cm from the trunk were trenched. Each plot was dug along its boundary to 60 cm below the ground surface (most of the root zone of grape is distributed

over 60 cm; Schreiner 2005) with a steel knife. The trench walls were lined inside with four sheets of polyethylene film (each 100 μm thick) to prevent roots from entering. Then, the roots in the excavated soil were removed, and the trenches were backfilled with the same soil. The aboveground parts of all visible living organisms were artificially removed. Each control and exclusion plot was covered with a square iron mesh (Fig. 1c) to prevent litter from falling into the observation ring. The sampling frequency of the measurement was once an hour. We inserted the soil collars in the soil one week before the first measurement to allow the soil to recover from the disturbance and provide an undisturbed measurement of soil respiration.

The soil temperature and soil volumetric water content were measured hourly (TDR probes; Campbell Scientific, Logan, NE, USA) and simultaneously at soil depths of 5, 10 and 20 cm (ST_5 , ST_{10} , ST_{20} , SWC_5 , SWC_{10} , SWC_{20}) (Fig. 1 c). The net ecosystem CO_2 exchange (*NEE*) was measured with a three-dimensional sonic anemometer (Gill Instruments Ltd., Lymington, UK) and an open-path CO_2 / H_2O infrared gas analyzer (LI7500; Li-Cor Inc., Lincoln, NE, USA) installed above the eddy covariance (EC) system at a height of 4 m (see details in Bai et al. 2015; Wang et al. 2019). The sampling frequency of the EC system was 10 Hz, and half-hour fluxes were calculated for CO_2 flux. The EddyPro software package (Version 5.0, www.licor.com/eddypro) was employed for the quality control of the data, including spike detection, coordinate rotation by the planar fit method, sonic virtual temperature conversion, and density fluctuation correction (Mauder et al. 2006). In the spike detection algorithm, half-hourly flux data were excluded if rain fell, instruments malfunctioned or the friction velocity (u^*) was lower than 0.1 m s^{-1} (Zhu et al. 2006). Data gaps were filled using the following method: (1) The short data gaps (<2 h) in a day were filled with the linear interpolation method; (2) larger data gaps were filled using the Michaelis–Menten equation (Supporting Information 1) between the daily *NEE* and the daily photosynthetically active radiation. The coefficients of the Michaelis–Menten equation were determined based on monthly data. Missing nighttime *NEE* values were estimated using the van’t Hoff equation (Supporting Information 1).

We also continuously monitored the wind speed (*WS*), daily photosynthetically active radiation (*PAR*), air temperature (T_a) and relative humidity (*RH*) using an automatic weather station at the site during the

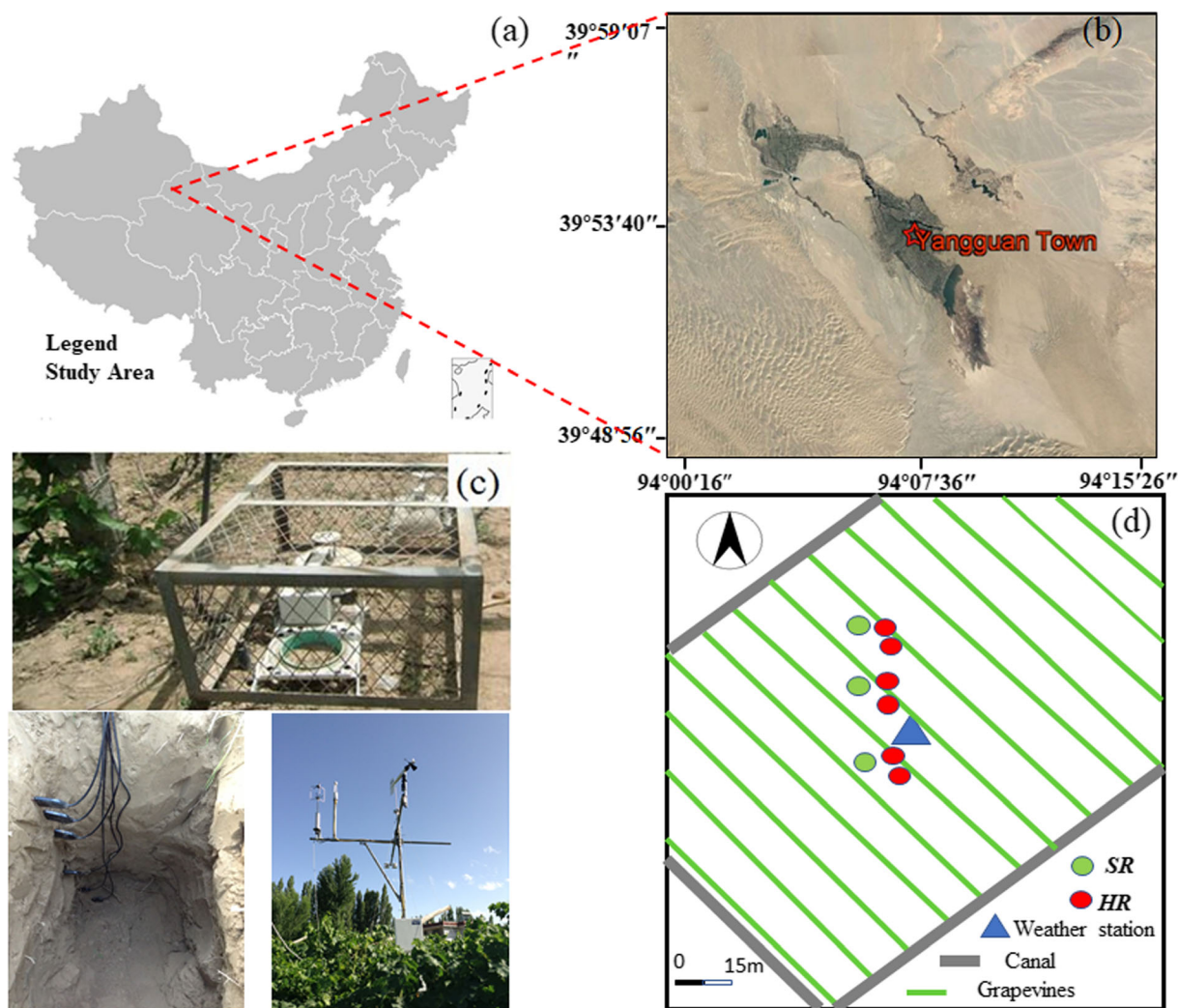


Fig. 1 Overview of the study area: **a** location within China, **b** aerial photograph of the study area, **c** instrumentation (soil respiration chambers, soil temperature and soil moisture sensors, and weather station) at the sample sites; and **(d)** location of the sampling positions

observation period. The leaf area index was measured once a month using a leaf area index meter (LAI2200, Li-COR) during the growing season from April to September. Three layers of soil samples (0–5 cm, 5–10 cm, and 10–20 cm) were collected twice during the early spring and fall of 2015 by soil drilling near the chambers. Table 1 summarizes the physical and chemical properties of the different soil layers at the study site.

Soil respiration model

The following exponential function was used to describe the temperature dependence of soil respiration: (Lloyd and Taylor 1994)

$$SR = ae^{bST_5} \quad (1)$$

where SR is the measured soil respiration (TSR and HR) ($\mu\text{mol m}^{-2} \text{s}^{-1}$), ST_5 ($^{\circ}\text{C}$) is the soil temperature at 5 cm, and a and b are fitting parameters. Q_{10} (temperature sensitivity) represents the relative increase in respiration as the temperature rises by 10°C (Lloyd and Taylor 1994), the temperature coefficient b provides an estimate of Q_{10}

$$Q_{10} = e^{10b} \quad (2)$$

The daily relationship between soil respiration and soil water content can be approximated with a parabolic

Table 1 Soil properties in the three depth layers at the study site

Soil depth	Bulk density Mg m ⁻³	pH	Total N g kg ⁻¹	Organic C g kg ⁻¹	Sand g kg ⁻¹	Silt g kg ⁻¹	Clay g kg ⁻¹
0-5 cm	1.18 (0.03)	8.05 (0.11)	2.43 (0.05)	8.69 (1.02)	305 (47)	408 (43)	287 (31)
5-10 cm	1.16 (0.06)	7.99 (0.08)	2.41 (0.33)	7.71 (0.91)	413 (91)	338 (52)	249 (38)
10-20 cm	1.32 (0.09)	8.02 (0.15)	2.35 (0.15)	6.80 (1.00)	372 (41)	376 (26)	252 (17)

Soil properties were determined using soil cores collected near the CO₂ flux chambers at the end of the experiment (0 to 20 cm in depth). Values in parentheses are the standard deviations of nine chambers

equation (Moyano et al. 2013; Subke et al. 2003; Wood et al. 2013)

$$SR = \beta_0 + \beta_1 \times SWC_5 + \beta_2 \times SWC_5^2 \quad (3)$$

where SR is the measured soil respiration (TSR and HR) ($\mu\text{mol m}^{-2} \text{s}^{-1}$), SWC_5 (%) is soil water content at 5 cm soil depth, β_0 , β_1 and β_2 are fitting coefficients from Eq. (3). The co-variant effects of soil temperature and soil water content on soil respiration were fitted for daily and seasonal scales:

$$SR = (\alpha_1 e^{\alpha_2 ST_5}) \times (\alpha_3 SWC_5^2 + \alpha_4 SWC_5) \quad (4)$$

where SWC_5 (%) is soil water content at 5 cm; α_1 , α_2 , α_3 and α_4 are fitting coefficients from Eq. (4). Moreover, the following exponential model was used to express the seasonal relationship between soil respiration and soil water content (Zhang et al. 2015).

$$SR = e^{(\varepsilon_0 + \varepsilon_1 SWC_5 + \varepsilon_2 SWC_5^2)} \quad (5)$$

where SR is the measured soil respiration (TSR and HR) ($\mu\text{mol m}^{-2} \text{s}^{-1}$), SWC_5 (%) is soil water content at 5 cm soil depth, ε_0 , ε_1 and ε_2 are fitting coefficients from Eq. (5).

We also observed significant effects of ST_5 and SWC_5 and plant photosynthesis (i.e., gross primary production, GPP) on soil respiration at the study site and used a model (Eq. (6)) to simulate and interpolate the daily soil respiration patterns during observation period (Zhang et al. 2018).

$$SR = (c_1 e^{c_2 ST_5}) \times (c_3 SWC_5 + c_4 SWC_5^2) + c_5 GPP + c_0 \quad (6)$$

where SR is the measured soil respiration (TSR and HR) ($\mu\text{mol m}^{-2} \text{s}^{-1}$), GPP is the gross primary productivity ($\mu\text{mol m}^{-2} \text{s}^{-1}$) during the growing season and c_1 , c_2 , c_3 , c_4 , c_5 and c_0 are parameters of Eq. (6). GPP was estimated as (Reichstein et al. 2005)

$$GPP = R_{eco} - NEE \quad (7)$$

R_{eco} is ecosystem respiration ($\mu\text{mol m}^{-2} \text{s}^{-1}$). The net ecosystem CO₂ exchange (NEE) values during the growing season were obtained from eddy covariance tower. The nighttime observed net ecosystem CO₂ exchange NEE was considered as nighttime R_{eco} . Equation (8) establishes the relationship between nighttime R_{eco} and ST_5 .

$$R_{eco} = R_{ref} \times \exp\left(E_0 \left(\frac{1}{(T_{ref} - T_0)} - \frac{1}{(ST_5 - T)}\right)\right) \quad (8)$$

where R_{ref} denotes the ecosystem respiration rate at a reference temperature ($T_{ref} = 10$ °C), E_0 is a parameter associated with the activation energy and determines the temperature sensitivity of R_{eco} and T_0 is a constant temperature parameter (-46.02 °C). The parameters E_0 and R_{ref} were determined by fitting Eq. (8). Then the parameters were applied to determine the daytime R_{eco} . Nighttime R_{eco} plus daytime R_{eco} is all day R_{eco} . The total soil respiration (TSR) is divided into heterotrophic respiration (HR) and autotrophic respiration (AR). The AR is calculated by subtracting the HR from the observed TSR :

$$AR = TSR - HR \quad (9)$$

Statistical analyses

Hourly TSR (or HR) values less than 0 were considered abnormal and were removed from the data set. Instrument failure and the quality control procedures resulted in 28% missing data during the measurements (from July 2013 to October 2017). We averaged the 6 chamber measurements (including ST_5 and SWC_5) that were 50 cm from the trunk as the

TSR and those of the 3 chambers that were 150 cm (including ST_5 and SWC_5) from the trunk as the *HR* to account for spatial heterogeneity. The daily cycles of soil respiration and environmental factors were calculated by averaging the values per hour in each day. The monthly patterns of soil respiration and environmental factors were calculated by averaging the values per day in each month. Regression analysis was used to evaluate the relationships between soil respiration (*TSR*, *HR* and *AR*) and environmental factors (ST_5 , SWC_5 and *GPP*) at different scales. All of the analyses were performed using SPSS 16.0 statistical software (SPSS Inc., Chicago, IL, USA). The significance level was set as 0.01.

Results

Meteorological conditions and soil variables

The continuous soil temperature and soil water content at depths of 5, 10 and 20 cm (ST_5 , ST_{10} , ST_{20} , SWC_5 , SWC_{10} , SWC_{20}), leaf area index and soil respiration (including *TSR*, *HR* and *AR*) from 2013 to 2017 are shown in Fig. 2. The soil temperatures that measured continuously in the three soil layer depths gradually increased from January, reached their highest values in July, and then decreased consistently toward winter (Fig. 2a). The mean daily soil temperature ranged from 14.7 °C (December) to 29.4 °C (July), and the annual mean temperatures was 10.5 °C from 2013 to 2017 (Fig. 2a). The soil temperature at the 20 cm depth (ST_{20}) were slightly lower than the temperatures at the shallow depths. The daily SWC_{20} was significantly higher than that in the shallower layers (SWC_5 and SWC_{10}) during the study periods (Fig. 2b). The daily soil water content at 5 cm depth varied from 6.4% to 28.7%, and the variations were highly correlated with irrigation. During the study period, the vineyard was irrigated once a month during the growing season and each irrigation amount was about 225 mm. There was less precipitation in the study area, annual total precipitation was <70 mm and most of the precipitation occurred between May and September in the study area (Fig. 2b). The leaf area index of the vineyard exhibited minimum values in April ($0.39 \text{ m}^2 \text{ m}^{-2}$), increasing to its maximum in July ($4.5 \text{ m}^2 \text{ m}^{-2}$) and decreasing gradually in the

following three months (Fig. 2c). The daily *TSR* in the vineyard ranged from 0.24 to $8.21 \mu\text{mol m}^{-2} \text{ s}^{-1}$ and varied both daily and seasonally during the study period. Daily *HR* and *AR* had the same trends as *TSR* on daily and seasonal scales and the value of *HR* was greater than the *AR* during the study period growth seasons (Fig. 2d).

Relationship between soil respiration and ST_5 and *GPP* at different timescales

At the hourly scale, soil respiration (*TSR*, *HR* and *AR*) reached a minimum in the early morning hours (7:00) and then increased gradually, coinciding with increasing *GPP* levels. *TSR* and *HR* had maximum values in the afternoon hours (15:00–16:00) and then decreased slightly, while the peak of *AR* lagged the peaks of *TSR* and *HR* and reached maximum values at 20:00 (Fig. 3a). The maximum value of *GPP* occurred between 12:00 and 14:00 during the growing season (April to September) and preceded the peak of soil respiration (*TSR*, *HR* and *AR*) by 3 to 7 h.

The peak of ST_5 occurred at approximately 17:00, which lagged the peak of *TSR* (16:00) by 1 h and lagged the peak of *HR* (15:00) by 2 h. However, the peak of ST_5 preceded the *AR* peak (20:00) by 3 h. Plotting mean hourly respiration against mean hourly ST_5 each day during the growing season, we found that soil respiration (*TSR*, *HR* and *AR*) showed hysteresis loops with ST_5 during the growing season (Fig. 3b). Specifically, the relationship between *TSR* and ST_5 showed a clockwise hysteresis pattern with a narrow cycle loop (lagged 1 h), whereas that between *HR* and ST_5 showed a relatively round clockwise cycle loop pattern (lagged 2 h). In contrast, the relationship between *AR* and ST_5 on an hourly scale exhibited a counterclockwise hysteresis loop, and the peak value of *AR* lagged behind that of ST_5 by approximately 3 h on average during the growing season.

Since *AR* and *HR* have consistent daily and seasonal trends with *TSR* (Fig. 2d), we only considered the relationships between *TSR* and *GPP* and ST_5 (Supporting information II, Fig. 1). On the daily scale, daily *TSR* increased exponentially with daily ST_5 (Eq. (1)) in the nongrowth-season months (no irrigation events) (Fig. 4). However, during the growing season, the exponential model could not describe the relationship between daily ST_5 and daily *TSR* as a result of irrigation

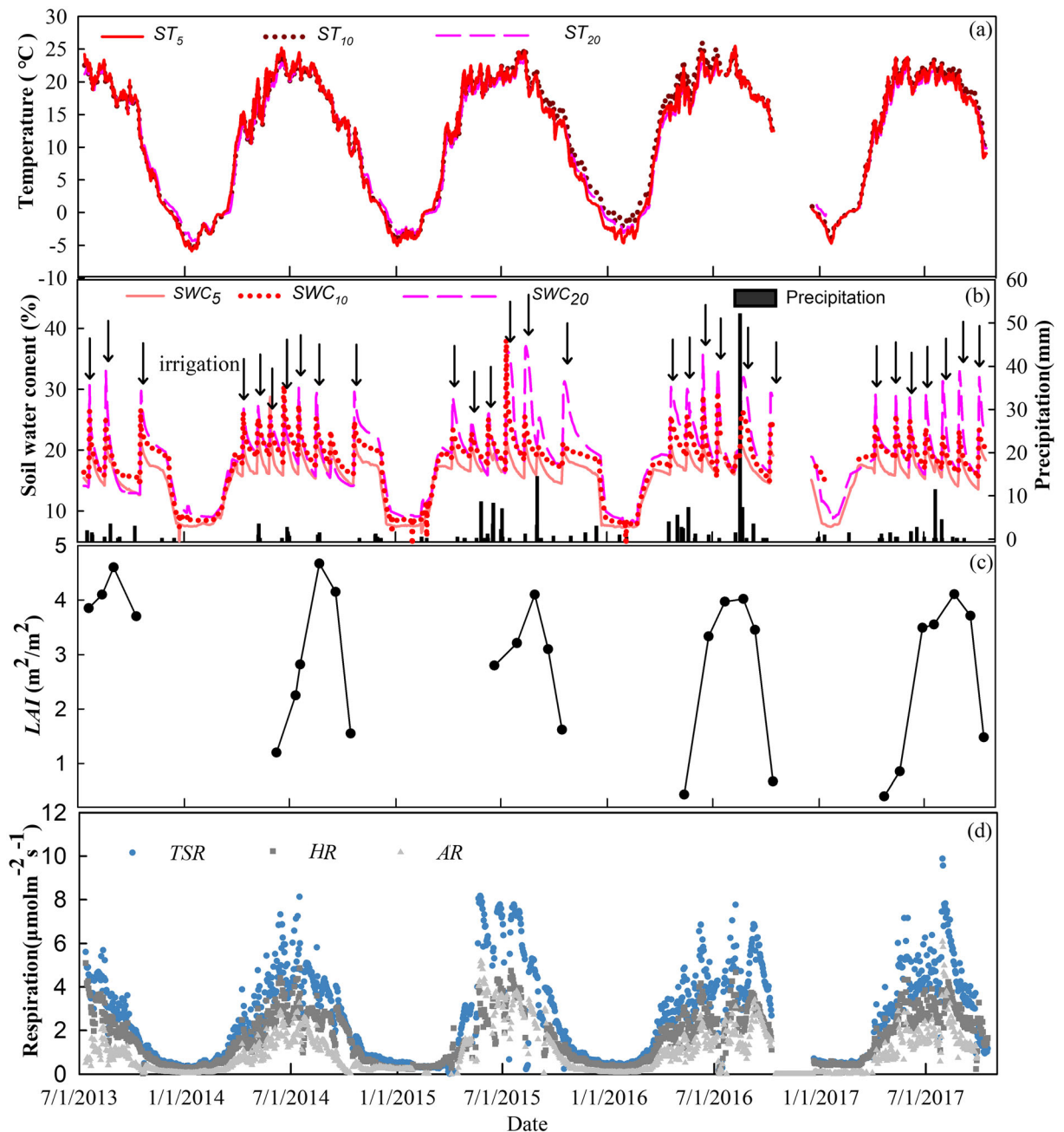


Fig. 2 The variation of key environmental factors and soil respiration during the 2013 and 2017 of the study period. **a** mean daily soil temperature at depths of 5, 10, and 20 cm (ST_5 , ST_{10} , and ST_{20}), respectively. **b** the daily sum of precipitation and mean daily soil water content at depths of 5, 10, and 20 cm (SWC_5 , SWC_{10} , and SWC_{20}), respectively and **(c)** the leaf area index

(LAI) during the growing season of the observation period ($n = 28$); **d** mean daily value total soil respiration (TSR) and its components autotrophic respiration (AR) and heterotrophic respiration (HR) ($n = 1403$). Blue circles indicate TSR, dark grey squares indicate HR and the grey triangles indicate AR

events. On the monthly scale, the relationship between TSR and ST_5 was a counterclockwise hysteresis loop from 2014 to 2017 (Fig. 5a). The value of TSR in

autumn was larger than that in summer at the same temperature. The exponential equation (Eq. (1)) overestimated TSR from January to July but

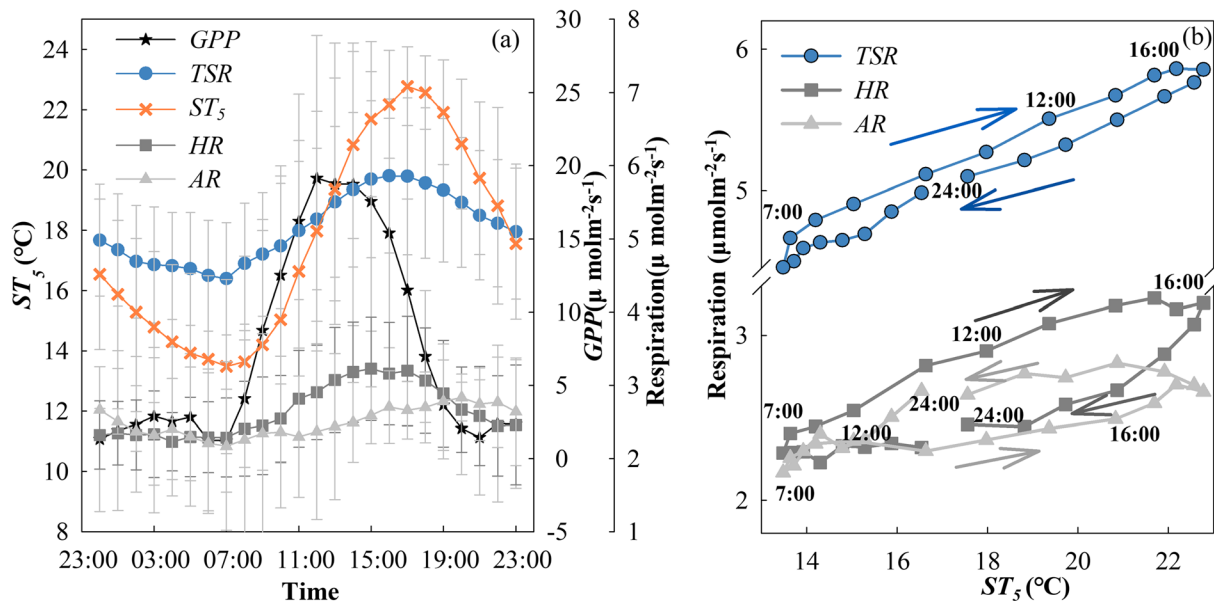


Fig. 3 **a** Hourly variation between soil respiration (total soil respiration (TSR), autotrophic respiration (AR) and heterotrophic respiration (HR)) and soil temperature at 5 cm depth (ST_5) and gross primary productivity (GPP) from April to September 2015. Error bars indicate the standard deviation of the corresponding diel

time from April to September 2015. **b** The diel hysteresis relationships between respiration (TSR , AR and HR) and ST_5 . Blue circles indicate TSR , dark grey squares indicate HR and the grey triangles indicate AR

underestimated TSR from August to December. However, the monthly mean GPP maximum (in August) occurred after the monthly mean TSR maximum (in July), so there was a clockwise hysteresis relationship between GPP and soil respiration from April to October of 2014 to 2017 (Fig. 5b).

Relationship between TSR and SWC_5 at different timescales

In our study, variation in soil water content caused by irrigation affected soil respiration by influencing both root and microbial activities. The irrigation was carried out every month during the growing season and strongly affected the soil respiration. After observing small variations in SWC_5 on the hourly scale, we studied daily changes in TSR and SWC_5 based on each irrigation event during the growing seasons. The daily scale results of the effects of SWC_5 on TSR in different months are shown in Fig. 6. We divided the daily scale by the time of the occurrence of the irrigation event, illustrating that the relationship between TSR and SWC_5 in

different months could be well described by a quadratic polynomial from 2014 to 2017 (Fig. 6). The quadratic polynomial fitting curves for each month were different, and the SWC_5 value at which the maximum TSR rate occurred (the optimum soil moisture content) varied seasonally. The maximum optimal water content was approximately 23%, and the minimum was approximately 18% over the whole study period.

Irrigation significantly affected soil respiration, and Fig. 7 shows an example of the changes in TSR before and after an irrigation event (August 2015). Irrigation in the amount of 225 mm caused the mean daily SWC_5 to increase to approximately 33% and the ST_5 to decrease by 5 °C. At the same time, the TSR dropped significantly (decreased by approximately 93%) for 3 days after irrigation due to the decrease in the diffusion rate and the oxygen supply. Then, TSR gradually increased again until the next irrigation. We also simulated TSR variation without irrigation events based on Eq. (3). The results showed that TSR increased by 40% after irrigation compared to TSR without irrigation.

On the monthly scale, the mean monthly SWC_5 during the nongrowing seasons had a wide range of

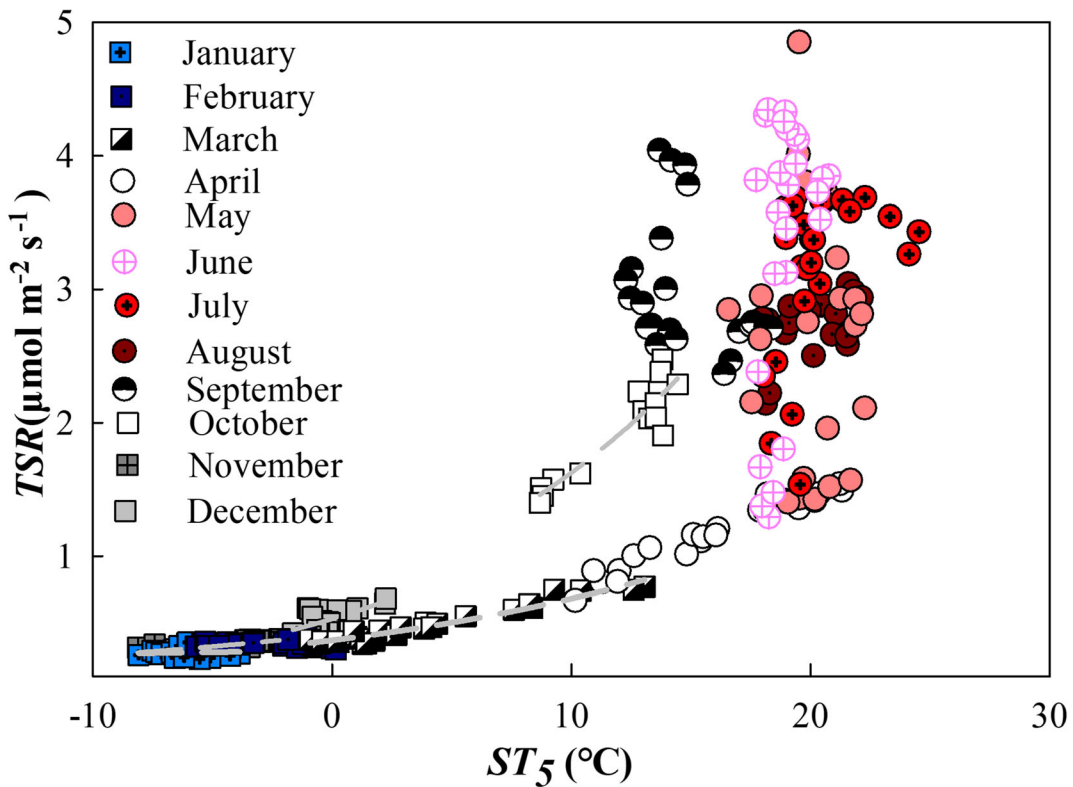


Fig. 4 The relationship between total soil respiration (*TSR*) and soil temperature at 5 cm depth (ST_5) on the daily scale. Each point is the mean daily value for a month in 2015 ($n = 285$)

variation and ranged from 5.1% to 14.2%. However, the mean monthly SWC_5 during the growing seasons had a relatively small range of variation and fluctuated

between 12.3% and 17.5% due to sufficient soil water supply. When the measured *TSR* was plotted against SWC_5 , there was a significant exponential relationship

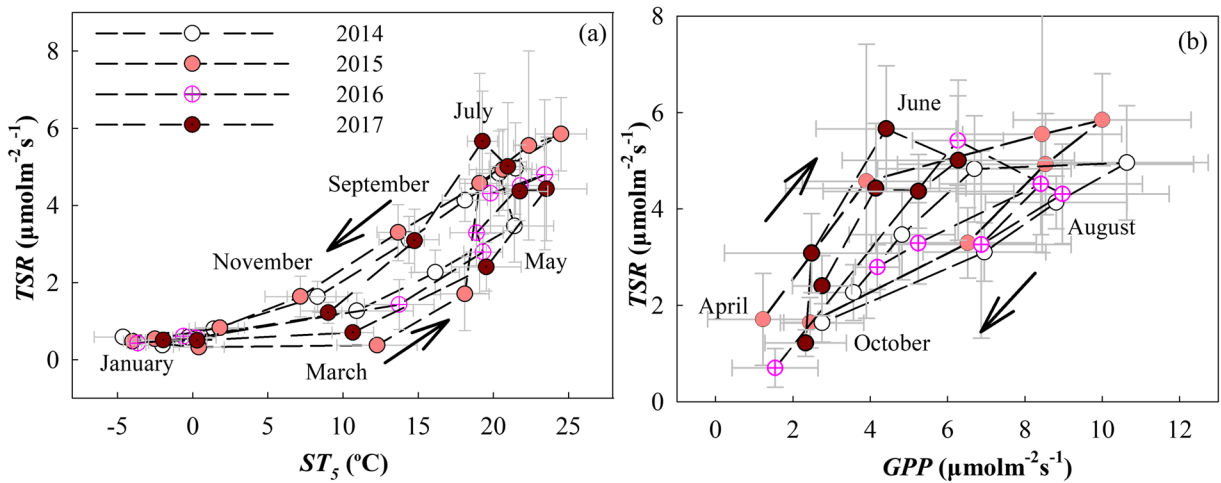


Fig. 5 a Seasonal variation in total soil respiration (*TSR*) and soil temperature at 5 cm depth (ST_5) from 2014 to 2017. **b** Seasonal variation in total soil respiration (*TSR*) and gross primary

productivity (*GPP*) during the growing season from 2014 to 2017. Error bars indicate the standard deviation of monthly *TSR*, ST_5 and *GPP* values from 2014 to 2017

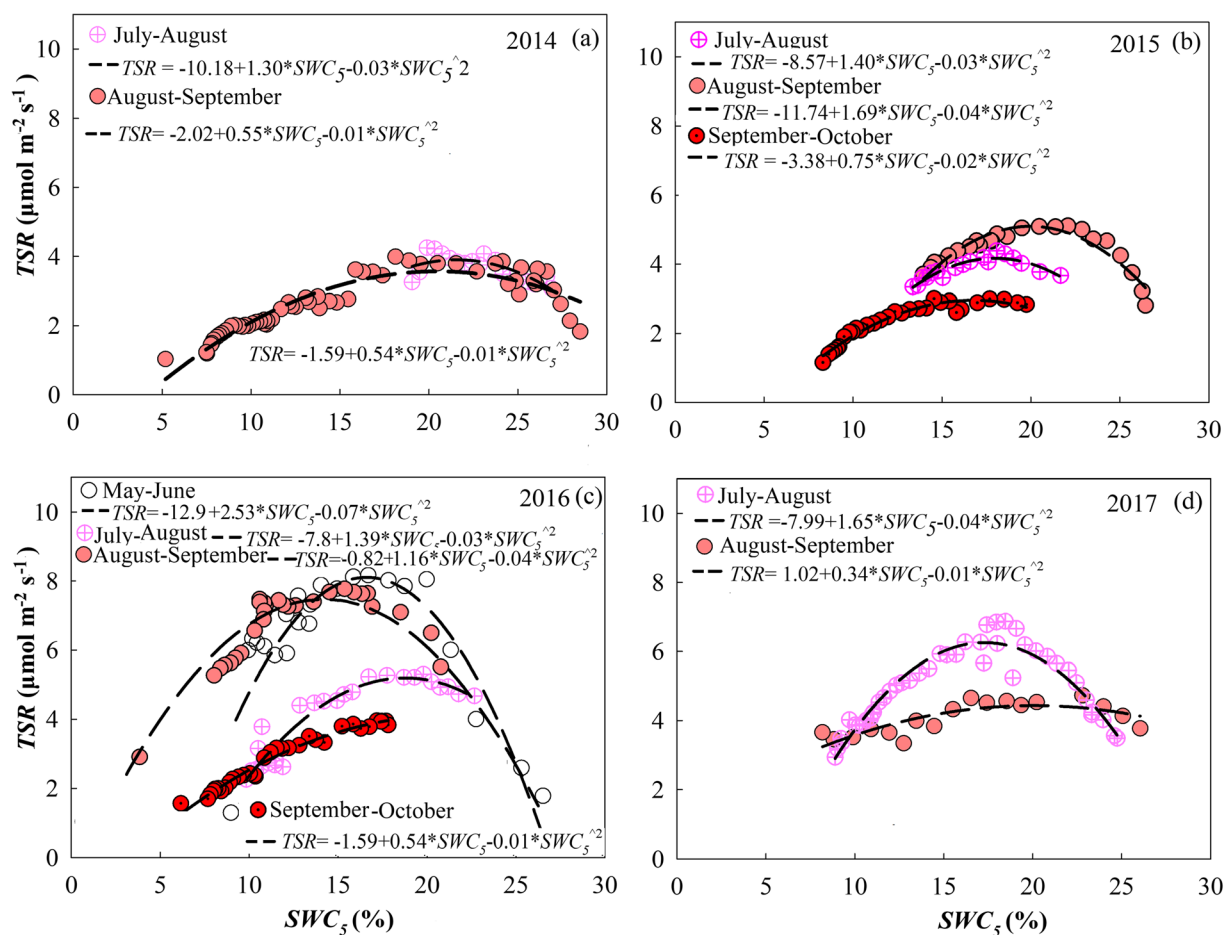


Fig. 6 The relationship between the mean daily total soil respiration (TSR) and soil water content at 5 cm depth (SWC_5) in different months during the growing seasons from 2014 to 2017. The daily

relationship between TSR and SWC_5 from 2014 to 2017 (Fig. 8). The monthly mean SWC_5 can explain 49% to 66% of the seasonal variation in TSR .

Estimation of annual respiration

Due to hourly and monthly hysteresis, the temperature-dependent model (Eq. (1)) was inadequate for predicting soil respiration variations at short-term scales. Compared with the temperature-dependent model, the multifactor model (Eq. (6)) with ST_5 , SWC_5 and GPP as independent variables provided a better estimate of the annual C release. In this study, the multifactor model was used to fit soil respiration variations at different timescales, and the results showed that the multifactor model of soil respiration can explain 65%, 76% and 90% of the hourly, daily and monthly soil respiration

scale was divided by the time of the irrigation event occurrence, and Eq. (3) was used to describe the relationship between daily TSR and daily SWC_5

variation, respectively (Supporting Information III, Table 2). Based on Eq. (6), we interpolated the missing data on a daily scale and calculated the annual TSR and HR for the vineyard. From 2014 to 2017, the annual TSR of the vineyard was 686.89, 702.41, 681.46 and 638.56 (until October) $g\ C\ m^{-2}\ yr^{-1}$, respectively. The AR contributions to TSR from 2014 to 2017 were 31%, 40%, 39% and 36%, respectively, and this contribution ratio was the largest in July and August. According to Eq. (2), the annual Q_{10} of the TSR was 2.44, 2.31, 2.30, and 1.78 from 2014 to 2017, respectively (Table 2).

Discussion

Based on 4 years of continuous observation with automated chambers and an eddy covariance system, we

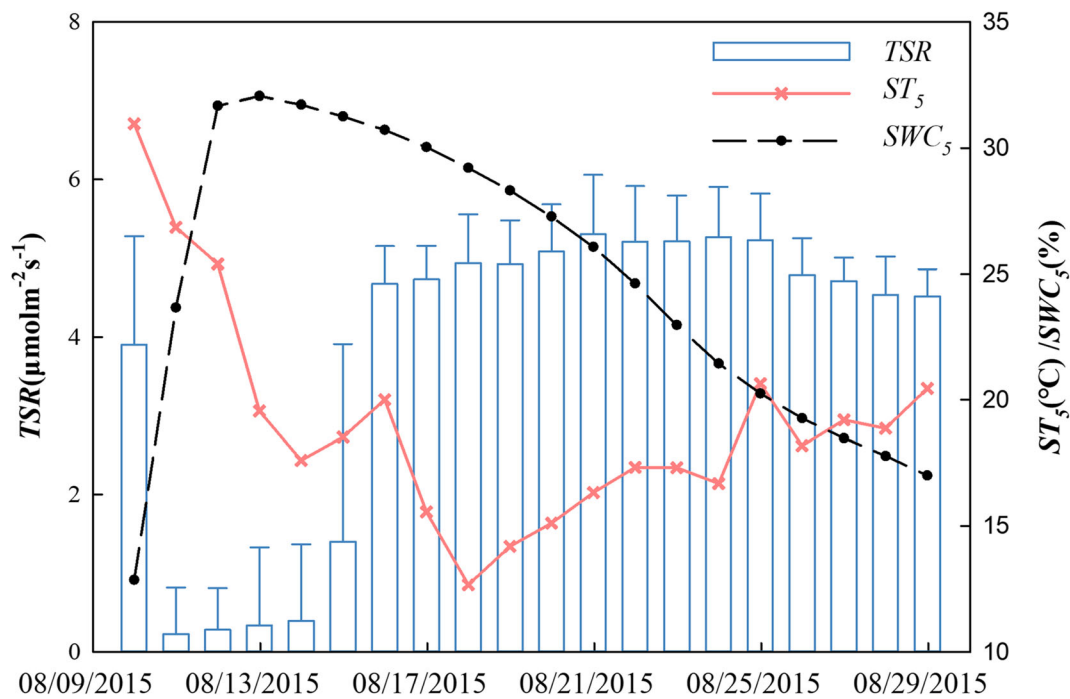


Fig. 7 The effect of an irrigation event on the daily mean total soil respiration (TSR) values. The black line with black circles indicates soil water content at 5 cm depth (SWC_5); the orange line with

red cross symbols indicates soil temperature at 5 cm depth (ST_5); bars indicate total soil respiration (TSR); whiskers indicate daily variability in the total soil respiration (TSR) data

characterized the effects of ST_5 , GPP and SWC_5 on hourly, daily and monthly variations in soil respiration (TSR , HR and AR) in a vineyard in an arid region. This information helps to better explain the relationship between soil respiration processes and environmental factors at different timescales and then to more accurately simulate soil respiration in agroecosystems.

Hysteresis of respiration with GPP and ST_5 on hourly and seasonal scales

Numerous studies have demonstrated the diel hysteresis between soil respiration and soil temperature (Högberg et al. 2001; Tang et al. 2005; Sampson et al. 2007; Gaumont-Guay et al. 2008). However, our research revealed that the HR and TSR peaked earlier than the ST_5 , showing a clockwise hysteresis loop with the ST_5 on the hourly scale. In contrast, the AR peaked later than the ST_5 , showing a counterclockwise hysteresis loop with the ST_5 (Fig. 3a and b). A similar phenomenon has also been observed in desert ecosystems (Song et al. 2015). These results suggest that the factors that control HR response to temperature on an hourly scale are different from the factors that control AR . The time

required to transport photosynthetic C to roots (from hours to a few days) is considered to be the main cause of AR peaking later than ST_5 (Kuzyakov and Cheng 2001; Sampson et al. 2007; Gaumont-Guay et al. 2008; Savage et al. 2013; Song et al. 2015; van Asperen et al. 2017). In this study, GPP , as a surrogate for plant photosynthesis, preceded the AR peak by 7 h, which may be evidence that photosynthesis affects soil respiration (Han et al. 2014). Furthermore, several field studies have found that thermal transport controls the speed at which heat moves through the soil and changes the diel variations in soil temperature, which can explain why HR peaked earlier than ST_5 (Phillips et al. 2011; Zhang et al. 2015).

On the daily scale, there was no significant correlation between TSR and ST_5 during the growing season due to irrigation (Fig. 4), but a counterclockwise hysteresis between monthly TSR and monthly ST_5 was observed at our site (Fig. 5a). At the ecosystem scale, daytime ecosystem respiration based on eddy covariance technology is usually extrapolated from the exponential relationship between nighttime respiration and soil temperature (Flanagan and Johnson 2005; Reichstein et al. 2005). Our results indicated that the

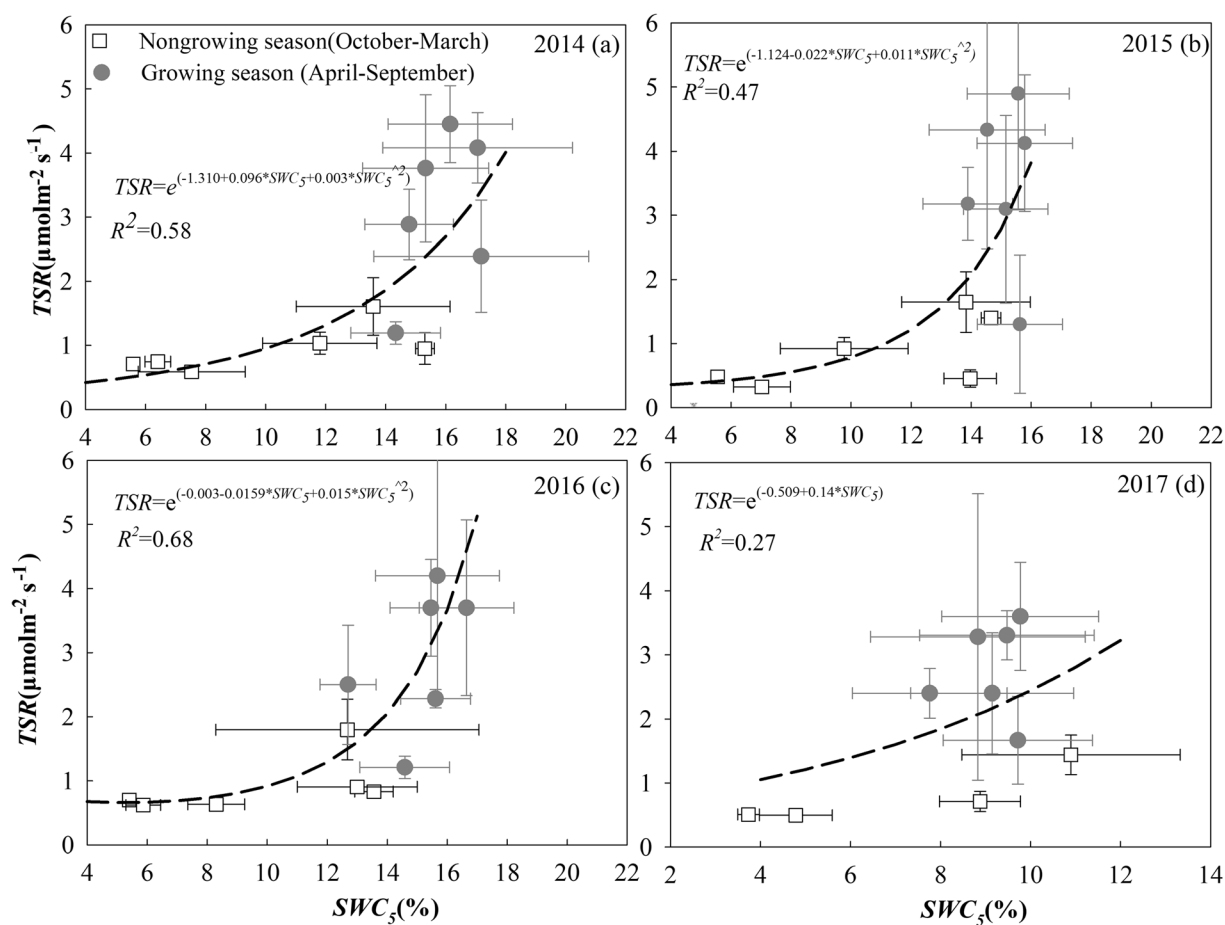


Fig. 8 The relationship between mean monthly total soil respiration (TSR) and soil water content at 5 cm depth (SWC_5) from 2014 to 2017. The circles represent the growing season, and the squares

represent the nongrowing season. Error bars indicate the standard deviations of the monthly TSR and SWC_5 . Equation (5) was used to fit the relationship between TSR and SWC_5 at seasonal scales

hysteresis of soil respiration at hourly and/or monthly scales may result in overestimation of the TSR in spring but underestimation of the TSR in autumn (Fig. 5a). In addition, some researchers have demonstrated that the transport of photosynthates from aboveground tissue to roots varies seasonally and affects the relationship between soil respiration and soil temperature (Savage et al.

2013; Makita et al. 2018). Plant phenology and accumulated photosynthates affect the belowground carbon supply and carbon allocation so that the higher carbon accumulation in the autumn can contribute to a larger TSR than that in spring at similar temperatures (Kuzakov and Gavrichkova 2010; Steenwerth et al. 2010). In vineyards, GPP rapidly increases during

Table 2 Annual total soil respiration (TSR), annual heterotrophic respiration (HR), annual autotrophic respiration (AR), and the contribution of autotrophic respiration to total respiration (AR/TSR),

annual average soil temperature at 5 cm (ST_5), annual average soil water content at 5 cm (SWC_5), and Q_{10} value during observation from 2014 to 2017

Year	TSR ($\text{g C m}^{-2} \text{ yr}^{-1}$)	HR ($\text{g C m}^{-2} \text{ yr}^{-1}$)	AR ($\text{g C m}^{-2} \text{ yr}^{-1}$)	AR/TSR (%)	ST_5 ($^{\circ}\text{C}$)	SWC_5 (%)	Q_{10}
2014	686.89	473.96	212.93	31	10.15	13.14	2.44
2015	702.41	421.45	280.96	40	10.95	13.17	2.31
2016	681.46	415.70	265.76	39	10.85	12.61	2.30
2017 (to October)	638.56	408.68	229.88	36	11.58	12.2	1.78

Table 3 Annual soil respiration in the different croplands

Crop	Experiment site	Location	Soil type	SR (g C m ⁻² yr ⁻¹)	References
Savanna grass	Lone, USA	38°29'N,120°58'W	Sandy loam	394-616	Tang et al. 2005a, b
Grass	Fort Collins, USA	40°39'N,104°19'W	Ustollic Camborthid	288-530	Pendall et al. 2003
Deciduous forest	Harvard Forest, USA	42°32'N,72° 11'W	Typic Distrochrep	760-870	Savage et al. 2001
Deciduous forest	Morgan-Monroe,	39°19'N,86°25'W,	Typic Dystrochrepts	1021-1207	Wayson et al. 2006
Hardwood forest	Mt.Jumbong, Korea, USA	38°02'N,128°06'E	Sandy loam	1070-1109	Kang et al. 2003
Orchard	Loess Plateau, China	35°13'N, 107°40'E	Uniform loam of loess	570	Wang et al. 2015
Maize	Wisconsin, USA	43°18'N,89°21'W	Typic agriudoll	508-534	Zhang et al. 2013
<i>Vitis vinifera</i> . Vine	Coquimbo Region, Chile	30°35'S,71°11'W	Clay	540	Franck et al. 2011
<i>Vitis vinifera</i> . Vine	Napa Valley, California	38°25'N,122°24'W	Bale loam Fine -loamy	1011	Steenwerth et al. 2010
<i>Vitis vinifera</i> . Vine	South of Italy	40°19'N,16° 33'E	Chromi-Luvic Kastanozems	507	Lardo et al. 2015
<i>Vitis vinifera</i> . Vine	Central Italy	43°30'N,12°14'E	Blue-grey clays	996	Brunori et al. 2016
<i>Vitis vinifera</i> . Vine	Napa Valley, California	-	Bale (variant) gravelly loam	702	Carlisle et al. 2006
<i>Vitis vinifera</i> . Vine	Dunhuang,China	39°52'N,94°06'E	Uuniform loam	689	This study

flowering (June–July) (Vivin et al. 2003; Bates et al. 2002), which can significantly increase *TSR*. As a result, the *AR* at our site accounted for a significant fraction of the *TSR* in summer, due to root and aboveground growth (Fig. 2d). Therefore, photosynthesis can affect soil respiration patterns on hourly and monthly timescales (Janssens et al. 2001; Curiel Yuste et al. 2004; Zhang et al. 2013; Makita et al. 2018).

Irrigation events affect seasonal changes in soil respiration

In our research area, irrigation, as the main factor affecting *SWC*₅, controlled the *TSR* monthly pattern. Our results showed that the relationship between *TSR* and *SWC*₅ on a monthly scale can be described by a quadratic curve (Moyano et al. 2013). However, the range of optimal water content in the quadratic function varied monthly. The soil temperatures in different months directly affect soil diffusivity and microbial activity (Hamamoto et al. 2010; Wallenstein and Hall 2012; Moyano et al. 2013; Auffret et al. 2016), which influence soil respiration under different soil water conditions. In addition, the relationship between soil respiration and soil water content is affected by the amount of

water required for plant growth (Reichstein et al. 2003; Wang et al. 2019). Therefore, considering the optimal moisture content in different months is needed for a more accurate model of daily soil respiration patterns. Interestingly, in our study, there was an exponential correlation between the *SWC*₅ and *TSR* on a monthly scale. This result is related to the synchronization of high soil temperature and high soil water content in the arid environment. The temperature effect is manifested only when there is sufficient soil water content to permit significant root and microbial respiration (Wildung et al. 1975; Reichstein et al. 2003). More importantly, the effect of soil water content on soil respiration in our study has been demonstrated to be different at daily and monthly timescales. We therefore suggest that, similar to soil temperature, soil water content has a specific relationship with soil respiration at certain scales.

The effect of soil water content from irrigation on soil respiration is also related to the irrigation methods, irrigation amount and soil conditions before irrigation (Jabro et al. 2008; Grünzweig et al. 2009; Steenwerth et al. 2010). In our study area, *TSR* increased 40% after flood irrigation events, but this increase was less than that caused by drip irrigation (Guo et al. 2017). The

225 mm irrigation amount inhibited *TSR* within 3 days as the result of the physical displacement of soil CO₂ by water after irrigation in our experiment, but then the *TSR* gradually increased as soil water content decreased to the optimal soil water content range. Previous researchers have found that 10–25 mm of rainfall or irrigation caused a significant increase in soil respiration within a few days, but the soil respiration decreased afterwards (Liu et al. 2006; Grünzweig et al. 2009). Therefore, irrigation strategies may be very important for influencing CO₂ emissions, and careful irrigation management will help minimize the loss of C to the atmosphere (Wang et al. 2019).

Annual soil respiration

Grapevines, as **deciduous** woody **vines**, have different soil respiration intensities than other crops and forest vegetation types. The temporal variations in soil respiration in vineyards could be better explained by a multifactor model (Eq. (6)), indicating that the temporal variations in soil respiration were coupled to biotic and abiotic factors. However, the multifactor model could not explain all the variation in soil respiration at different timescales, and other environmental drivers, such as stand openness, plant physiology and the quantity and quality of dead organic matter, may all affect soil respiration patterns (Kirschbaum 2004; Han et al. 2019). The annual Q_{10} varied between 1.78 and 2.44 in our site from 2014 to 2017, which was similar to the mean value deduced from a global survey of soil respiration (Raich and Schlesinger 1992) and consistent with previously reported values for several forest ecosystems (Yuste et al. 2003; Savage et al. 2009). Similar to other research results (Flanagan and Johnson 2005), the annual value of Q_{10} in our study declined with increasing annual mean temperature. During the growing season, the importance of temperature might decrease, and other parameters, such as root growth or variation in leaf area index, might increase in significance in controlling *TSR*.

During the observation period, the mean annual rate of *TSR* was 688 g C m⁻² yr⁻¹, which was much higher than the rates obtained from other cropping systems, such as rotation planting winter wheat fields (Zhang et al. 2013) and a range of annual crops (Wang et al. 2015), but lower than the results obtained from temperate forests (Savage and Davidson 2001; Wayson et al. 2006) (Table 3). This suggests that using forest parameters in the model may overestimate soil respiration in

the vineyard, but underestimation will occur if the parameters of an annual crop are used. In our study, the average contribution of *AR* to *TSR* during the observation period was 36.5% during the growing season. That result was lower than that for temperate forest (45–50%) (Wang and Yang 2006) but higher than that in other agricultural soils (e.g., a winter wheat field, 32%) (Zhang et al. 2013). The thicker root diameters of grapevines may cause higher physiological activities of root growth and belowground C allocation (Franck et al. 2011). However, this ratio may be slightly overestimated for *AR* because *HR* was measured in the trenched plots where the soil organic matter changed in amount and quality without roots or rhizodeposits. Some studies have shown that the number of microorganisms in the rhizosphere is 19 to 32 times larger than that in root-free soil (Bodelier et al. 1997; Kuzyakov 2002), and soil organic matter decomposition in rooted soil is faster than that in root-free soil.

Conclusions

The results of our field experimental studies have important implications for a more accurate estimation of the agricultural carbon cycle. First, there were contrasting responses of two components of soil respiration to soil temperature on an hourly scale, with a clockwise hysteresis loop for *HR* but a counterclockwise hysteresis loop for *AR*. On the monthly scale, soil respiration and soil temperature also showed a hysteresis relationship. Studies that fail to consider the hysteresis of soil respiration and soil temperature at hourly or monthly scales may underestimate or overestimate respiration. In addition, photosynthesis affects soil respiration and patterns at hourly and monthly timescales, and this variation in the hourly and monthly contribution of roots should be better quantified. Last, soil water content from the irrigation system exhibited different functional relationships with soil respiration at different timescales. Distinguishing the relationships between soil water content and soil respiration at different scales would help to more accurately simulate soil respiration in irrigation systems. Overall, we found that the responses of soil respiration to different environmental factors are different at different timescales and that the relationship between soil respiration and environmental factors derived for a certain timescale cannot be directly applied to other timescales.

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