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## Growing Season Carbon Dynamics and Stocks in Relation to Vine Ages under a Vineyard Agroecosystem in Northern China

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### ABSTRACT

An agroecosystem is considered a large stationary source where CO<sub>2</sub> can be captured from emissions through carbon stock in both crop plants and the soil. The aim of this study was to evaluate seasonal changes in the quantity of carbon effluxes and stocks in the vineyard agroecosystem. Three different vine ages (5, 10 and 18 years) were used to estimate the seasonal dynamics of CO<sub>2</sub> effluxes and stocks in both the grapevine and soil parts during the 2011 growing season. This study shows that daily carbon gain and carbon use efficiency to daily climatic and soil variables were varied among vine ages throughout the season. In addition, the seasonal carbon stock in vine dry matter production was significantly increased from the youngest to oldest vines, being highest in the 18 year old vines. The decomposition rate of organic carbon from litter and residues also showed significant differences among vine sites and seasonal changes. Despite the different carbon stocks in the vine biomass among the three vine ages, the amount of total soil organic carbon mostly remained stable among the three vine sites. The relationship between vine ages and total carbon stock in the vineyard could then be estimated by fitting a power function ( $y = 36.72x^{0.2577}$ ,  $r^2 = 0.998^*$ ). This study indicates that carbon effluxes and the potential carbon stock in the vineyards fluctuated seasonally according to vine ages.

**Key words:** Net ecosystem exchange, gross primary productivity, carbon efflux, soil carbon, sustainable management practice, carbon use efficiency, carbon sequestration

### INTRODUCTION

Agricultural land use for crop production is an important carbon (C) sink. CO<sub>2</sub> can be stored in crop plants and soil and it can be estimated along with other greenhouse gases (GHGs) for the mitigation potential of the agricultural sector (Smith *et al.*, 2007). More importantly, fruit orchards are an important part of agroecosystems, especially vineyards which are ecological management strategies defined by the farmers' management practices and farming systems according to the International Organization for Biological and Integrated Control (IOBC) (Malavolta and Boller, 1999).

Typically, the processes of plant photosynthesis and respiration represent the largest C effluxes in the ecosystem (Connor *et al.*, 2011). In the case of living plant parts, C storage mainly results from the photosynthesis process which varies diurnally and seasonally in response to variations of

climate conditions (Griffis *et al.*, 2003). Accordingly, in part of the soil, C has been suggested to have great potential for storage in the ecosystem as Soil Organic Carbon (SOC) (Pibumrung *et al.*, 2008). C is stored in soil under ecosystems through decomposed litter production from plant material (Wells, 2011). Meanwhile, some C sections have become mineralized and released from the ecosystem by microbial and root respiration (Fukuzawa *et al.*, 2012). The return of organic residues to the soil through the decomposition rate of litterfall is also an important determinant in the renewal capabilities of agroecosystems (Murovhi *et al.*, 2012).

In addition to seasonal variation, there are numerous crop models that provide a direct link between models and agrometeorology to estimate seasonal C efflux and C balance (Pallioti *et al.*, 2004; Lakso *et al.*, 2008). Crop models are also used for fruit trees to estimate C allocation based on the responses of crop growth and yield during the seasonal changes in management and environmental factors (Genard *et al.*, 2008). Modeling can then be applied as a tool to evaluate the potential C stock in an agroecosystem as a function of climate and soil conditions such as in apple orchards (Wu *et al.*, 2012), coffee (Hergoualch *et al.*, 2012), olives (Villalobos *et al.*, 2006), peaches (Sofa *et al.*, 2005) and vineyards (Orlandini *et al.*, 2008).

Vineyard agroecosystems have resulted in high levels of C pools in vines (Pallioti *et al.*, 2004) or in the soil (Steenwerth and Belina, 2008). Similarly, vines are frequently exposed to different light intensities and temperature ranges as the local climate leads to the limitation of vegetation growth and C cycles (Lebon *et al.*, 2004). Moreover, vineyards are most likely becoming one of the world's most important agroecosystems, totaling 7,500,000 ha in area and 70 million tons in production (OIV, 2012). Accordingly, China is among the top ten nations in vineyard area. In recent years, China has seen a rapid expansion of domestic vineyards, with the total vineyard area covering more than 450,000 ha in 2009 (National Bureau of Statistics of China, 2009).

The primary objective of this study is to quantify seasonal changes in the quantity of C effluxes and stock from grapevines and within the soil throughout the growing season according to farming and management practices. Therefore, this study focuses mainly on the potential role of vineyard agroecosystems in northern China to evaluate the different vine ages and the sequestration of C.

## MATERIALS AND METHODS

**Experimental site and plant material:** The study was performed during the 2011 growing season (late April-September). The experiment was conducted in a commercial vineyard ( $\approx 1$  ha) in the Beijing region of China ( $39^{\circ}73'N$ ,  $116^{\circ}33'E$ ). The vineyard was separated into three different sites (5-, 10- and 18-year-old vines) based on the same variety of vineyard. Each site ( $60 \times 50$  m<sup>2</sup>) was planted with a hybrid vine cultivar (*Vitis vinifera* L.  $\times$  *Vitis labrusca* L. 'Kyoho'). Each vine was trained with a Y-shape trellis system under a planting density of approximately 4,000 vines ha<sup>-1</sup> ( $0.70 \times 3.00$  m<sup>2</sup>). In addition, a drainage irrigation system was used in the field when the broken-bud stage began with a monthly frequency, but lighter irrigation was used at the beginning of the harvesting stage.

**Climate and soil in the vineyard:** The hourly datasets of Photosynthetically Active Radiation (PAR), air temperature ( $T_a$ ) and soil temperature ( $T_s$ ) were monitored continuously by the data logger of a micro weather station (H21-002 Data Logger, Onset HOBO, Massachusetts, USA) with a PAR sensor (S-LIA-M003) and a 12 bit temperature smart sensor (S-TMB-M006). Volumetric soil water content ( $\Theta_v$ ) was measured using a thermocouple (U12-014 Data Logger, Onset HOBO, Massachusetts, USA) with a 10HS-soil moisture smart sensor (S-SMD-M005). The hourly climate

dataset was analyzed using Data Assistants (HOBOWare® Pro software, Onset HOBOWare, Massachusetts, USA) to calculate CO<sub>2</sub> effluxes in the vine leaves and the soil at a 10 cm soil depth.

**Soil sampling and measurements:** The soil samples were collected randomly from each site at soil depths of 0-20, 20-40 and 40-60 cm. To analyze the soil properties of each site, five soil core samples were collected using a soil auger (10 cm diameter). Three soil samples representing the same depth were analyzed for soil texture, pH and bulk density (oven-dry mass per unit volume). SOC was determined using the Walkley and Black method (Schumacher, 2002) at three time intervals: after harvesting the 2010 growing season (October 2010) (S1), at the beginning of the 2011 growing season (March 2011) (S2) and after harvesting the 2011 growing season (October 2011) (S3). The soil samples were mostly classified as clay loam at the 20 cm soil depth while the mean soil pH and bulk density varied from 7.69±0.03-7.98±0.05 and 1.10±0.07-1.55±0.05 g cm<sup>-3</sup> at the 0-60 cm soil depth (Table 1). For soil management, chemical fertilizer (N-P-K) (20-10-15/46-0-0) was applied in the beginning of the spring season (late March). Chicken manure was applied in each row of the vineyard to add organic matter to the soil and improve the overall health of the soils. Weeds in the row were removed by hand while the regrowth of weeds between the rows was occasionally controlled by the application of herbicides. After harvesting and pruning in the late season, the grape vines were laid down and covered with the mounded soil to protect them from the cold winter by moldboard plowing of the vineyard rows at a depth of 30 cm.

**Estimation of cumulative C gain in grapevines:** To calculate the cumulative amount of C gain per ground area (m<sup>2</sup>), the Daily Carbon Gain (DCG) was estimated as a gas exchange rate at the above- and belowground leaf and soil-root levels. Photosynthesis rates were randomly measured from the middle shoots of three grapevines of each vine age in every month under an altered

Table 1: Soil properties and soil management practices in the vineyard sites

Characteristic	Soil depth (cm)	Site (years)		
		5	10	18
<b>Soil properties</b>				
Soil texture	20	Clay loam	Clay loam	Clay loam
	40	Loam	Loam	Clay loam
	60	Clay loam	Clay loam	Clay
pH	20	7.73±0.01	7.79±0.04	7.81±0.05
	40	7.90±0.03	7.83±0.03	7.71±0.05
	60	7.83±0.01	7.98±0.05	7.69±0.03
Soil bulk density (g cm <sup>-3</sup> )	20	1.44±0.07	1.10±0.07	1.22±0.04
	40	1.52±0.07	1.22±0.10	1.55±0.05
	60	1.35±0.01	1.25±0.07	1.38±0.07
<b>Soil management practices</b>				
Chemical fertilizers: Total nitrogen				
(20-10-15/46-0-0) (kg ha <sup>-1</sup> )		300	400	600
Chicken manure (kg ha <sup>-1</sup> )		400	500	600
Tillage (moldboard plowing)		Once/season	Once/season	Once/season
Weed control (herbicides/hand weeding)		2-3 times/season	2-3 times/season	2-3 times/season

Values presented here are means and standard deviation

ambient LED light source (6400-02B) using a portable photosynthesis system (LI-6400XT, Li-Cor Inc., Lincoln NE, USA). The empirical constants of a nonrectangular hyperbola curve fitting of monthly photosynthetic light responses were used to calculate photosynthetic acclimation to the light environment of the vine leaves (Evans *et al.*, 1993; Thornley, 1998). In addition, the respiration-temperature responses of the leaves were calculated as a proportion of the maximum photosynthetic rate ( $P_{max}$ ) at different leaf temperatures, as modeled by Wythers *et al.* (2005). Therefore, DCG can be calculated by Eq. 1:

$$DCG = \left[ \{(P_n + R_{sr})(t_{light})\} - \{(R_d - R_{sr})(t_{dark})\} \right] (12) / \text{vine} \quad (1)$$

where, DCG is the daily C gain ( $\text{g C vine}^{-1}$ ),  $P_n$  is net photosynthesis rate ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$ ),  $R_{sr}$  is the soil-root respiration ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$ ) as the hourly duration of the light period ( $t_{light}$ ) and  $R_d$  is dark respiration ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$ ) as the hourly duration of the dark period ( $t_{dark}$ ). The molar weight of the C was  $12 \text{ g mol}^{-1}$ , adapted according to Timlin *et al.* (2006). These estimated data were then used to calculate the mean C gain by scaling of the land surface area basis ( $\text{g C m}^{-2}$ ) over the growing season. Furthermore, the Carbon Use Efficiency (CUE) ( $\text{mol C gain mol}^{-1} \text{ C fixed}$ ) was obtained as the DCG divided by the daylight duration of gross photosynthesis ( $P_{gross}$ ) ( $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$ ) from the same time period (Frantz and Bugbee, 2005).

**Soil CO<sub>2</sub> efflux analysis:** The soil-root Respiration ( $R_{sr}$ ) was measured using a soil CO<sub>2</sub> efflux chamber (LI-6400-09) with an LI-6400XT soil CO<sub>2</sub> efflux system (LI-6400XT, Li-Cor Inc., Lincoln NE, USA). Two soil collars (10 cm diameter) per vine were placed at a 5 cm soil depth on opposite sides under the canopy area of the vine. Three vines at each site were used to measure the  $R_{sr}$  between 08.00 and 16.00 h on a clear day once a month.  $T_s$  was also measured adjacent to the soil collar using a soil temperature probe (6000-09TC, Li-Cor Inc.). Soil moisture was measured using a portable soil moisture meter (TRIME-FM TDR, IMKO, Ettlingen, Germany) at the same sampling time. The relationship between  $R_{sr}$  and  $T_s$  was calculated according to the exponential Eq. 2:

$$R_{sr} = a \cdot \exp(bT_s) \quad (2)$$

where,  $R_{sr}$  is soil-root respiration ( $\mu\text{mol m}^{-2} \text{ sec}^{-1}$ ),  $a$  and  $b$  are the constants and  $T_s$  is soil temperature ( $^{\circ}\text{C}$ ) (Lloyd and Taylor, 1994). The mean hourly soil CO<sub>2</sub> efflux was then estimated throughout growing season by fitting with the interaction of the  $R_{sr}$  response to  $T_s$  changes at a soil moisture ranging from 13-27% during the study period, as described by Huang *et al.* (2005).

**Organic carbon decomposition and accumulation analysis:** The accumulation of Organic Carbon (OC) in the vineyard floor was estimated from the decomposition of two different parts: plant parts remaining in the soil surface (litter, weeds and vineyard pruning residues) and covered manure storage at a 30 cm soil depth along the vineyard rows, based on the management practices of farmers. The double-exponential model was used to estimate the existence of available C between the two pools with different resistance against microbial degradation as a best-fitted mineralization kinetic model by Sleutel *et al.* (2005) Eq. 3:

$$C_i = C_{A,s} [1 - \exp(-k_r t)] + C_{A,s} [1 - \exp(-k_s t)] \quad (3)$$

where,  $C_t$  is the accumulation and storage of C mineralization, present at time t.  $C_{A,f}$  and  $C_{A,s}$  are the turnover of C pools with fast and slow turnover rates. Both  $k_f$  and  $k_s$  are the rate constants of a decomposable part of SOC pools.

**Plant biomass sampling analysis:** Five sampled vines were randomly selected in each site for biomass partitioning analysis. To evaluate the C stock in the aboveground biomass in relation to vine ages, five selected shoots and bunches in grapevines were marked with plastic tags and measured for growth development every month. In addition, the root sizes (<5 mm diameter) of three vines in each site were assessed by an image processing method, as described by Metcalfe *et al.* (2007). Two columns per vine of 90 cm long minirhizotron tubes (5 cm diameter) at a 45° angle from vertical alignment were set up on opposite sides. Images of fine root settlement in the soil surrounding the tubes were recorded up to a 60 cm soil depth from the soil surface using a WinRHIZO Tron (WinRHIZO Tron, Regent Instruments, Quebec, Canada). Then, the mean of the root length density ( $\text{cm}^2$ ) was analyzed using commercial WinRHIZO Tron® software. Other sampled roots were collected using a soil auger at a 20 cm interval from the soil surface to a 60 cm depth. After the soil was washed out of all of the roots, the fresh weight, length and diameter were individually recorded based on the root diameter classification (0.5-5 mm range). All images were taken with calibration scaling by a digital camera (DSC-P100, Sony, Tokyo, Japan) at a resolution of 1280×960 pixels. Then, after dry weighing, the individual dry weight per root volume ( $\text{mm}^3$ ) was used for calibration with root length measurements which were made by the WinRHIZO Tron every month at the same location surrounding the tube. Finally, the root biomass per soil volume from each vine ( $0.23 \text{ m}^3$ ) was calculated.

To determine weed biomass and litter production, five sample locations in each site of weeds and vineyard pruning residues were randomly taken in  $1 \text{ m}^2$  quadrats between the rows. All samples on the ground surface were oven dried at  $70^\circ\text{C}$  for 72 h and recorded every month.

The whole plant biomass was separately harvested into bunches, leaves, shoots, stems and roots by a destructive method at the harvesting stage. In each treatment replicate, three vines of similar size were excavated up to a 60 cm soil depth. Furthermore, 1 year old seedlings were also destructively sampled for the initial value of biomass accumulation in different vine ages. All fresh samples were weighed in the field while the dry weight of each part was oven dried at  $70^\circ\text{C}$  for at least 72 h until constant weight and used to calculate the whole dry mass of the vine. Then, a correlation analysis of the relationship between stem biomass and stem size was carried out to calculate the changes in stem biomass per year which varied from 1-18 years old.

**Assessment of total C stock in the vineyard:** To assess the C stock in the vine biomass and soil, the total C stock was calculated as the change in total vine above- and belowground biomass, including the accumulation of SOC and litter production for the vineyard with increasing vine ages. All measurement values can be calculated as Eq. 4:

$$CS_T = \sum_{i=1}^n (C_{Ti} B_{Ti}) + \sum_{j=1}^n (C_{Lj} B_{Lj}) + \sum_{i=1}^n (C_{si} B_{Di}) \quad (4)$$

where,  $CS_T$  is the total C stock in vineyard site ( $\text{Mg ha}^{-1}$ ).  $C_{Ti}$  is the C concentration in vine tissue i (leaf, bunch, shoot, stem and root) (%).  $B_{Ti}$  is the parts of vine biomass i (leaf, bunch, shoot, stem

and root) ( $\text{Mg ha}^{-1}$ ).  $C_{L_j}$  is the C concentration in litter production (%).  $B_{L_j}$  is the litter production on the soil surface ( $\text{Mg ha}^{-1}$ ).  $C_{S_1}$  is the SOC concentration of the mineral soil (%).  $BD_1$  is the soil bulk density at a 0-60 cm soil depth ( $\text{g cm}^{-3}$ ), calculated according to Zheng *et al.* (2008). The C content for living vine parts was assumed to equal 45.30% of the dry mass (Gokbayrak *et al.*, 2009). The equation could then be calculated by fitting a power regression to the relationship between vine ages and C stocks in the grapevines and vineyard.

**Statistical analyses:** The statistical analyses were performed using SPSS 15.0 (SPSS Inc., Chicago, USA). Two-way analysis of variance (ANOVA) was used to compare the mean differences in vines and seasons for all the measured parameters. Pearson's correlation and simple linear regression procedures were also used to examine significant differences in the relationships between vine ages and C stock parameters. All statistical tests were considered significant at  $p \leq 0.05$  using Tukey's HSD (honestly significant difference) test.

## RESULTS

**Seasonal microclimate characterization in the vineyard:** The hourly continuous incident PAR,  $T_a$ ,  $T_s$  and  $\Theta_v$  in the vineyard are shown in Fig. 1. As the microclimate curves, mean hourly PAR had been slowly decreased since May ( $909.23 \pm 244.71 \mu\text{mol m}^{-2} \text{sec}^{-1}$ ) until the harvesting stage in September ( $646.08 \pm 240.32 \mu\text{mol m}^{-2} \text{sec}^{-1}$ ) (Fig. 1a). Meanwhile, the mean hourly  $T_a$  values increased with time until they reached their highest value in July ( $33.16 \pm 3.83^\circ\text{C}$ ), then gradually declined again until September ( $25.32 \pm 6.45^\circ\text{C}$ ) (Fig. 1b). Although the mean hourly  $T_s$  increased or decreased with a pattern similar to  $T_a$ , the high temperature ranged from  $30.34 \pm 2.67$ - $31.50 \pm 2.32^\circ\text{C}$  during June-August. The lower  $T_s$  similarly occurred in May and September ( $24.26 \pm 3.67$  and  $25.06 \pm 4.11^\circ\text{C}$ , respectively) (Fig. 1c). During the same period, although the lowest mean hourly  $\Theta_v$  was observed throughout June ( $0.11 \pm 0.04 \text{ cm}^3 \text{ cm}^{-3}$ ), the range for the mean hourly  $\Theta_v$  was  $0.21 \pm 0.03$ - $0.25 \pm 0.01 \text{ cm}^3 \text{ cm}^{-3}$  between July and September (Fig. 1d).

**CO<sub>2</sub> effluxes in grapevines and soil:** The dynamics of the CO<sub>2</sub> effluxes in the grapevines and soil are shown in Fig. 2. The highest  $P_n$  was found in June in both 5 and 10 year old vines ( $13.52 \pm 2.96$  and  $12.73 \pm 3.72 \mu\text{mol m}^{-2} \text{sec}^{-1}$ , respectively). The significant lowest  $P_n$  rate was found in May in either 10 or 18 year old vines ( $8.30 \pm 1.40$  or  $7.14 \pm 1.18 \mu\text{mol m}^{-2} \text{sec}^{-1}$ ) ( $p \leq 0.001$ ), as obtained by the values for daytime (Fig. 2a). Meanwhile, the estimated values for  $R_d$  ranged from  $1.39 \pm 0.27$ - $1.90 \pm 0.17$ ,  $1.34 \pm 0.17$ - $1.67 \pm 0.17$  and  $1.12 \pm 0.10$ - $1.66 \pm 0.17 \mu\text{mol m}^{-2} \text{sec}^{-1}$  ( $p \leq 0.001$ ), as represented by their respective sites (Fig. 2b). Additionally, as with the values of  $R_{gr}$ , there were significantly lower  $R_{gr}$  in the 5 year old site than in the 10 and 18 year old sites ( $p \leq 0.001$ ), especially from May to June (Fig. 2c). In the 10 and 18 year old sites, similar patterns of  $R_{gr}$  were observed throughout the growing season.

**Changes in C gain and CUE:** The changes in DCG, as evidenced by the CO<sub>2</sub> effluxes in the grapevines and soil, are shown Fig. 3. The DCG reached its maximum value in August ( $3.53 \pm 0.48 \text{ g C m}^{-2}$ ) at the 5 year old site. Despite its overall lowest value in September ( $1.93 \pm 0.86 \text{ g C m}^{-2}$ ), the DCG differed greatly at the beginning stage, ranging from  $2.14 \pm 0.78$ - $2.22 \pm 0.90 \text{ g C m}^{-2}$ , compared with the other sites (Fig. 3a). The seasonal patterns for both the 10 and 18 year old sites were very similar to each other starting in June, although significant differences were observed ( $p \leq 0.001$ ). In addition, the CUE steadily decreased since the

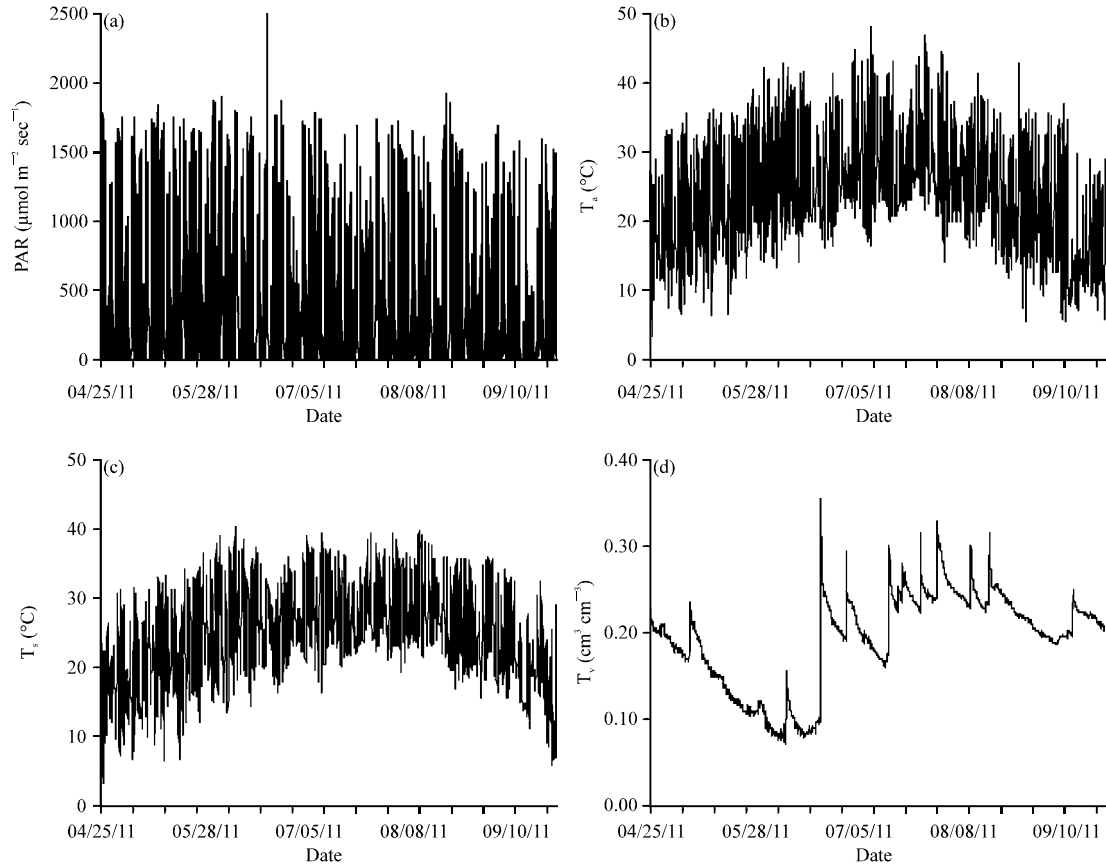


Fig. 1(a-d): (a) Seasonal patterns in the values of photosynthetically active radiation (PAR), (b) Air temperature ( $T_a$ ), (c) Soil temperature ( $T_s$ ) and (d) Volumetric soil water content ( $\Theta_v$ ) in a vineyard agroecosystem during the 2011 growing season

early growing season. On the other hand, the CUE in the 5 year old site steadily increased from May ( $0.021 \pm 0.004 \text{ mol mol}^{-1}$ ) to August ( $0.031 \pm 0.009 \text{ mol mol}^{-1}$ ) and then rapidly decreased in September ( $0.023 \pm 0.008 \text{ mol mol}^{-1}$ ) (Fig. 3b). Although a significant difference was found between sites ( $p < 0.001$ ), the CUE values were markedly lower in the 5 year old site than in both the 10 and 18 year old sites during May-June.

**Accumulation of above and belowground dry matter in grapevines:** There was a significant vine age effect on the dry matter accumulation in the above and belowground grapevines ( $p < 0.001$ ) (Fig. 4). The fruit bunch exhibited an increasing trend of dry mass from May-September. The significantly lower bunch dry mass of either 5 or 10 year old vines than 18 year old vines was found since the first month (Fig. 4a). Similarly, the dry matter increment of grape leaves was significantly higher in the 18 year old vines than in both the 5 and 10 year old leaves of (Fig. 4b). While the shoot dry matter accumulation was similar between the 10 and 18 year old vines, it was significantly higher in both these vine ages than in the 5 year old vines (Fig. 4c). On the other hand, the root dry matter accumulation was slightly different between vine ages during the growing season, except in June which was significantly greater in the 18 year old vines than in either the 5 or 10 year old vines (Fig. 4d). During the growing season, the litter dry



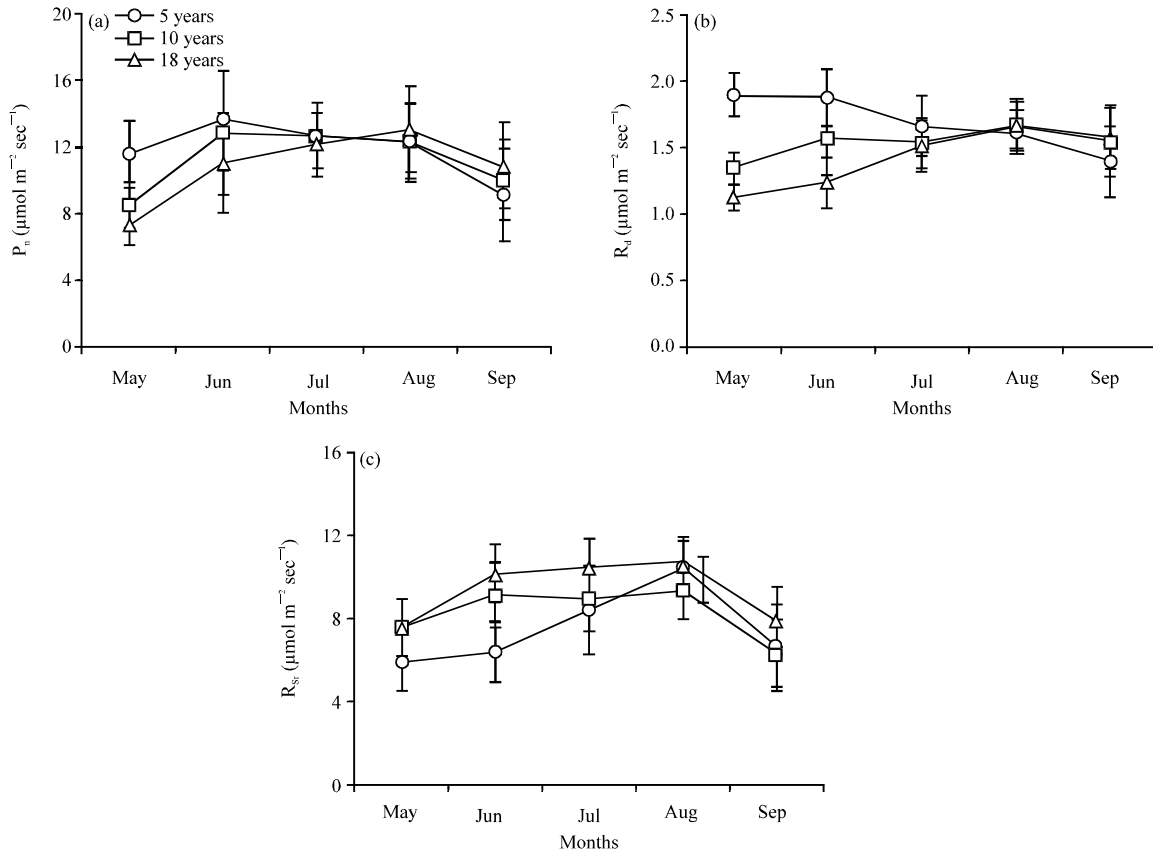


Fig. 2(a-c): (a) Seasonal patterns in the values of photosynthesis rate ( $P_n$ ), (b) Dark respiration ( $R_d$ ) and (c) Soil-root respiration ( $R_{sr}$ ) in three different vineyard sites during the growing season (error bars are the standard deviation)

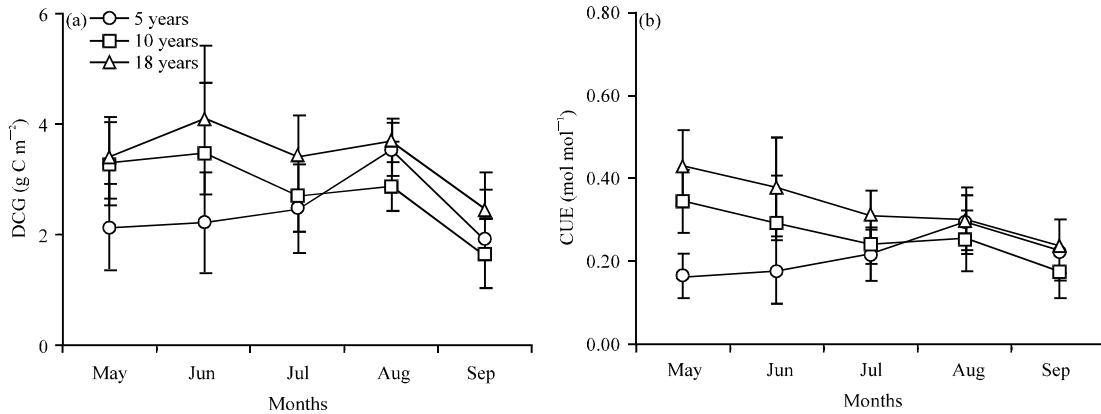


Fig. 3(a-b): (a) Seasonal patterns in the values of daily carbon gain (DCG) and (b) Carbon use efficiency (CUE) in three different vine ages during the growing season (error bars are the standard deviation)

mass was slightly higher in the 18 year old vines than either the 5 or 10 year old vines, whereas the highest litter dry mass was found in September. For all three vine ages, the relationship between stem dry mass and vine ages is given in Fig. 4e.

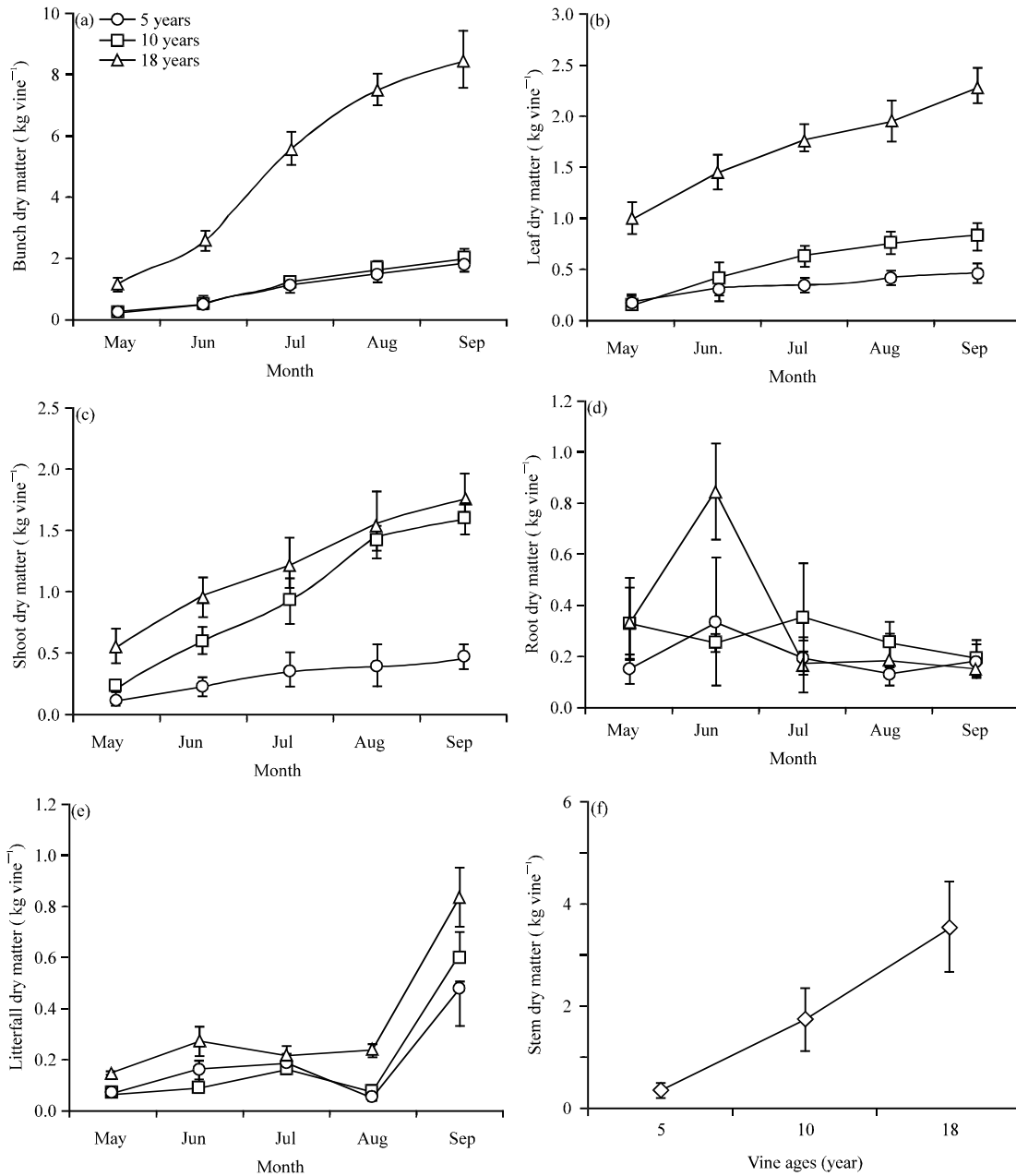


Fig. 4(a-f): (a) Seasonal patterns in dry matter values of bunches, (b) Leaves, (c) Shoots, (d) Roots and (e) Litterfall during the growing season and (f) The accumulation of stem dry mass in three different vine ages (error bars are the standard deviation)

**Carbon decomposition and accumulation in the vineyard:** Representative curves of C decomposition and accumulation throughout the growing season for vineyard pruning residues and manure are shown in Fig. 5. The total added C from pruning residues was significantly greater in the 18 year old site than in either the 5 or 10 year old sites (Fig. 5a). For all three sites, the C accumulation progressively increased from the early to end stages, especially in October which showed similar patterns and rates of the amount of total added C. In manure, C added to the soil was rapidly reduced after 30 days and steadily decreased throughout the experimental period. The

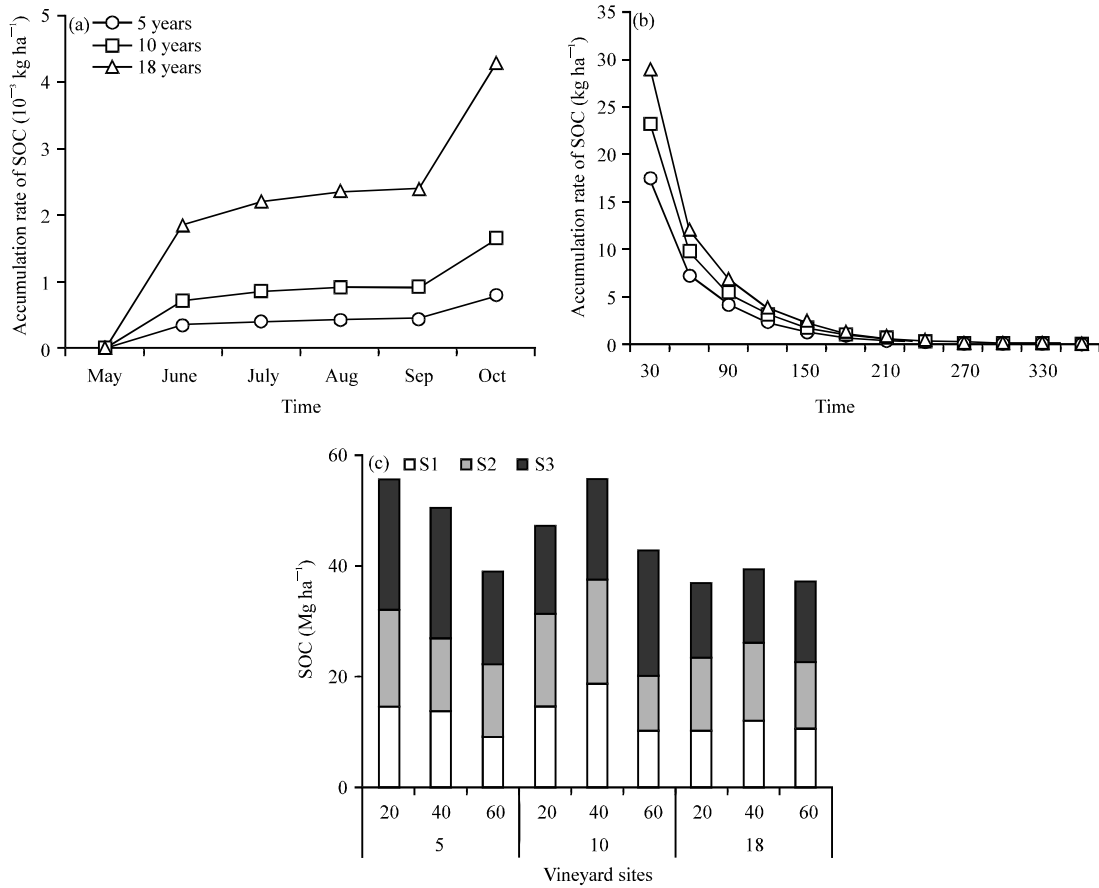


Fig. 5(a-c): (a) The estimation of soil organic carbon (SOC) accumulation rate from the litter production during 5 months after management, (b) Accumulation rate from the manure during 360 days after application and (c) Changes of SOC in October 2010 (S1), March 2011 (S2) and October 2011 (S3) at soil depths of 20, 40 and 60 cm in three different vineyard sites

highest decomposition rate was found in the 18 year old site (Fig. 5b). Of the three sites where SOC was measured, the largest difference in SOC between seasons was found at the last season (S3), being higher in both the 5 and 10 year old sites than the 18 year old site (Fig. 5c). However, at a 60 cm soil depth, the SOC was lower than the above two soil levels while it was slightly higher at 40 than 60 cm soil depths in the 18 year old site.

**Total C stock in the vineyard:** The total C stock values were different at each site (Fig. 6). The total C stock at the 18 year old site ( $77.04 \text{ Mg ha}^{-1}$ ) was greater than that of either the 5 or 10 year old sites ( $55.41$  and  $66.92 \text{ Mg ha}^{-1}$ , respectively). Although, the highest C stock in plant living parts and litter production was found in the 18 year old site ( $38.72$  and  $0.51 \text{ Mg ha}^{-1}$ , respectively) there was a slightly lower SOC in the 18 year old site than in the 5 or 10 year old sites ( $48.46$  and  $48.62 \text{ Mg ha}^{-1}$ , respectively). Therefore, the relationship between vine ages and C stock in the grapevine could be calculated by the power regression equation ( $y = 0.7413x^{1.3736}$ ,  $r^2 = 0.999^*$ ) (Fig. 7a). Meanwhile, the power regression between vine ages and total C stock in the vineyard was represented by the following equation:  $y = 36.72x^{0.2677}$  ( $r^2 = 0.998^*$ ) (Fig. 7b).

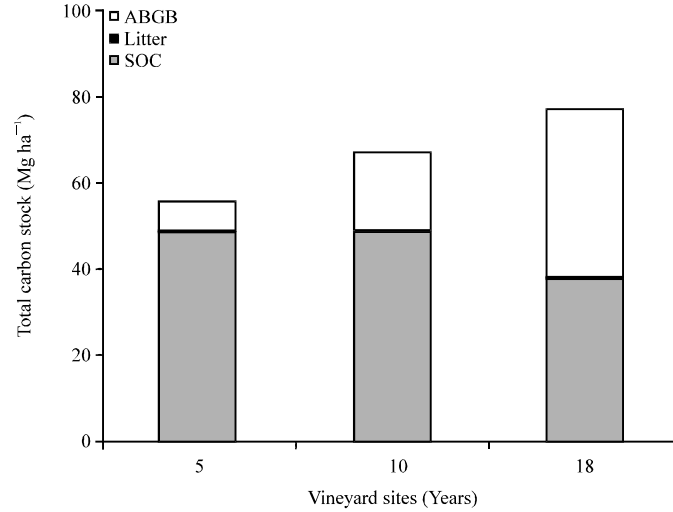


Fig. 6: Total carbon stock from above-belowground biomass (ABGB), litterproduction and soil organic carbon (SOC) in three different vineyard sites during the growing season 2011

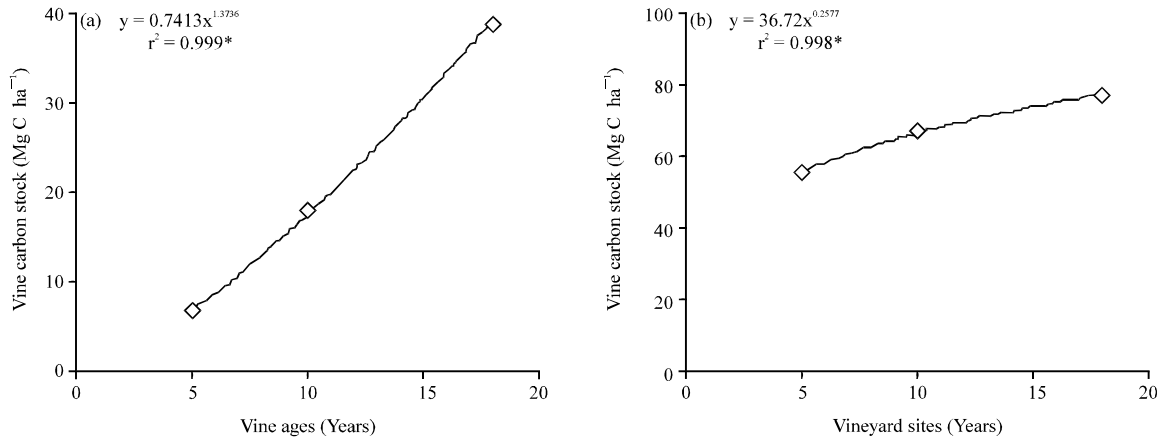


Fig. 7(a-b): (a) Relationship between vine ages and vine carbon stock from above-belowground biomass and (b) Relationship between vineyard sites and total carbon stock in a northern China vineyard

## DISCUSSION

**Seasonal microclimate factors and CO<sub>2</sub> effluxes in grapevines and soil:** In this study, the P<sub>n</sub> response was due to the effect of leaf ages which may be attributed to their acclimation rate of photosynthesis with changing leaf development stages. It was previously reported that different ages of leaves could be subjected to variable photosynthetic capacities during the growing season (Zhang *et al.*, 2008; Whitehead *et al.*, 2011).

However, the acclimation of R<sub>d</sub> to diurnal temperature varied by different vine ages and seasons because the seasonal dynamics in R<sub>d</sub> were derived from a proportion of P<sub>max</sub> which had the highest values in 5 year old vines during May to June. This study indicates that seasonal changes in R<sub>d</sub> depended on the response of individual leaves to variations in diurnal temperature which was particularly sensitive to respiration at the leaf level of the vines (Zufferey *et al.*, 2000).

Differences in  $R_{sr}$  between the sites during this study period were substantial. Because  $R_{sr}$  increased or decreased with temperature, these variations in soil warmth were larger in the summer than the other seasons (Jia *et al.*, 2012). Additionally,  $R_{sr}$  was particularly responsive to the variation in  $\Theta_v$ , especially for the changes in the 5 year old vines which were the lowest in this regard in the early season. This relation suggests that the soil moisture range influences soil respiration directly, although the possibility of  $CO_2$  efflux may have been limited when the  $\Theta_v$  decreased below  $0.15 \text{ m}^3 \text{ m}^{-3}$ , as was found in the 5 year old site during May to June. However, the temperature may have been a main controlling factor when  $\Theta_v$  exceeded  $0.15 \text{ m}^3 \text{ m}^{-3}$  (Xu *et al.*, 2004) under the 10 and 18 year old sites throughout the growing season. Other factors controlling root respiration, such as root age, root diameter and soil nitrogen concentration, have also been reported in forest ecosystems (Fukuzawa *et al.*, 2012).

Therefore, the  $CO_2$  effluxes of grapevines and soil organisms were markedly changed in the seasonal pattern fluctuation by the limiting of PAR,  $T_a$ ,  $T_s$  and  $\Theta_v$  under the vineyard ecosystem. This effect was due to the local climate conditions in both the short- and long-term climatic variables which are principal drivers controlling C effluxes in plants and soil (Perez-Quezada *et al.*, 2010).

**Growing season changes in DCG and CUE:** In the DCG result, it was also affected by leaf development stages. This difference is evidence that the response of DCG was associated with the photosynthetic capacity and respiration (Wythers *et al.*, 2005) which may exhibit high rates during the initial growth period (Timlin *et al.*, 2006). Therefore, in addition to environmental factors, it is likely that leaf development contributed appreciably to limiting the C gain in relation to vine ages.

Despite the influence of temperature acclimation in CUE which declined with increasing temperature in the crop plants (Frantz and Bugbee, 2005) or in the soil (Tucker *et al.*, 2012), CUE could be decreased by responses to light conditions (Frantz *et al.*, 2004). Therefore, management practices in term of the vine canopy light environment may play an important role in determining CUE in the vineyard, as PAR had large effects on leaf photosynthesis responses (Albrizio and Steduto, 2003). Similarly, CUE could possibly be linked to the estimation of gross primary production in the apple orchard (Zanotelli *et al.*, 2012).

**Vine ages and C stock in the vineyard:** It is generally accepted that because grapevines are indeterminate in growth habits, the amount of all biomass partitioning is continuously produced in different living parts under seasonal growth and development (Poni *et al.*, 2000). Despite the environmental factors, vine canopy size may vary with the number of nodes per vine retained by pruning management (Field *et al.*, 2009). Therefore, the seasonal dynamics of vegetative dry biomass usually vary between years in total vine mass (Tarara *et al.*, 2009). Although the results show that there were significantly greater values for dry biomass in the canopy of the oldest grapevine compared with both younger grapevines ( $p < 0.001$ ), particularly in the bunch and leaf dry mass, the growth performance in their seasonal patterns should be considered to influence their biomass production (Lin *et al.*, 2010). The result indicates that C storage in different parts of the grapevine to vine dry mass differed between vine ages and varied seasonally. Thus, more C should be assumed to be fixed per vine in 18 year old vines as the highest dry mass per vine seasonally.

As a result of the variability due to growing seasons, the litter product from the leaf litterfall and returned prunings accounted for significantly more OC in terms of dry mass in the 18 year old vineyard than the other vineyards. This result was due to the seasonal leaf litter production in high

vegetation which was mainly a result of the accumulation of OC (Murovhi *et al.*, 2012). Therefore, the decomposition of OC from surface residue returning to the vineyard floor also showed significant differences among sites and seasonal changes. This study indicates that although the amount of C return through total litterfall was very low, it was eventually decomposed to provide a valuable SOC in the vineyard agroecosystem.

Accordingly, in part of the soil, each vine site showed less variation in the soil section, with a range of 37.82-48.62 Mg C ha<sup>-1</sup> which was consistently higher in the C stock than the living grapevine parts. Not surprisingly, there was also less C stock in the vine parts than in the vineyard soil (84.10 Mg C ha<sup>-1</sup>) as obtained to a 1 m soil depth (Williams *et al.*, 2011). However, C sequestration in agroecosystems may be gradually increased in the soil or decline under different production practices, depending mainly on the implementation of long-term seasonal changes (David *et al.*, 2009).

This study shows that the total C stock in the different vineyard sites varied from 55.41-77.04 Mg C ha<sup>-1</sup>. The results are also similar to those previously reported for sugarcane plantation (50 Mg C ha<sup>-1</sup>) (Moundzeo *et al.*, 2011) and tropical agroforestry systems (95 Mg C ha<sup>-1</sup>) (Albrecht and Kandji, 2003). Meanwhile, the total C stock in other vineyards was, on average, approximately 87.10 Mg C ha<sup>-1</sup> in California (Williams *et al.*, 2011).

## CONCLUSION

The seasonal C balance of various parts of grapevines can be determined as daily local climate and soil variables in vineyards. Consequently, seasonal patterns in the C dynamics of effluxes and stocks can be acclimated differently under different environmental conditions, seasonal changes and vine ages. Moreover, a large portion of the C which is mainly stored both by the vine biomass and the soil under the vineyard agroecosystems, is dependent on the role of its production and soil quality under manipulated management practices. This study indicates that a vineyard can be potentially considered as an important C sink under future climate change scenarios. Therefore, it is an important strategy to consider the potential C stock in vineyard agroecosystems to mitigate impacts on the environment and to evaluate the capability to quantify C dynamics in China's vineyards.

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